Effects of Ethanol Addition to LPG or to Gasoline on Emissions of Motorcycle Engines Operating Under Urban Conditions

Bui Van Ga*, Tran Thanh Hai Tung, Bui Thi Minh Tu, and Bui Van Tan

Abstract—The paper presents the effects of ethanol addition to LPG or gasoline on CO and NOx emissions of motorcycle engines operating under urban conditions. Compression ratio, engine speed, advance ignition timing and ethanol content in the fuel mixtures have been taken into account. The addition of ethanol to LPG or gasoline reduces the emission of CO and NOx as compared to the sole fuels. At a given ethanol content, ethanol-LPG fueling mode produces less CO and NOx concentrations than those of ethanol-gasoline fueling mode. The increase of the compression ratio results in a decrease of CO concentration but an increase of NOx concentration. Effects of compression ratio on CO, NOx emission becomes moderate with an increase of ethanol content. The higher is the loading regime, the higher is the CO emission but the lower is the NOx emission. At a fixed advance ignition angle, the higher engine speed results in a higher CO concentration but a lower NOx concentration. At any given engine speed, the CO emission is reduced but the NOx emission is increased with early ignition timing. Motorcycle engine fueled with ethanol-LPG, operating at speed in range 4000-5000 rpm is optimal for pollutant emission control.

Keywords—Alternative fuels, air Pollution, ethanol, motorcycle emission, renewable fuels.

1. INTRODUCTION

The emissions of pollutants from two-wheelers are becoming a major problem for air quality control in many countries [1]. Currently, motorcycles constitute about 30% of total motorized vehicles worldwide [2]. In middle- and low-income countries in Asia, the share of motorcycles is much higher, varying between 50% and 90% depending on socio-economic characteristic [2]. The five largest motorcycle markets are India, China, Indonesia, Vietnam, and Pakistan [3]. For example, in Vietnam the number of motorcycles has increased from 1.2 million in 1990 to over 58 million in 2018. Hanoi and Ho Chi Minh City have the largest numbers, with nearly 6 million and 8.5 million, respectively [3]. The emissions from these vehicles seriously degrade air quality and thus, negatively affect the living environment.

Some developing countries are considering banning motorcycles from inner city areas but the infrastructure for public transportation is not well developed, and therefore, the motorcycles remain the main means of transportation for a long future. Many attempts have been made to reduce the emissions of motorcycles but due to the compactness of the vehicle, there are not many technology solutions that can be applied. The ideal solution maybe the electric motorcycle. This kind of motorcycles has been commercialized by different constructors around the world. However the limited capacity of energy storage of the batteries is the barrier to the wide use of electric motorcycles in practice [4].

The motorcycle powered by hydrogen fuel cell can be perhaps a future solution. It has been studied and patented by several well-known motorcycle companies, such as Honda, Suzuki…[5-6]; however the biggest problem must be solved before commercialization of the vehicles is the technology of hydrogen storage onboard of the vehicle. Hybrid motorcycle with an alternative use of electrical energy and traditional fuels maybe a competitive vehicle for traditional motorcycle in near future [7-8].

The above fundamental revolution of power solution for motorcycle needs a strong investment in research development. In looking for future of new cleaner motorcycle generation, the research to reduce the emissions of the current and in-used motorcycles will be very helpful for air pollution control in many countries in South East Asia.

There are many works on the application alternative fuels such as CNG, LPG on motorcycles. CNG is a potential alternative fuel to reduce pollution. The average of HC and CO emissions of the CNG maybe 92 % and 78 % respectively lower than that of the gasoline [9]. However the bulky CNG cylinder and high-pressure of natural gas storage are the main barriers to the wide application of this alternative fuel on the compact size of motorcycles. Because LPG with low liquefied pressure can overcome the inconvenience of CNG, application of LPG on motorcycle has been demonstrated as an appropriate solution to reduce emission of the vehicle [10-12].

