EMISSION CHARACTERISTICS OF ISO-PROPANOL/GASOLINE BLENDS IN A SPARK-IGNITION ENGINE COMBINED WITH EXHAUST GAS RE-CIRCULATION

by

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Experiments were carried out in a spark-ignition engine fueled with iso-propanol/gasoline blends. Emission characteristics of this engine were investigated experimentally, including gaseous emissions (HC, CO, NO_x) and particulate matter emission in term of number and size distributions. The effects of different iso-propanol percentages, loads and exhaust gas re-circulation rates on emissions were analyzed. Results show that the introduction of exhaust gas re-circulation reduces the NO_x emission and NO_x emission gives the highest value at full load condition. HC and CO emissions present inconspicuous variations at all the loads except the load of 10%. Additionally, HC emission shows a sharp increase for pure propanol when the exhaust gas re-circulation rate is up to 5%, while little variation is observed at lager exhaust gas re-circulation rates. Moreover, the particulate matter number concentration increases monotonically with the increase of load and the decrease of exhaust gas re-circulation rate. There exists a critical spark timing that produces the highest particulate matter number concentration at all the blending ratios.

Key words: *spark-ignition engine, iso-propanol, gasoline, exhaust gas re-circulation, particulate matter, emission*

Introduction

With the increasing concern of environmental degradation and energy shortage, biofuels have obtained steady growth during the last decade due to their renewability and the potential of pollutant reduction. According to the target of International Energy Agency [1], although biofuels occupied only 3% of global road transport fuel consumption in 2010, the share in total transport fuel would go up to 27% in 2050. Such a great growth is calling for accelerated investments and investigations in biofuels. Alcohol such as methanol, ethanol, and butanol, as an important member of biofuel family, has been extensively investigated and used to reduce the consumption of fossil fuel [2-9], and these studies showed that engine fueled with alcohol give lower emissions. Additionally, some studies [10-12] suggested that the addition of lower alcohols (methanol and ethanol) might give different performances from those of higher alcohols (butanol and pentanol). Yacoub *et al.* [10] found that the knock resistance was improved with the addition of methanol, ethanol, and propanol to gasoline and reduced with the addition of butanol and pentanol. While Campos *et al.* [11] stated that the addition of butanol and pentanol gave better performance than methanol and ethanol. Gravalos *et al.* [12] investigated the addition of the alcohol mixture (C_1-C_5) to gasoline and concluded that the presence of alcohol in gas-

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oline reduced CO and HC emission and increased NO. Besides, the addition of higher alcohols (C_3-C_5) brought higher emissions except CO. Hence, iso-propanol, which can be regarded as the transitional alcohol to separate the lower and higher carbon alcohols, is worthy of further investigation. However, the study on iso-propanol is limited. Kellar *et al*. [13] reported that the addition of iso-propanol would cause an insignificant difference in thermal efficiency compared with the addition of methanol, ethanol, and butanol in a spark-ignition engine. Saeed *et al.* [14] carried out experiments in a direct-injection diesel engine and stated that the ignition timing would be postponed with the increase of iso-propanol fraction and the addition of iso-propanol generated longer ignition delay time than that of ethanol addition. Keskin and Guru [15] indicated the addition of iso-propanol decreased NO_x and CO_2 emissions, while increased CO and HC emissions. Lu *et al*. [16] reported that a large proportion of iso-propanol addition combined with cold exhaust gas recirculation (EGR) could reduce the combustion rate and increase CO and HC emissions.

The emissions from the transportation vehicles are the main source of environmental pollutions in urban areas, especially the emission of particulate matter. Moreover, a near tripling of the number of cars on the planet by 2050 is expected with the fast economic development of developing countries [17]. The emission law and regulation must be more stringent. Particulate matter (PM), as one of the six common air pollutions, is a complex mixture of extremely small particles and liquid droplets. And these particles threaten the health of humans to a certain extent depending on the size. Environmental Protection Agency pointed out that the particles smaller than 10 micrometers in diameter, generally passing through the throat and nose and entering the lungs, are more harmful to human health than the larger particles [18]. Thus the small particle emission has become the main concern of particle emission. Actually, the Euro 5 and 6 legislations, have already proposed a PM number emission limit in addition to the mass-based limits [19]. It suggests that the PM number and size distributions should be considered as well as the other regulated emissions to evaluate the performance of alternative fuel utilization. Up to now, many investigations on PM number and size distributions have focused on diesel engines [4, 20]. Little work has been reported on gasoline engines, especially on the gasoline engine fueled with iso-propanol/gasoline blends [21]. For the future utilization of propanol as an alternative in the engine, one of the objectives of this study is to investigate the extensive emissions, including $NO_{x,}$ CO, CO_2, and PM emissions, in a spark-ignition engine fueled with various iso-propanol/gasoline blends. Additionally, the effects of the parameters such as load, blending ratio, EGR rate and spark timing on the engine emissions are studied.

