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.

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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 maybe 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 NO_x 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, CO_2 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 NO_x 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 NO_x. 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 NO_x emission [24]. Rahman [25] has tested SI engine fueled with LPG enriched $E20_G$ and noted that as compared to $E20_G$, when LPG is inducted to the fuel, the reduction of HC, CO, CO_2 is in range of 13-14%, 14-15% and 12-18% respectively but the concentration of NO_x was increased by13-16% 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 NO_x 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, NO_x 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 NO_x 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 whileas original fuel tank remains for liquid fuel.

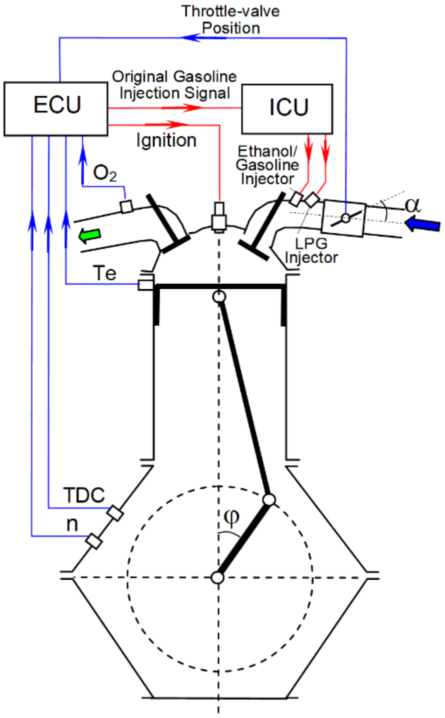


Fig. 1. Retrofit Honda motorcycle engine to operate with ethanol-LPG or ethanol-gasoline.

Table 1. Specifications of Honda 110 cc Engines

Engine characteristics	Engine 1 (Honda Lead 110 cc)	Engine 2 (Honda Wave Alpha 110 cc)
Engine type	4-stroke, Fuel Injection	4-stroke, Fuel Injection
Number of cylinders	1	1
Bore (mm)	50	50
Stroke (mm)	55	55.6
Displacement (cm^3)	108	109.1
Compression ratio	11:1	9:1
Rated power/speed gasoline fueling (kW/rpm)	6.4/7500	6.12/7500
Rated torque/speed gasoline fueling (Nm/rpm)	9.2/6000	8.44/6000

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

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

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

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

The net rate of NOx formation is given by:

$$\frac{d[NO]}{dt} = k_{f,1}[O][N_2] + k_{f,2}[N][O_2] + k_{f,3}[N][OH] - k_{r,1}[NO][N] - k_{r,2}[NO][O] - k_{r,3}[NO][H] \qquad (4)$$

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 NO_x 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:

$$\frac{1}{2}H_2 = H \qquad (5)$$

$$\frac{1}{2}O_2 = O \qquad (6)$$

$$H_2O = OH + \frac{1}{2}H_2 \qquad (7)$$

$$2H_2O = 2H_2 + O_2 \qquad (8)$$

$$CO_2 + H_2 = H_2O + CO \qquad (9)$$

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

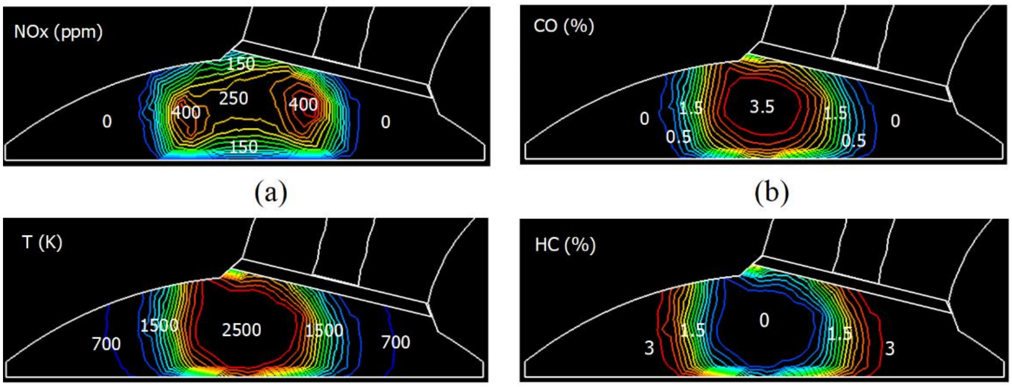
3. RESULTS AND DISCUSSION

3.1. Variation of CO and NO_x concentrations in combustion chamber

Fig. 2 presents the contours of NO_x concentration, CO concentration, temperature and total hydrocarbon at 5°CA after ignition of the engine 1 fueled with stoichiometric mixture of $E20_L$, 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 NO_x 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

Fuel property	Ethanol [11]	Gasoline [11]	Propane [25]	Butane [25]
Formula	C_2H_5OH	C_8 to C_{12}	C_3H_8	C_4H_{10}
Molecular weight [g/mol]	46.07	105	44	58
Carbon [mass%]	52.2	88	82	83
Hydrogen [mass%]	13.1	12-15	18	17
Oxygen [mass%]	34.7	2.7	0	0
Liquid density [kg/m^3]	790	751	508	584
Boiling point [°C]	78	27-225	-42	-0.5
Vapor pressure [kPa] at 38°C	15.9	48-103	858.7	215.1
Specific heat [kJ kg^{-1} K^{-1}]	2.4	2	1.63	1.675
Latent heat of vaporization [kJ/kg]	840	305	426	385
Low heating value [MJ/kg]	26	43	46.1	45.5
Autoignition temperature [°C]	423	257	480	440
RON	108.6	98	111	103
Stoichiometric air/fuel	9	14.7	15.65	15.43
Laminar flame velocity at 100 kPa, 325 K (cm/s)	39	33	38	37



(a) (b)

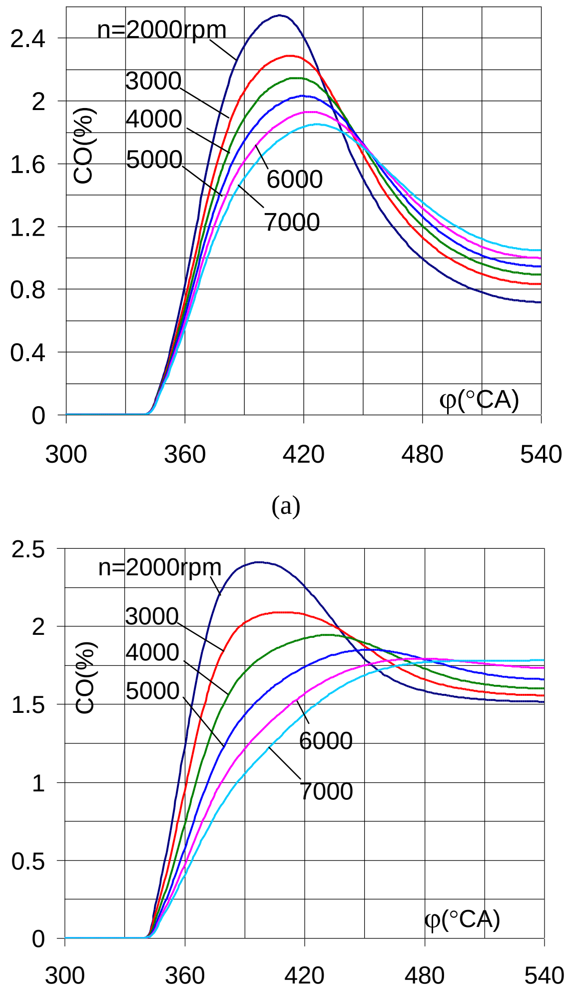
(c) (d)

Fig. 2. Contours of NO_x concentration (a), CO concentration (b), temperature (c) and total hydrocarbon (d) at 5°CA after ignition (ε=11, α=45°, $E25_L$, ϕ=1, φ_s=20°CA)

The CO concentration tends to its equilibrium value by the reaction (5-9) whileas the NO_x 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 NO_x 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 φ_s=20°CA, operating under the same partial loading α=45° but fueled with $E25_L$ and $E25_G$. 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 $E25_L$ or $E25_G$. 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 $E25_G$ drops down more quickly with the increase of engine speed as compared to the case of $E25_L$. 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.