Although LPG is advantageous against other liquid fossil fuels in general, the emissions of the LPG motorcycle engines should be considered as it operates under urban conditions. In fact, in downtown, the vehicle often operates under partial loading regime which worsen the combustion, resulting in an increase of pollutant emission. Thus, the technology of reduction of motorcycle emission at partial loading regime is necessary to improve air quality in cities.
The combination of potential LPG as alternative fuel and the advantage of renewable fuels maybe an appropriate way to improve the combustion efficiency and reduce the pollution emissions under urban operating conditions. Among the renewable fuels, ethanol is more attractive because it has better physical properties such as greater enthalpy of vaporization, larger octane number, higher flame speed and good lean-burn behaviors [13-15]. Besides, the presence of oxygen within the ethanol fuel allows a faster combustion, improves engine efficiency and reduce emission [16]. High latent heat of vaporization of ethanol can cool down the charge which allows an increase of engine volume efficiency [17-18]. With these advantageous properties, ethanol is widely applied as an additive to gasoline in many countries around the world.

However, the charge cooling effect due to high latent heat of ethanol evaporation in gasoline-ethanol blend can result in a difficulty at cold start and low loading regime of SI engine. In these regimes, to ensure efficient operation, a rich mixture is needed. The over-fueling in low loading regime can result in a negative effect on engine performance and pollutant emissions in exhaust gas [19].

Using ethanol as an additive for LPG may be overcome the above inconvenience. LPG can evaporate and diffuse in the air at very lower inlet temperature than is possible with any liquid fuels. As it is in gaseous state at ambient conditions, the operating conditions of the engine are not affected to the homogeneity of the mixture. Thus, the engine can operate with very lean mixture, particularly at low loading conditions of urban regime. The emission levels of LPG engine are almost independent with intake air temperature [20]. As compared to gasoline, the emissions of LPG vehicle are significantly reduced. In general, the emissions of NOx and CO of LPG fueled vehicle are 20% and 60% less than those of gasoline fueled vehicle [21]. When LPG is in blend with ethanol, high oxygen content in the alcohol fuel can accelerate the combustion speed, promoting the complete combustion so HC and CO emissions are still lower obviously. Lanje [22] studied the performance and emission characteristics of single cylinder, 4-stroke, SI engine fueled with blends of LPG-Ethanol. The obtained result shows that blend of LPG-Ethanol fuel have closer performance to gasoline fuel, but the concentration levels of CO, CO2 and unburned HC are found to be lower than the gasoline fueled engine. Paolo et al. [23] remarked generally that the higher oxygen content in fuel, the lower CO and NOx emissions were observed.

Cetin [24] carried out experimental study of SI engine fueled with LPG-ethanol blend and found that 15% ethanol in the mixture with LPG was the most suitable for reduction of emissions of CO and NOx. As ethanol content is higher than this limit, CO emission increased with engine speed [24]. When ethanol is added to LPG, combustion temperature decreases leading to a decrease of NOx emission [24]. Rahman [25] has tested SI engine fueled with LPG enriched E20 and noted that as compared to E20, when LPG is inducted to the fuel, the reduction of HC, CO, CO2 is in range of 13-14%, 14-15% and 12-18% respectively but the concentration of NOx was increased by 13-16% at full operational mode.

As SI engine fueled with LPG, CO and HC emissions increase as the engine speed and loading regime increase [26]. Chitragar [27] reported that induction of LPG with gasoline improves CO, HC and NOx emissions. The induction of LPG with ethanol is thus, a renowned interest in the recent time [26].

The above bibliography research shows the interest of application ethanol-LPG fuel mixture in SI engine to reduce the emission, but the results are almost concerning the car engines and at rate operating conditions. The motorcycle engines have some different specifications such as small cylinder, high speed, air cooling... It is thus anticipated that the study on emissions behaviors of the SI engine fueled with ethanol additive to LPG or to gasoline in partial loading regime will be essential for an insight of pollutants emission of motorcycle in urban operating conditions. In present work, the simulation of combustion and CO, NOx emissions was performed on two types of 110cc Honda motorcycle SI engine: One with compression ratio of 11 and the other with compression ratio of 9. They are the most popular engines used to motorize the two-wheelers recently.

The aim of this research is to elucidate the effects of engine specifications, operating conditions and ethanol content in the mixture with LPG or gasoline on the emission of CO and NOx of motorcycle engines under urban condition. The results of this research suggest an appropriate way to control the air pollution emission in cities with high density of two-wheelers.