Experimental set-up

All the experiments were conducted in a three-cylinder, port-injection and spark-ignition engine. The specifications of the engine are tabulated in tab. 1. Horiba MEXA-554JA analyzer was employed to measure the exhaust HC and CO concentration with accuracies of 12 ppm and 0.06%, and Horiba MEXA-720 NO_x analyzer was used to measure NO_x emission with an accuracy of 30 ppm. Ignition timing and excess air ratio (λ), which was monitored by ECM MXEA-7001 with an accuracy of 5%, were regulated by an electronic control unit (ECU) controlled step motor.

Table 1. Engine specification

Type	HH368Q spark-ignition engine
Bore and stroke [mm]	68.5 × 75
Displacement [cm^3]	796
Compression ratio	9.4
Ignition sequence	1-3-2
Rated power [kW]	26.5
Rated speed [rpm]	5500

The ECM EGR5230 analyzer was used to monitor the EGR rate with an accuracy of 0.5% based on the volumetric percentage of EGR rate. The definition of EGR is $EGR\,(\%) = V_{\mathrm{EGR}}/(V_{\mathrm{i}} + V_{\mathrm{EGR}})$, where V_{EGR} indicates the volume flow rate of EGR and V_{i} refers to the volume flow rate of intake air-fuel mixture. In the experiments, the increase of EGR was adjusted by the valve opening, which was controlled by a self-designed EGR control system. An electrical low-pressure impactor (ELPI) (Dekati Ltd., Finland), a real-time particle size spectrometer, was used to detect the aerosol particle size and number distribution covering the size from 7 nm to 10 m in aerodynamic diameter. The detailed process and principle have been well described by many researchers [22-26]. To prevent overload, the exhaust gas samples were diluted using a two stage-diluter before being introduced into the system and the dilution ratio remained fixed in all the experimental cases. To avoid possible nucleation, condensation and particle loss effects on the measurements, the first diluter was heated. In the experiments, the engine was operated at stoichiometric condition with a speed of 3000 rpm. The blending ratios, x, which involves the volume fraction of iso-propanol in the blend, were x = 0, 10%, 20%, 40%, and 100%. EGR rates were EGR = 0, 5%, 10%, 15%, and 20%, and loads, L, were 10%, 20%, 40%, and WOT (wide open throttle), respectively. The main properties of gasoline and iso-propanol used in the experiments are shown in tab. 2.

Table 2. Properties of gasoline (97#) and pure iso-propanol

	Gasoline	Iso-propanol
Typical formula	C_4~C_{12}	C_3H_7OH
Molecular weight	–	60.1
Lower heat value [MJkg^{-1}]	44.4	30.4
Density (20 °C) [kgm^{-3}]	746	785
Oxygen content [wt. %]	0	26.62
Boiling point [°C]	25~215	82.35
Latent heat of vaporization (20 °C) [kJkg^{-1}]	380~500	749

Results and discussion

Maximum brake torque timing

Tables 3 and 4 present the maximum brake torque timing (MBT) at different blending ratios and loads. MBT increases with the increase of blending ratio and decreases with the increase of load. Iso-propanol has lower heat value than that of gasoline. This lowers the cylinder temperature and decreases the flame propagation speed, thus the MBT of iso-propanol/gasoline blend is advanced with the increase of blending ratio. While increasing load results in the increase of temperature and then the increase of flame propagation, leading to the postponement of MBT.