(a)

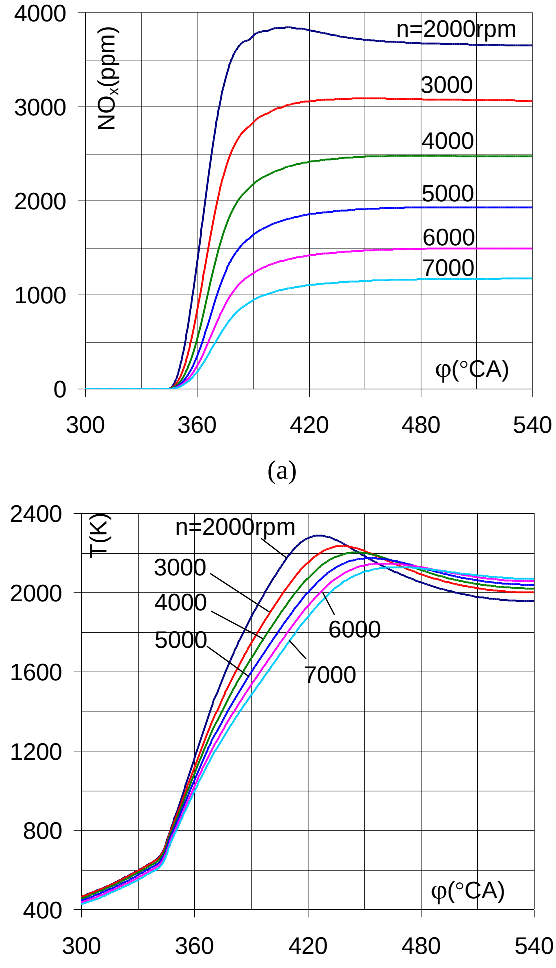
(b)

Fig. 3. Effects of engine speed on variation of CO concentration with crankshaft angle.
(a): $\varepsilon=11$, $\alpha=30°$, $E25_L$, $\phi=1$, $\varphi_s=20°CA$
(b): $\varepsilon=11$, $\alpha=45°$, $E20_G$, $\phi=1.05$, $\varphi_s=20°CA$

Fig. 4a shows the variation of NO_x concentration with respect to crank angle as engine speed varies from 2000 rpm to 7000 rpm. The engine is fueled with a slightly rich mixture $\phi=1.05$ of $E25_L$. The NO_x concentration increases brutally just after ignition and reach peak value during the main phase of combustion. The formation of NO_x inside the combustion chamber can be described by the Zeldovich mechanism as mentioned above. NO_x forms in post-flame combustion process in the high-temperature regions (Fig. 2a). The maximum concentration of NO_x firstly depends on combustion temperature and then, it depends on existent duration of product under high temperature conditions. It can be seen in Fig. 4b that the increase of engine speed lowers down the combustion temperature and furthermore, reduces the available time for combustion, the reduction of NO_x concentration in the exhaust gas is as a result.

3.2. Effects of ethanol content in fuel mixture on CO and NO_x emissions

The increase of ethanol content in the fuel mixture lowers down the CO emission as shown in Fig. 5. This can be attributed to the fact that the oxygen within the ethanol benefits for enhancing the complete combustion. Moreover, syngas and producer gas produced during oxidation at the elevated temperature might be burned with this oxygen to yield CO_2.



(a)

(b)

Fig. 4. Effects of engine speed on variation of NO_x concentration (a) and temperature (b) with crankshaft angle ($\varepsilon=11$, $\alpha=45°$, $E25_L$, $\phi=1.05$, $\varphi_s=20°CA$).

