Case Studies in Thermal Engineering 6 (2015) 147–154

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

journal homepage: www.elsevier.com/locate/csite

The effects of hydrous ethanol gasoline on combustion and emission characteristics of a port injection gasoline engine

Xiaochen Wang [a], Zhenbin Chen [a,b,*], Jimin Ni [b], Saiwu Liu [a], Haijie Zhou [a]

[a] School of Mechanics and Electronics Engineering, Hainan University, Haikou 570228, China
[b] School of automobile, Tongji University, Shanghai 201804, China

A R T I C L E I N F O

Article history:
Received 21 July 2015
Received in revised form
14 September 2015
Accepted 14 September 2015
Available online 16 September 2015

Keywords:
Port injection gasoline engine
Hydrous ethanol gasoline
Combustion characteristics
Emission characteristics

A B S T R A C T

Comparative experiments were conducted on a port injection gasoline engine fueled with hydrous ethanol gasoline (E10W), ethanol gasoline (E10) and pure gasoline (E0). The effects of the engine loads and the additions of ethanol and water on combustion and emission characteristics were analyzed deeply. According to the experimental results, compared with E0, E10W showed higher peak in-cylinder pressure at high load. Increases in peak heat release rates were observed for E10W fuel at all the operating conditions. The usage of E10W increased NO_X emissions at a wide load range. However, at low load conditions, E10W reduced HC, CO and CO_2 emissions significantly. E10W also produced slightly less HC and CO emissions, while CO_2 emissions were not significantly affected at higher operating points. Compared with E10, E10W showed higher peak in-cylinder pressures and peak heat release rates at the tested operating conditions. In addition, decreases in NO_X emissions were observed for E10W from 5 Nm to 100 Nm, while HC, CO and CO_2 emissions were slightly higher at low and medium load conditions. From the results, it can be concluded that E10W fuel can be regarded as a potential alternative fuel for gasoline engine applications.

1. Introduction

The shortage of petroleum and the stringent of emission have boosted the advancement of alternative fuels for internal combustion engines applications. In the last decades, ethanol gasoline blends have been investigated extensively and regarded as a potential alternative fuel for gasoline engine [1–3]. Researchers have investigated on performance and emissions of gasoline engines fueled with various ratios of ethanol gasoline blends and their application in ethanol flex-fuel vehicles [1–3]. According to their researches, ethanol additives bring oxygen into blends, increasing combustion efficiency and reducing hydrocarbon (HC) and carbon monoxide (CO) emissions. Besides, higher talent heat of ethanol gasoline blends makes mixture better, leading to a more complete combustion. However, due to the stronger hydrophilicity of ethanol, blended fuels mix easily with water in the air, which results in a lower stability of the blended fuels and a higher cost in storage and transportation. In addition, anhydrous ethanol production has high energy consumption, especially in the dehydration process. Hydrous ethanol, a promising additive for gasoline, can save a large consumption of energy and equipment without the further dehydration step [4–5]. Mixing with hydrous ethanol is becoming more popular due to both the conservation of energy and reduction of harmful emissions.

* Corresponding author at: School of Mechanics and Electronics Engineering, Hainan University, Haikou 570228, China. Fax: +86 898 6626 7576.
E-mail address: zhenbin1208@hainu.edu.cn (Z. Chen).

http://dx.doi.org/10.1016/j.csite.2015.09.007

Liu et al. [6] investigated the stability of E10 hydrous ethanol gasoline blend, using self-developed compound emulsifier. According to their experimental results, the stability of hydrous ethanol gasoline blend can be improved effectively with the method of emulsification, the addition of intensifier and antifreeze, and the increase of ethanol concentration can improve its low temperature stability. Kyriakides et al. used methyl tert-butyl ether (MTBE), tert-Amyl methyl ether (TAME) and palmitic acid as additives to prepare gasoline–ethanol–water ternary mixtures, which was proved that the additives promote water tolerance in gasoline–ethanol blends [7].