Table 3. MBT at different blending ratios

WOT, EGR = 0, excess air ratio λ = 1.0					
Blending ratio (x)	0	10%	20%	40%	100%
MBT [° CA bTDC]	26	27	29	32	33

Table 4. MBT at different loads

Blending ratio x = 10, EGR = 0, excess air ratio λ = 1.0				
Load (L)	10%	20%	40%	WOT
MBT [° CA bTDC]	35	33	30	27

Gaseous emissions

Effect of load on gaseous emissions

Figure 1 shows the brake specific gaseous emission *vs.* the spark timing at different loads with blending ratio x = 10%. The formation of NO_x is mainly controlled by the cylinder temperature and the local oxygen concentration. The NO_x emission gives its highest value at full

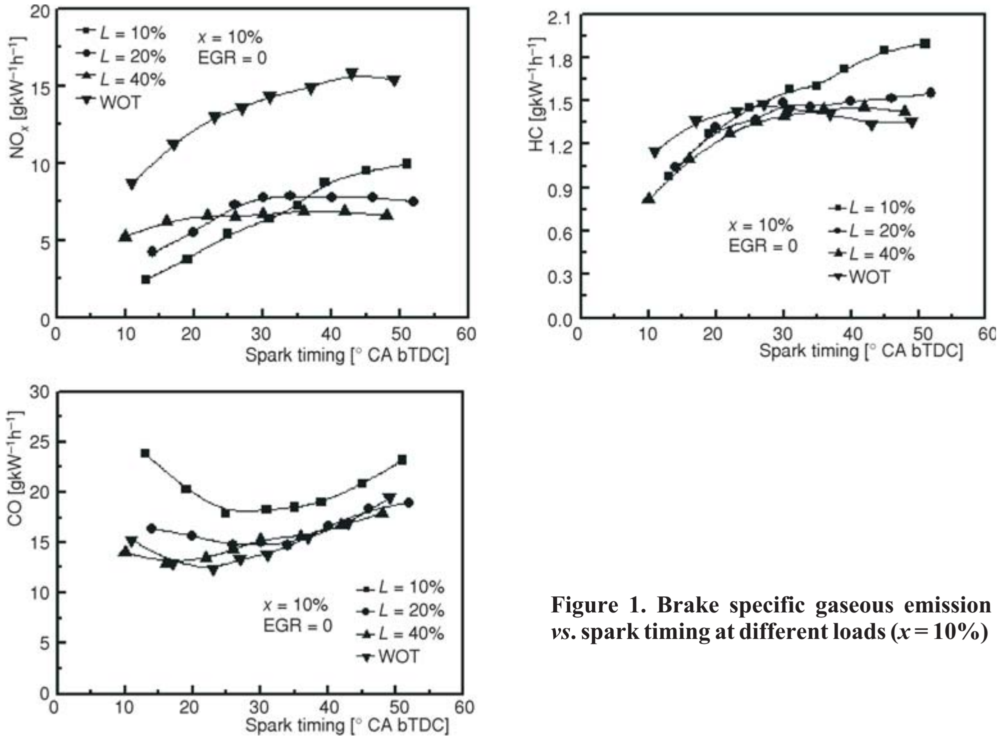

Figure 1. Brake specific gaseous emission *vs.* spark timing at different loads (x = 10%)

load since the increased fuel/air charge results in higher cylinder pressure and temperature. HC and CO are the products of incomplete combustion, relying on the formation and post-flame oxidation. The fact that HC and CO emissions are higher at L = 10% can be attributed to the low temperature which weakens the post-flame oxidation of HC and CO. The similar trends of the gaseous emissions for the other blending ratios are also observed in the experiments.

Effect of EGR rate and blending ratio on gaseous emissions

Figure 2 presents the effect of EGR rate and blending ratio on the brake specific gaseous emissions at MBT. NO_x emission is decreased monotonically with the increase of EGR rate, resulting from the reduced cylinder temperature caused by the addition of EGR. NO_x formation is strongly related to the combustion temperature and local oxygen concentration. Higher temperature and local oxygen favor the thermal NO_x formation. At a specific blending ratio, the introduction of EGR dilutes the mixtures, leading to a lower combustion temperature and burning velocity. The presence of EGR also weakens the total heat release and combustion temperature due to the reduced fresh air/fuel charge. Besides, the gases included in the EGR like CO_2 and H_2O, having relatively large specific heat capacity, absorb the released heat partly and therefore decrease the cylinder temperature. While NO_x emission exhibits a first increase (x = 0, 10%, 20%) and late decrease (x = 40%, 100%) trend with the increase of blending ratio. This results from the competition between cylinder temperature and local oxygen. Iso-propanol is an oxygenated fuel and has lower heat value compared with that of neat gasoline. Although the addition of iso-propanol lowers the total heat release and inhibits the formation of NO_x, the additional oxygen content in iso-propanol promotes the local oxygen and enhances the NO_x formation. NO_x emission decreases with the increase of blending ratio when $x > 20\%$ reveals the effect of reduced temperature overwhelms the effect of increased local oxygen.