The results in the figure show concretely that as the engine 2 operates at partial loading $\alpha=30°$, CO concentration in the exhaust gas decreases by 25% as shifting from sole LPG fueling mode to $E50_L$ 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 $E50_L$ 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.

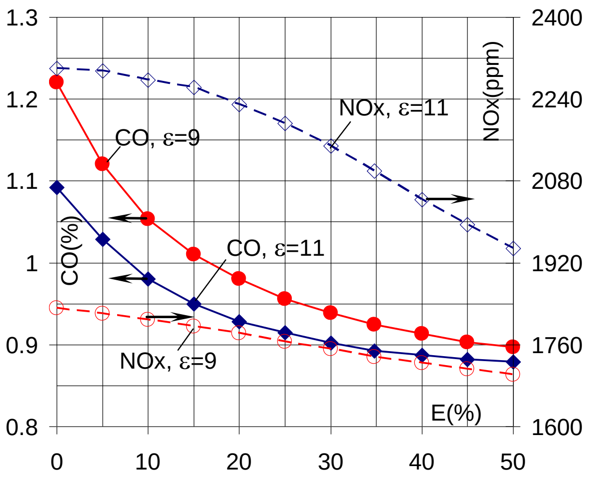
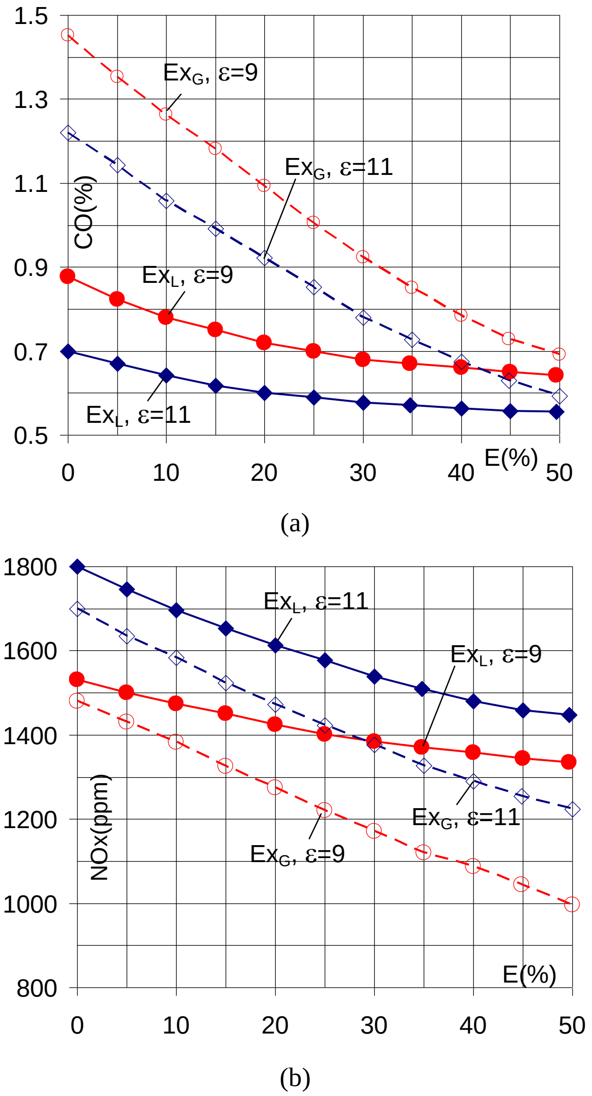


Fig. 5. Variation of CO and NO_x concentrations with respect to additive ethanol concentration to LPG (n=5000 rpm, α=30°, ϕ=1, $φ_s$=20°CA).

It can be noted as well that the high content of ethanol in the fuel lowers down the NO_x 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 NO_x concentration. It can be seen in Fig. 5, as compared to sole LPG fueling mode, the $E50_L$ fueling mode can reduce by 15% NO_x emission for the engine 1 and 7% for the engine 2. The NO_x 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 NO_x emission gradually moderate as ethanol content in the fuel mixture increases. As compression ratio increases from 9 to 11, the NO_x concentration increases by 25% in case of sole LPG fueling mode and by 15% in case of $E50_L$ fueling mode.