2. MATERIAL AND METHOD

Fig. 1 presents the motorcycle engine with retrofit injection system for fueling ethanol/gasoline/LPG. An ICU (Injection Control Unit) and a LPG injector are added to control the injection. The ECU and the sensors are kept as their originals. The output signal of the ECU is the input of the ICU instead of actuating the original gasoline injector. The output modular signal of the ECU is divided in two channels with determined ratio of injection duration, one controls the ethanol/gasoline injector and the other controls the LPG injector. The ratio of injection duration determines the proportion of fuel injected. It can be controlled automatically by the embedded program or by manual.

In this study, ethanol and gasoline is mixed together with a given volume ratio before injection (namely pre-blended injection) meanwhile ethanol and LPG are injected separately (dual injection). Two models of 110cc Honda motorcycle engine were used in the study. They are practically of the same displacement volume but compression ratio is 11 for the engine 1 and 9 for engine 2. The specifications of the engines are shown in Table 1.

Gasoline injector of the engine is used for injecting ethanol or ethanol-gasoline blend. A LPG injector of automobile is adopted for injecting LPG in gaseous state. A 2-liter LPG cylinder is added to luggage box of the motorcycle whereas original fuel tank remains for liquid fuel.
Retrofit Honda motorcycle engine to operate with ethanol-LPG or ethanol-gasoline.

Table 1. Specifications of Honda 110 cc Engines

<table>
<thead>
<tr>
<th>Engine characteristics</th>
<th>Engine 1 (Honda Lead 110 cc)</th>
<th>Engine 2 (Honda Wave Alpha 110 cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine type</td>
<td>4-stroke, Fuel Injection</td>
<td>4-stroke, Fuel Injection</td>
</tr>
<tr>
<td>Number of cylinders</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Bore (mm)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Stroke (mm)</td>
<td>55</td>
<td>55.6</td>
</tr>
<tr>
<td>Displacement (cm³)</td>
<td>108</td>
<td>109.1</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>11:1</td>
<td>9:1</td>
</tr>
<tr>
<td>Rated power/speed</td>
<td>6.4/7500</td>
<td>6.12/7500</td>
</tr>
<tr>
<td>gasoline fueling (kW/rpm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rated torque/speed</td>
<td>9.2/6000</td>
<td>8.44/6000</td>
</tr>
<tr>
<td>gasoline fueling (Nm/rpm)</td>
<td></td>
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</tbody>
</table>

The modified ethanol/LPG/gasoline motorcycles operated smoothly in practice. In this work the emissions of the motorcycle engines were studied by numerical simulation. The experimental measurements will be carried out in the next step of our research.

The simulation of combustion and emissions of the motorcycle engines was carried out with help of the commercial Computational Fluid Dynamics (CFD) package ANSYS Fluent. The fundamental governing equations of fluid dynamics closed by the k-ε turbulence model. The 3D pressure based implicit unsteady solver available in ANSYS Fluent code is used to solve the basic governing equations. The equations are spatially discretized by means of the finite volume method using the STANDARD scheme for pressure interpolation. The discretization scheme for the convective term of transport equations used the first-order upwind scheme. The pressure-velocity coupling in the discretized equations is performed using the semi-implicit method for pressure linked equations (SIMPLE) algorithm to solve the pressure field. A similar simulation has been described in detail in our previous work [28]. The basic properties of considered fuels are shown in Table 2.

The formation of thermal NOₓ is determined by a set of highly temperature-dependent chemical reactions known as the extended Zeldovich mechanism as follows:

O + N₂ = N + NO  \hspace{1cm} (1)
N + O₂ = O + NO  \hspace{1cm} (2)
N + OH = H + NO  \hspace{1cm} (3)

The net rate of NOₓ formation is given by:

\[
\frac{d[NO]}{dt} = k_{f,1}[O][N₂] + k_{f,2}[N][O₂] + k_{f,3}[N][OH] - k_{r,1}[NO][N] - k_{r,2}[NO][O] - k_{r,3}[NO][H] \hspace{1cm} (4)
\]

where \(k_{f,1}, k_{f,2}\) and \(k_{f,3}\) are the rate constants for the forward reactions (1-3), respectively, and \(k_{r,1}, k_{r,2}\) and \(k_{r,3}\) are the corresponding reverse rate constants.