HC and CO emissions are the productions of incomplete combustion as mentioned before. As indicated in fig. 3, pure propanol gives the highest HC and CO emissions due to the weakened oxidation resulting from the extremely reduced temperature, even though the high oxygen concentration is favorable to the oxidation. Besides, HC emission shows no obvious difference in all the blending ratios except pure propanol when CO emissions are close to each other at x = 0, 10%, 20% and gives the lowest emission at x = 40%. It is the combined effects between the temperature decrease and oxygen increase with the increase of propanol percentage.

Noteworthy, HC emission shows a sharp increase at pure propanol when EGR rate is up to 5%, while little variation is observed at lager EGR rates. It may result from the reinforcement of the wall quenching. The temperature remarkably decreases at pure propanol condition, the introduction of EGR further deteriorates this situation. The possibility of flame quenching near the wall is enhanced, where unburned hydrocarbons escape from oxidation and release into the exhaust gas later. However, the dilution effect of EGR is promoted with the increase of EGR percentage, reducing the total amount of HC quenching near the wall. This partly offsets the effect of decreased temperature and induces the slight variation of HC emission at large EGR rates.

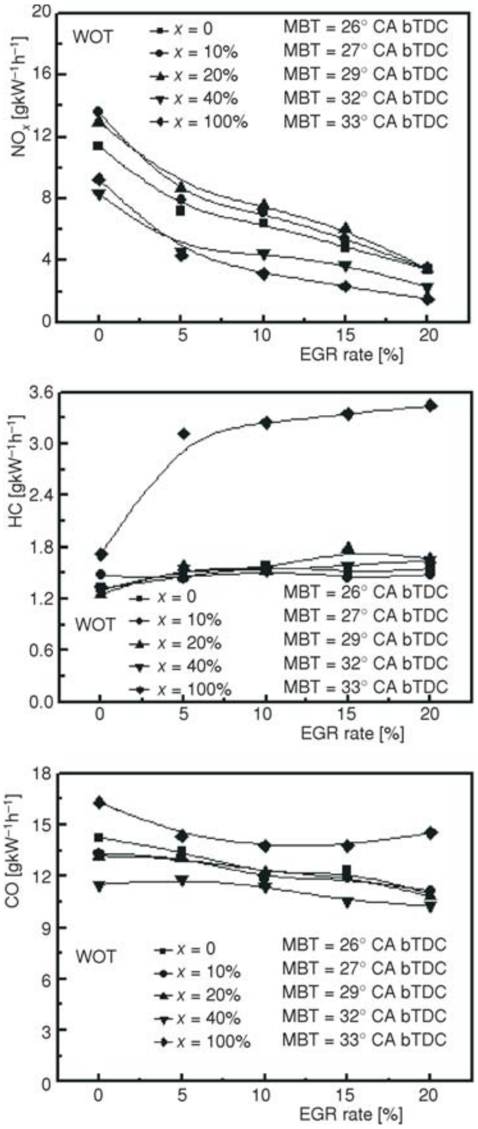

Figure 2. Effect of EGR rate and blending ratio on the gaseous emissions at full load

Particulate matter emission

Effect of load on PM emission

The effect of the engine load on PM number concentration is given in fig. 3. PM number concentration increases monotonically with the increase of load. The amount of nucleated particles is related to the gas and liquid phase fuel availability and temperature [27]. The increased load leads to increased intake air/fuel charge and decreased residual gas fraction. Thus, the peak cylinder temperature and pressure increase. Conversely, the intake temperature decreases with the increased flow rate, resulting in weakened evaporation of liquid fuel. Finally, not only the concentration of gas phase but also the amount of liquid phase is increased. Consequently, the PM nucleation is enhanced and thus the PM number concentration is increased as

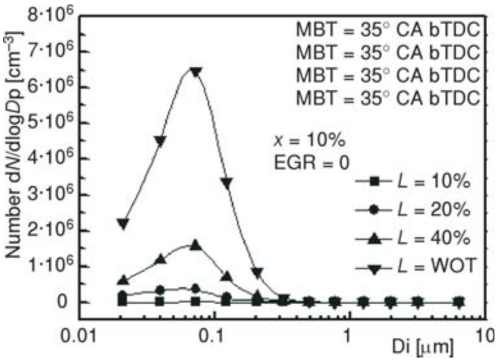

Figure 3. Effect of load on PM emission and size distribution

the load increases. Moreover, the post-flame ignition of liquid fuel depends strongly on the post-flame oxygen concentration [28]. The increased cylinder pressure and decreased residual gas fraction with the increase of load lead to higher local oxygen concentration. This promotes the possibility of soot production from the liquid fuel ignition and further increases the PM emission [27].