The throttling or loading regime of the engine affects to CO and NO_x 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 NO_x emissions are thus, reduced. Fig. 6a and Fig. 6b present the variation of CO and NO_x concentrations with respect to ethanol content in the mixture with LPG and gasoline in case of partial charge α=45°. As compared to Fig. 5 in case of α=30°, it can be noted that the CO and NO_x 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 α=30° to α=45°, the reduction of CO and NO_x 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 NO_x formations.



(a)

(b)

Fig. 6. Comparison of variation of CO concentration (a) and NO_x concentration (b) in the exhaust gas of the engine 1 and the engine 2 with respect to the additive ethanol content to LPG and to gasoline (n=5000 rpm, α=45°, ϕ=1, $φ_s$=20°CA).

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 CO_2 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 NO_x 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, φ_s=20°CA, due to the higher adiabatic combustion temperature of ethanol-LPG mixture as compared to ethanol-gasoline mixture, the NO_x emission increases as shifting from Ex_G fueling mode to Ex_L fueling mode at any ethanol content in the fuel mixture. Contrarily in case of CO emission, the difference in NO_x 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 NO_x concentration decreases by 5% and 20% as the considered engines are fueled with sole fuels and with the addition 50% ethanol respectively.

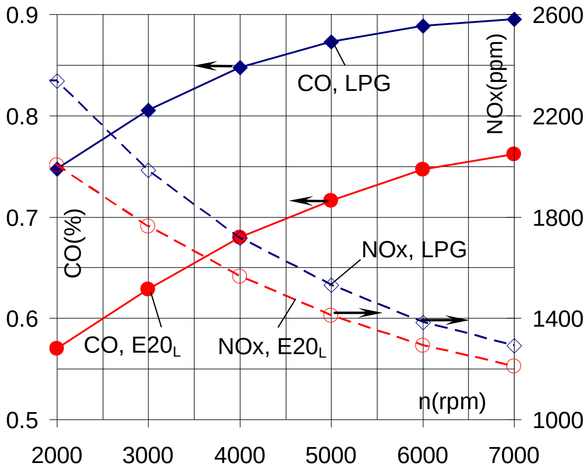
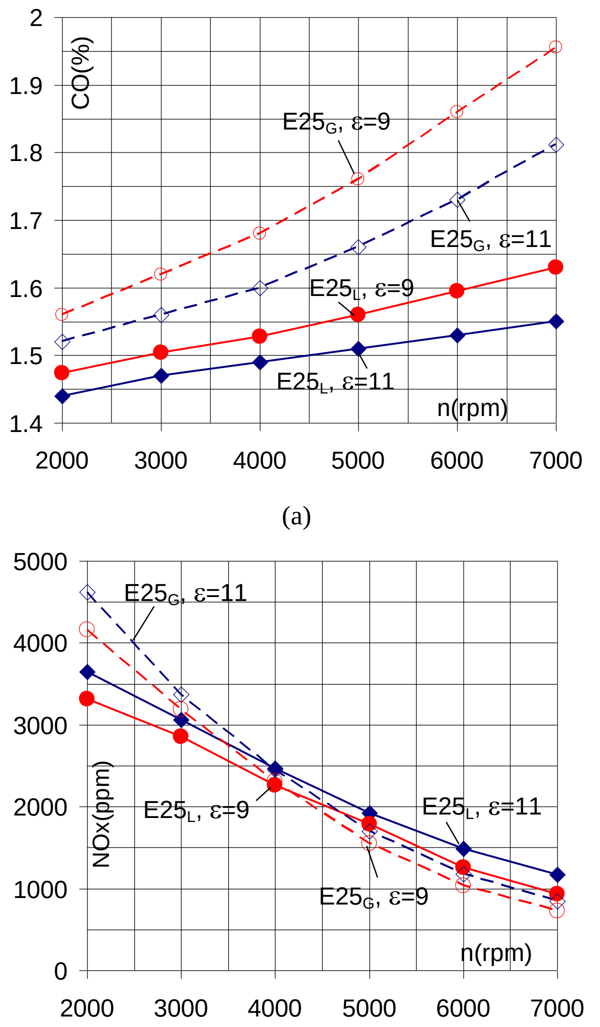