To calculate the NOₓ formation rate, the concentrations of O, H and OH are required. They are the equilibrium values of species in the following set of combustion reactions:

\[
\frac{1}{2} H₂ = H  \hspace{1cm} (5)
\frac{1}{2} O₂ = O  \hspace{1cm} (6)
H₂O = OH + \frac{1}{2} H₂  \hspace{1cm} (7)
2H₂O = 2H₂ + O₂  \hspace{1cm} (8)
CO₂ + H₂ = H₂O + CO  \hspace{1cm} (9)
\]

Thus, in the following section, CO concentration is calculated by equilibrium schema with help of Partially Premixed Combustion Model and NOₓ emission is calculated by Thermal NOₓ model integrated in the Fluent software.

3. RESULTS AND DISCUSSION

3.1. Variation of CO and NOₓ concentrations in combustion chamber

Fig. 2 presents the contours of NOₓ concentration, CO concentration, temperature and total hydrocarbon at 5°CA after ignition of the engine 1 fueled with stoichiometric mixture of E20L, operating at 5000 rpm. It can be seen from these figures that the highest CO concentration is found in the center of the burned zone while as the highest NOₓ concentration zone was found in the reaction region which displaces gradually from the ignition point to the cylinder wall.
Table 2. Chemical and Physical Properties of Ethanol, Gasoline, Propane and Butane

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Formula</td>
<td>C₂H₅OH</td>
<td>C₈ to C₁₂</td>
<td>C₃H₈</td>
<td>C₄H₁₀</td>
</tr>
<tr>
<td>Molecular weight [g/mol]</td>
<td>46.07</td>
<td>105</td>
<td>44</td>
<td>58</td>
</tr>
<tr>
<td>Carbon [mass%]</td>
<td>52.2</td>
<td>88</td>
<td>82</td>
<td>83</td>
</tr>
<tr>
<td>Hydrogen [mass%]</td>
<td>13.1</td>
<td>12-15</td>
<td>18</td>
<td>17</td>
</tr>
<tr>
<td>Oxygen [mass%]</td>
<td>34.7</td>
<td>2.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Liquid density [kg/m³]</td>
<td>790</td>
<td>751</td>
<td>508</td>
<td>584</td>
</tr>
<tr>
<td>Boiling point [°C]</td>
<td>78</td>
<td>27-225</td>
<td>-42</td>
<td>-0.5</td>
</tr>
<tr>
<td>Vapor pressure [kPa] at 38°C</td>
<td>15.9</td>
<td>48-103</td>
<td>858.7</td>
<td>215.1</td>
</tr>
<tr>
<td>Specific heat [kJ kg⁻¹ K⁻¹]</td>
<td>2.4</td>
<td>2</td>
<td>1.63</td>
<td>1.675</td>
</tr>
<tr>
<td>Latent heat of vaporization [kJ/kg]</td>
<td>840</td>
<td>305</td>
<td>426</td>
<td>385</td>
</tr>
<tr>
<td>Low heating value [MJ/kg]</td>
<td>26</td>
<td>43</td>
<td>46.1</td>
<td>45.5</td>
</tr>
<tr>
<td>Autoignition temperature [°C]</td>
<td>423</td>
<td>257</td>
<td>480</td>
<td>440</td>
</tr>
<tr>
<td>RON</td>
<td>108.6</td>
<td>98</td>
<td>111</td>
<td>103</td>
</tr>
<tr>
<td>Stoichiometric air/fuel</td>
<td>9</td>
<td>14.7</td>
<td>15.65</td>
<td>15.43</td>
</tr>
<tr>
<td>Laminar flame velocity at 100 kPa, 325 K (cm/s)</td>
<td>39</td>
<td>33</td>
<td>38</td>
<td>37</td>
</tr>
</tbody>
</table>

Fig. 2. Contours of NOₓ concentration (a), CO concentration (b), temperature (c) and total hydrocarbon (d) at 5°CA after ignition (ε=11, α=45°, E25L, ϕ=1, ϕₛ=20°CA)

The CO concentration tends to its equilibrium value by the reaction (5-9) whereas the NOₓ concentration depends on the time by the reaction rate (4). Thus, the any factors affecting the combustion duration such as engine speed, advance ignition timing, laminar flame speed… obviously affects to CO and NOₓ emissions.