While the increased cylinder temperature and oxygen content are also favorable to PM oxidation. The experimental result that PM number concentration increases with the increase of load suggests the increase of PM nucleation dominates the overall PM number emission rather than PM oxidation.

Effect of EGR on PM emission

Figure 4 depicts the effect of EGR on PM number and size distribution at different blending ratios. All the PM number emissions demonstrated here were measured at MBT. The peak value of PM number concentration increases as the addition of propanol due to the increase of small size particles, resulting from the promoted PM nucleation because of the additional oxygen content.

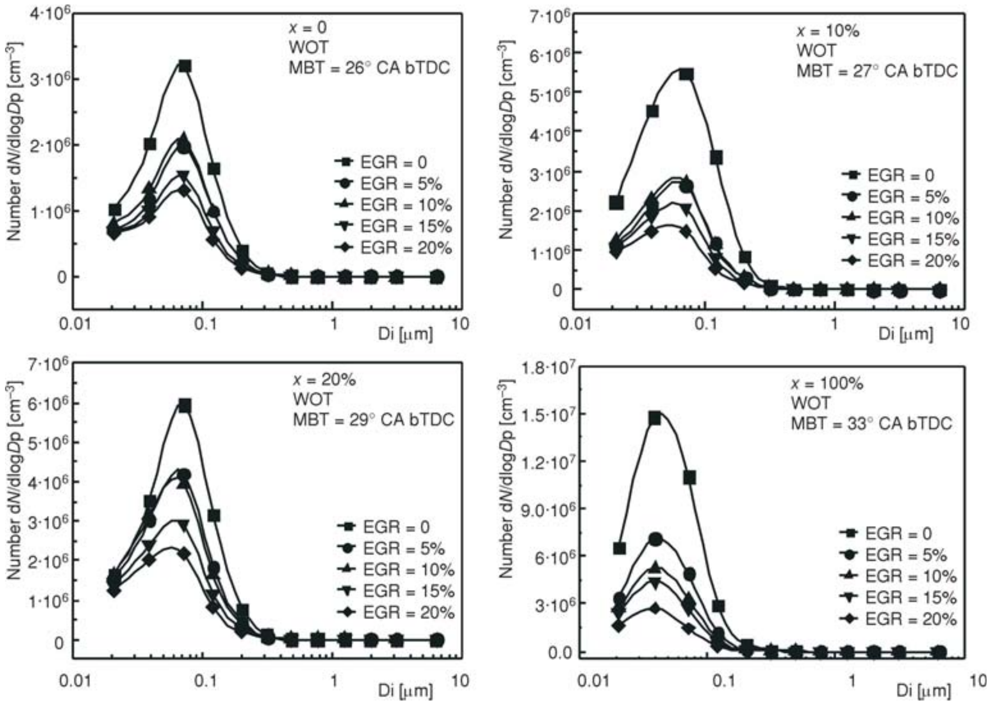

Figure 4. Effect of EGR on PM number and size distribution at different blending ratios

The presence of hot EGR reduces PM number emission for all the blending ratios. This phenomenon is the same as the result of butanol [8], while differs from the observation in diesel engine which indicates an increased PM number concentration with the addition of EGR [29]. Hot EGR heats the intake fuel/air charge in advance and improves the evaporation of liquid fuel. This contributes to the decrease of PM formation through liquid fuel. More importantly, the introduction of EGR reduces the total fuel/air charge and the subsequent heat release and cylinder temperature. In premixed homogeneous mixture, soot precursors are mainly formed by the H-abstraction reactions at high temperature. The lowered cylinder temperature moderates the H-abstraction rate and thus the soot precursors. Additionally, the presence of EGR lowers the fuel fraction in the total mixture charge and this decreases the PM number concentration in the total exhaust gas.