Fig. 7. Comparison of variation of CO and NO_x concentrations with respect to engine speed as the engine 2 is fueled with LPG and $E20_L$ (ε=9, α=45°, ϕ=1, φ_s=20°CA).

3.3. Effect of engine speed

As it has been mentioned above, the concentrations of CO and NO_x 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 present the variation of CO and NO_x 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.



(a)

(b)

Fig. 8. Comparison of variation of CO concentration (a) and NO_x concentration (b) in the exhaust gas with respect to engine speed as the engine 1 and the engine 2 are fueled with E25G and $E25_L$ (α=45°, ϕ=1.05, φ_s=20°CA).

Contrarily to the CO emission, at a given operating conditions and fueling mode, the NO_x concentration decreases as the engine speed increases. As it has been explained in above section, the NO_x concentration is controlled by the formation rate which depends on temperature and the combustion time. As engine speed increases, both combustion temperature and combustion duration are reduced, the reduction of NO_x concentration is as a result.

Fig. 8a illustrates a comparison of variation of CO concentration with respect to engine speed as the engine 1 and the engine 2 are fueled with a slightly rich mixture, ϕ=1.05, of $E25_L$ and $E25_G$. It is obvious that at a given engine speed, the CO concentration in case of $E25_G$ is 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 NO_x emission of the engine 1 and the engine 2. It can be seen that at low engine speed, $E25_G$ fueling mode produces more NO_x than $E25_L$ fueling mode. But the NO_x concentration of $E25_G$ fueling mode drops down more significantly with the increase of engines speed. Thus at high engine speed, NO_x emission of $E25_G$ fueling mode becomes lower than that of $E25_L$ fueling mode. This is due to the combustion temperature of $E25_G$ decreases more quickly with the increase of engine speed as compared to the case of $E25_L$.

3.4. Effect of advanced ignition timing

Fig. 9 presents the variation of CO and NO_x 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 $E20_L$. The results show that the increase of advance ignition angle results in a decrease of CO concentration but an increase of NO_x 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 NO_x 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 NO_x emission increases by 35%.

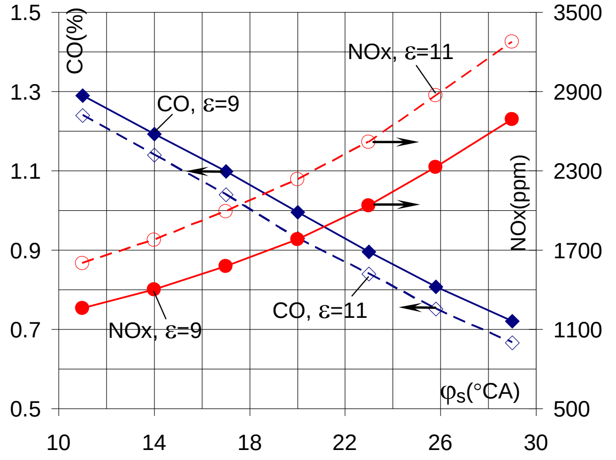


Fig. 9. Variation of CO and NO_x concentrations with respect to the advance ignition angle as the engine 1 and the engine 2 are fueled with $E25_L$ (n=5000rpm, α=30°, ϕ=1).

Fig. 10 illustrates the effect of equivalence ratio on variation of CO and NO_x concentrations with advance ignition angle as the engine 1 (ε=11) is fueled with $E25_G$. It is obvious that CO concentration decreases significantly but the NO_x 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 NO_x 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 NO_x emission increases by 80%.