Fig. 3a and Fig. 3b illustrates the variation of CO concentration with crank angle of the engine 1 with fixed advance ignition angle at ϕₛ=20°CA, operating under the same partial loading α=45° but fueled with E25L and E25G. Engine speed varies from 2000 rpm to 7000 rpm. In any case of fuel supplying, the CO concentration increases sharply during the first phase of combustion. It reaches a peak and then decreases gradually to a stable value at the end of expansion stroke. This can be explained by the fact that the CO concentration in combustion chamber is produced by incomplete combustion and the water-gas reaction (9). CO production mainly occurs during the robust combustion phase with high products temperature. After this phase, it is burned and reach equilibrium value. As it has been mentioned above, the long combustion duration (low engine speed regime) favorites the equilibrium of CO concentration in combustion products.

The results show that the profiles of CO concentration curves are not quite different as the engine is fueled with E25L or E25G. However the CO concentration in the exhaust gas increases significantly in fuel rich mixture. Otherwise, the rate of increasing CO concentration in the case of E25G drops down more quickly with the increase of engine speed as compared to the case of E25L. This is because the laminar flame speed of the first case is lower than that of the second case. In urban operating conditions, motorcycles often operate with low loading
regime. In these conditions, if the engine is fueled with traditional liquid fuels, the charge mixture must be rich to ensure normal combustion, thus, the emissions increase. However, if a blend of LPG and liquid fuels is used, the engine can operate with leaner charge at low loading regime due to the mixture is more homogeneous, hence the emissions can be reduced.

The results in the figure show concretely that as the engine 2 operates at partial loading $\alpha=30^\circ$, CO concentration in the exhaust gas decreases by 25% as shifting from sole LPG fueling mode to E50\textsubscript{l} fueling mode. At a given ethanol content, the CO concentration decreases with an increase of compression ratio. This can be ascribed by the fact that the combustion temperature increases with the increase of compression ratio resulting in an increase of laminar flame speed which lowers down the CO emission. The higher ethanol content is, the...
lower effect of the compression ratio on CO emission is. The results in Fig. 5 show that as the compression ratio increases from 9 to 11, the reduction of CO concentration is by 13% in case of sole LPG fueling mode, but by only 2% in case of E50, fueling mode. This is because of charge temperature reduction as increasing ethanol content in the fuel mixture dominates the effect of the increase of compression ratio.

Fig. 5. Variation of CO and NOx concentrations with respect to additive ethanol concentration to LPG (n=5000 rpm, \(\alpha=30^\circ\), \(\phi=1, \phi_s=20^\circ\text{CA}\)).

It can be noted as well that the high content of ethanol in the fuel lowers down the NOx concentration. In fact, due to high heat latent of ethanol, the charge temperature decreases as ethanol content in the fuel mixture increases. This leads evidently to a decrease of NOx concentration. It can be seen in Fig. 5, as compared to sole LPG fueling mode, the E50, fueling mode can reduce by 15% NOx emission for the engine 1 and 7% for the engine 2. The NOx concentration increases with the increase of compression ratio due to the increase of combustion temperature. Similarly the CO emission, the effects of compression ratio on NOx emission gradually moderate as ethanol content in the fuel mixture increases. As compression ratio increases from 9 to 11, the NOx concentration increases by 25% in case of sole LPG fueling mode and by 15% in case of E50, fueling mode.

The throttling or loading regime of the engine affects to CO and NOx emissions through pressure and temperature of combustion. As loading regime of the engine decreases, less charge is inducted into the cylinder leading to the decrease of pressure and temperature of combustion, the CO and NOx emissions are thus, reduced. Fig. 6a and Fig. 6b present the variation of CO and NOx concentrations with respect to ethanol content in the mixture with LPG and gasoline in case of partial charge \(\alpha=45^\circ\). As compared to Fig. 5 in case of \(\alpha=30^\circ\), it can be noted that the CO and NOx concentrations significantly decrease with a decrease of engine loading regime. In average, with the same compression ratio and ethanol content in the fuel mixture, as the butterfly valve close from \(\alpha=30^\circ\) to \(\alpha=45^\circ\), the reduction of CO and NOx emission is by 30% and 20% respectively. This can be ascribed by the fact that the decrease of engine loading regime leads to an decrease of charge mass and combustion temperature which lowers down the reaction rate of CO and NOx formations.