Effect of spark timing on PM emissions

Figure 5 gives PM number concentration at different spark timings. There exists a critical spark timing, which is larger than MBT timing from the experimental observation, generating the highest PM number concentration for all the blending ratios. The effect of advanced spark timing on PM number concentration is an increase before this critical spark timing. While the increase of spark timing over this critical value leads to a decrease in PM number concentration.

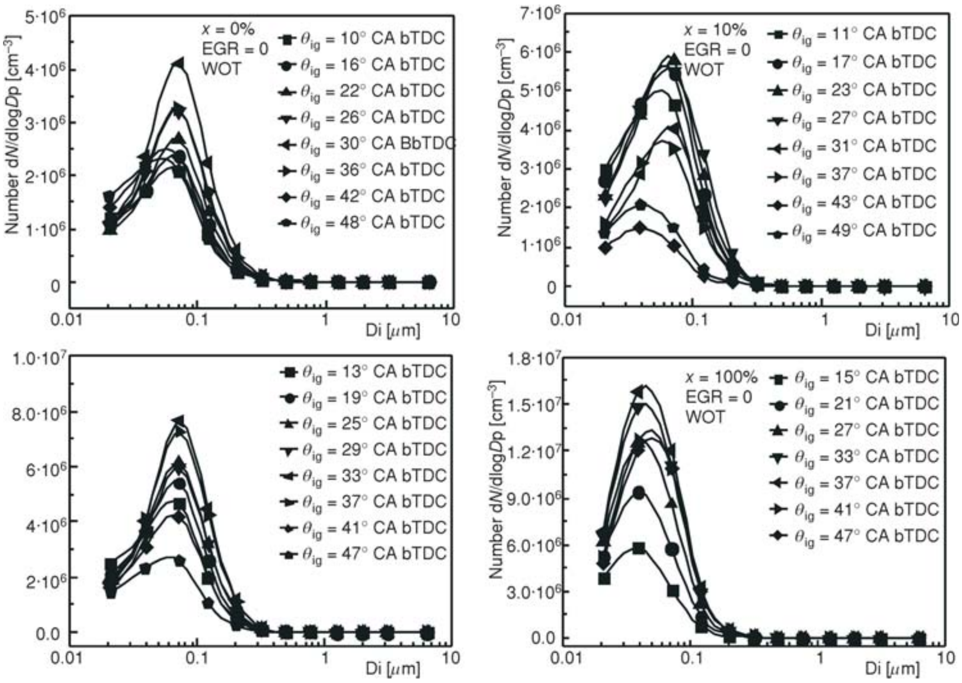

Figure 5. Effect of spark timing on PM and size distribution at different blending ratios

PM nucleation and oxidation are Arrhenius-dependent and the rates are significantly affected by temperature [28]. High temperature accelerates PM nucleation as well as oxidation. When the spark timing is small, the increase of the spark timing advancement leads to the increase of peak temperature. However, the combustion in the exhaust process increases and peak temperature decreases when the spark timing is too large. The existence and the value of this critical spark timing reflects the combined effect of the combustion, nucleation and oxidation.

Conclusions

The various emission characteristics of the engine, including NO_x, CO, CO_2, and particulate matter emissions, were studied in a spark-ignition engine fueled with various iso-propanol/gasoline blends. The effects of load, EGR rate, blending ratio, and spark timing on the emissions are clarified. The main results are as follows.

- NO_x emission gives the highest value at full load. The introduction of EGR reduces NO_x emission and NO_x emission indicates a first increase ($x = 0$, 10, 20%) and late decrease ($x = 40\%$, 100%) trend with the increase of blending ratio.
- HC and CO emissions show inconspicuous variations at all the loads except $L = 10$. HC emission indicates no obvious difference in all the blending ratios except pure propanol while CO emission gives the lowest value at $x = 40\%$. Additionally, HC emission presents a sharp increase at pure propanol when EGR rate is up to 5%, while little variation is observed at lager EGR rates.
- PM number concentration increases monotonically with the increase of load and the decrease of EGR. There exists a critical spark timing, lager than MBT timing, generating the highest PM number concentration for all the blending ratios.

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Nomenclature

EGR – exhaust gas recirculation
ELPI – electrical low-pressure impactor
L – load
MBT – maximum brake torque timing
PM – particulate matter
WOT – wide open throttle
x – blending ratio
λ – excess air ratio

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