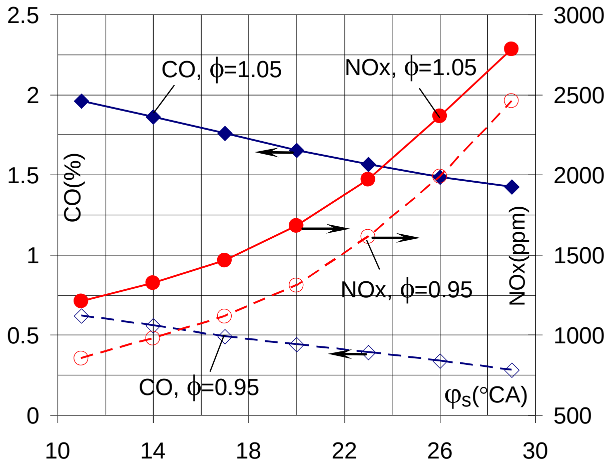


Fig. 10. Variation of CO and NO_x concentrations with respect to the advance ignition angle as the engine 1 is fueled with $E25_G$ (n=5000rpm, ε=11, α=45°).

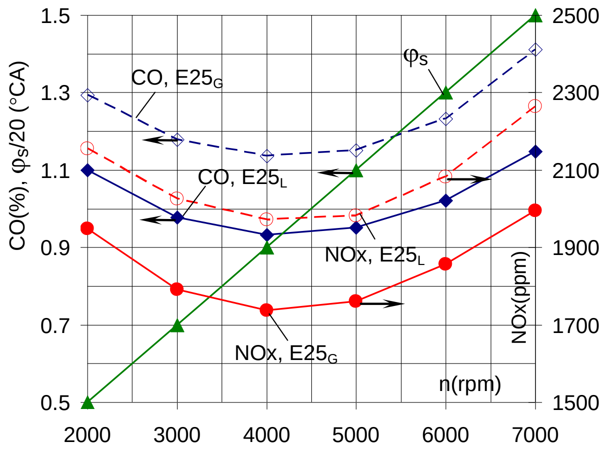


Fig. 11. Variation of CO and NO_x concentrations with respect to engine speed as the engine 1 is fueled with $E25_L$ and $E25_G$ and the advance ignition angle increases linearly with engine speed (ϕ=1.02, ε=11, α=45°).

Generally, the increase of combustion duration lowers down the CO emission but rises up the NO_x emission. Therefore, the CO emission increases with an increase of engine speed or/and with a decrease of advance ignition angle. Inversely, NO_x emission decreases with an increase of engine speed or/and with an decrease of advance ignition angle. In SI engine, the advance ignition timing normally increases with the engine speed to improve the combustion efficiency. Thus the CO emission is practically lower and NO_x emission is higher than those in case of fixed advance ignition angle presented in Fig 9 and Fig. 10. Fig. 11 shows the variation of CO and NO_x concentrations with the speed of the engine 1 fueled with $E25_L$ and $E25_G$ 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 NO_x curves exhibite a minimum value corresponding to engine speed in the range of 4000-5000rpm. Outside of this range, the emissions of CO and NO_x 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 NO_x emissions of the engine 1 (ε=11) fueled with a stoichiometric mixture of $E50_L$ 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 NO_x 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 NO_x concentration increases by 10% on average. Effects of compression ratio on CO, NO_x emission are gradually moderate with an increase of ethanol content in the fuel mixture.
- At a given compression ratio, CO mission increases but NO_x 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 NO_x 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 NO_x concentration. At a given engine speed, the increase of the advance ignition angle leads to a reduction of CO emission but an increase of NO_x concentration.
- At a given ethanol content, CO emission of ethanol-LPG fueling mode is lower than that of ethanol-gasoline fueling mode while NO_x 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 (%)
Ex_G	: Ethanol-gasoline blend containing x% mole fraction of ethanol
Ex_L	: 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
φ	: Crankshaft angle (°CA)
φ_s	: Advance ignition timing (°CA)

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