Generally, the induction of ethanol with LPG or gasoline could reduce CO emission as compared to the sole fuel-operated engine. This can be ascribed by the fact that the induction of ethanol improves oxidation reaction to convert CO into CO2 at elevated temperature as it has been mentioned above. However, it can be observed a significant difference between ethanol-gasoline fueling mode and ethanol-LPG fueling mode in CO and NOx emissions as shown in Fig. 6a and Fig. 6b. With the same compression ratio, the CO concentration of ethanol-gasoline fueling mode decreases more sharply than that of the ethanol-LPG fueling mode. The CO concentration in the exhaust gas reduces about 50% as
shifting from gasoline fueling mode to LPG fueling mode. However, there is almost no difference between these two fueling modes as the engines is fueled with E50_G and E50_L. In fact, as the ethanol content in the fuel mixture increases, the charge cooling due to evaporation of ethanol becomes more significant that moderates the difference of combustion temperature of E50_G and E50_L fueling modes.

With a given compression ratio and n=5000 rpm, \( \varphi_s=20^\circ\text{CA} \), due to the higher adiabatic combustion temperature of ethanol-LPG mixture as compared to ethanol-gasoline mixture, the NOx emission increases as shifting from ExG fueling mode to ExL fueling mode at any ethanol content in the fuel mixture. Contrarily in case of CO emission, the difference in NOx emission between the two fueling modes significantly increases with the increase of ethanol content in the fuel mixture. As shifting from ethanol-LPG fueling mode to ethanol-gasoline mode, the NOx concentration decreases by 5% and 20% as the considered engines are fueled with sole fuels and with the addition 50% ethanol respectively.

![Fig. 7. Comparison of variation of CO and NOx concentrations with respect to engine speed as the engine 2 is fueled with LPG and E20L (\( \varphi_s=9 \)) and \( \varphi_s=20^\circ\text{CA} \).](image)

3.3. Effect of engine speed

As it has been mentioned above, the concentrations of CO and NOx in exhaust gas depend on combustion duration, hence depend on engine speed. As engine speed decreases, the combustion duration becomes longer leading to an equilibrium of CO concentration in combustion products. Contrarily in case of high engine speed, the peak of CO concentration is shifted far away the TDC, product temperature decreases moderating the reduction reaction of CO, thus CO concentration in exhaust gas increases. Fig. 7 presents the variation of CO and NOx concentrations with respect to engine speed as the engine 2 is fueled with LPG and E20_L. It can be seen from the figure that the CO emissions increased with the increase of engine speed. At low engine speed, the long combustion duration contributes to the enhanced combustion of the fuel-air mixtures, hence the combustion is more complete. Otherwise, the long presence of combustion mixture under high temperature helps in the oxidation to convert CO to CO\(_2\), syngas (CO+H\(_2\)), via endothermic process leading to a reduction of CO in the exhaust gas. The results show that when the engine speed increases from 2000 rpm to 7000 rpm, the CO emission of the engine 2 increases by 20% and 30% as it is fueled with sole LPG and with E25_L respectively.

![Fig. 8. Comparison of variation of CO concentration (a) and NOx concentration (b) in the exhaust gas with respect to engine speed as the engine 1 and the engine 2 are fueled with E25G and E25L (\( \alpha=45^\circ\), \( \phi_s=1.05 \), \( \phi_s=20^\circ\text{CA} \)).](image)
higher than that of case E25L. The difference between these two fueling modes becomes larger at high engine speed. This can be ascribed by the fact that the wide diffusion of LPG gaseous fuel benefits the homogeneity of the mixture which reduces the probability of occurrence of incomplete combustion thus, reduce CO emission as compared to liquid fuels.

Fig. 8b presents a comparison of NOx emission of the engine 1 and the engine 2. It can be seen that at low engine speed, E25G fueling mode produces more NOx than E25L fueling mode. But the NOx concentration of E25G fueling mode drops down more significantly with the increase of engines speed. Thus at high engine speed, NOx emission of E25G fueling mode becomes lower than that of E25L fueling mode. This is due to the combustion temperature of E25G decreases more quickly with the increase of engine speed as compared to the case of E25L.

#### 3.4. Effect of advanced ignition timing

Fig. 9 presents the variation of CO and NOx concentrations with respect to advance ignition angle of the engine 1 and the engine 2. The engines operate at speed of 5000 rpm, fueled with stoichiometric mixture of E20. The results show that the increase of advance ignition angle results in a decrease of CO concentration but an increase of NOx concentration. This can be ascribed by the fact that at a given engine speed, the increase of advance ignition angle leads to an increase of combustion duration, a decrease in CO concentration and an increase in NOx concentration are thus, as a result. It is the same reason as engine speed decreases at a fixed advance ignition timing. The results show that as advance ignition angle increases from 11°CA to 29°CA, the CO emission is reduced by 40% and the NOx emission increases by 35%.

![Figure 9](image1)

Fig. 9. Variation of CO and NOx concentrations with respect to the advance ignition angle as the engine 1 and the engine 2 are fueled with E25L. (n=5000rpm, α=30°, ϕ=1).

Fig. 10 illustrates the effect of equivalence ratio on variation of CO and NOx concentrations with advance ignition angle as the engine 1 (ϕ=11) is fueled with E25G. It is obvious that CO concentration decreases significantly but the NOx concentration decreases slightly as the equivalence ratio of the mixture decreases from 1.05 to 0.95. With a given equivalence ratio, the CO emission decreases but NOx emission increases with the increase of advance ignition angle. The results show that as the advance ignition angle increases from 11°CA to 29°CA, the CO emission decreases by 25% while the NOx emission increases by 80%.

![Figure 10](image2)

Fig. 10. Variation of CO and NOx concentrations with respect to the advance ignition angle as the engine 1 is fueled with E25G (n=5000rpm, ϕ=11, α=45°).

![Figure 11](image3)

Fig. 11. Variation of CO and NOx concentrations with respect to engine speed as the engine 1 is fueled with E25L and E25G, and the advance ignition angle increases linearly with engine speed (ϕ=1.02, ϕ=11, α=45°).

...
presented in Fig 9 and Fig. 10. Fig. 11 shows the variation of CO and NOx concentrations with the speed of the engine 1 fueled with E25L and E25G at stoichiometric mixture. The advance ignition angle is assumed to increase linearly with engine speed. The results show that in both cases of fueling mode, CO and NOx curves exhibit a minimum value corresponding to engine speed in the range of 4000-5000rpm. Outside of this range, the emissions of CO and NOx increase.

4. CONCLUSIONS

The following conclusions may be drawn from the study:

- The addition of ethanol to LPG or gasoline reduces the pollutant emissions. The CO and NOx emissions of the engine 1 (ε=11) fueled with a stoichiometric mixture of E50h are 25% and 15% respectively, lower than those of sole LPG fueling mode at 5000 rpm and α=30°.

- Increase of compression ratio results in a decrease of CO concentration but an increase of NOx concentration. As the compression ratio increases from 9 to 11, the CO concentration increases by 6% at n=7000 rpm and by 2% at n=2000 rpm while the NOx concentration increases by 10% on average. Effects of compression ratio on CO, NOx emission are gradually moderate with an increase of ethanol content in the fuel mixture.

- At a given compression ratio, CO emission increases but NOx emission decreases with the increase of engine loading regime. On average, as the butterfly valve closes from 30° to 45°, the reduction of CO and NOx emissions is by 30% and 20%, respectively, as the engine is fueled with ethanol additive to LPG.

- At a fixed advance ignition angle, the increase of engine speed results in an increase of CO concentration but a decrease of NOx concentration. At a given engine speed, the increase of the advance ignition angle leads to a reduction of CO emission but an increase of NOx concentration.

- At a given ethanol content, CO emission of ethanol-LPG fueling mode is lower than that of ethanol-gasoline fueling mode while NOx emission of ethanol-LPG fueling mode is lower at low engine speed but higher at high engine speed as compared to ethanol-gasoline fueling mode.

- Motorcycle engines with a high compression ratio fueled with ethanol additive to LPG operating at speed in the range of 4000rpm to 5000 rpm will be optimal for pollutant emission control under urban conditions.

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NOMENCLATURE

≥CA : Degree of crankshaft angle
E : Mole fraction of ethanol in the fuel mixture (%)
EXG : Ethanol-gasoline blend containing x% mole fraction of ethanol
ELP : Ethanol-LPG blend containing x% mole fraction of ethanol
n : Engine speed (rpm)
SI : Spark Ignition
T : Mean temperature of gas mixture in the cylinder (K)
TDC : Top Dead Center
α : Position of butterfly valve (°)
ε : Compression ratio
ϕ : Equivalence ratio
ψ : Crankshaft angle (°CA)
ψa : Advance ignition timing (°CA)

REFERENCES


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