Munsin et al. [8] studied the effects of the use of hydrous ethanol with high water contents up to 40% on the performance and emissions of a small spark ignition engine. The effects of water contents in hydrous ethanol on engine performance and emissions were investigated. Schifter et al. [9] tested a single cylinder engine fueled by mid-levels (0–40% volume) hydrous ethanol and ethanol–gasoline engine with air/fuel mixture equivalence ratio varying from 0.9 to 1.1. According to Clemente et al. [10], with respect to ethanol-gasoline blend (22% ethanol and 78% gasoline), the use of hydrous ethanol (water concentration 7%) improved peak torque, peak power and SFC by 9%, 14% and 35%, respectively.

Costa et al. [11] evaluated a production 1.0–1 flex-fuel engine's performances when fueled with hydrous ethanol (ethanol with 6.8% water mass content) and regular gasoline (with 22% v/v anhydrous ethanol). Cordeiro de Melo et al. [12] performed an experimental investigation on the combustion and emission performance of a flex-fuel engine working with different hydrous ethanol blends. According to their research, NO_X results presented complex trends with ethanol addition, depending on the operating condition, spark advance timing and other parameters.

According to the previous literatures above, it can be found that researchers focused on the stability of hydrous ethanol gasoline blend and its influences on performance and emissions of engines or flex-fuel vehicles. There is still the need of additional research to better understand the effects of the blends and the engine loads on a port injection gasoline engine's combustion and emission characteristics.

To evaluate the effect of the addition of ethanol and water on combustion characteristics deeply, this study compares the combustion characteristics of hydrous ethanol gasoline (E10W), anhydrous ethanol gasoline (E10) and pure gasoline (E0) in a port-injected gasoline engine at various load conditions. Furthermore, to enrich the emission characteristics, nitrogen oxides (NO_x), CO, HC, and carbon dioxide (CO_2) emissions will be studied in detail over a wide range of engine load, from 5 Nm to 100 Nm. This case study is the comparative and further investigation on combustion characteristics of three fuels and it also enriches the investigations of emission characteristics of hydrous ethanol gasoline. Thus, this study is helpful for the evaluation of hydrous ethanol gasoline (E10W) as an alternative fuel for gasoline engine applications.

2. Engine test

2.1. Experiment setup

The experiment was conducted on a four-cylinder, port injection, and electronic controlled automotive engine. The detailed specifications of tested gasoline engine are listed in Table 1. The engine was loaded with a GW160 eddy current dynamometer. A pressure transducer, Model Kistler 6056A, was installed to monitor the in-cylinder pressure connected with a charge amplifier, Model Kistler 2613B. The cylinder pressure data was recorded in 0.5° CA increments. For each test point, 100 consecutive cycles were recorded and computed by combustion analyzer DEWE-5000. The exhaust gases including NO_X, CO, HC and CO_2 were measured with a gas analyzer, Model AVL Digas 4000. NO_X and HC emissions were measured using a chemiluminescent detector (CLD) and flame ionization detector (FID), respectively. CO and CO_2 were measured by the method of nondispersive infrared (NDIR). The accuracies of the measurements in this experiment are presented in Table 2. The uncertainty of this experiment was determined by parameters including engine speed, engine torque, crank angle, in-cylinder pressure, NO_X, CO, HC and CO_2. The total uncertainty of this experiment was computed to be 1.16% with the method of root-sum-square (RSS) [13]. The experimental setup is shown in Fig. 1.

2.2. Test fuel and method

In this study, the engine was tested and fueled with commercially available pure gasoline which also was the base fuel, 10% anhydrous ethanol-90% gasoline and 10% hydrous ethanol (containing 5% water by volume)-90% gasoline. Physical and chemical properties of anhydrous ethanol, hydrous ethanol and gasoline are shown in Table 3. The engine was initially run

Table 1
Main specifications of the tested engine.

Type	Port injection, naturally inspired
Bore × stroke	75.0 mm × 84.4 mm
Compression rate	10.5:1
Rated power	80 kW@6000 r/min
Rated tongue	130 Nm@4500 r/min
Displacement	1.5 L

Table 2
Accuracies of the measurement instruments.

Instrument	Parameters	Accuracy
Eddy current dynamometer	Engine speed	± 1 rpm
	Engine torque	± 0.2% F.S.
Exhaust gas analyzer	HC	± 1 ppm
	CO	± 0.01%
	NO_x	± 1 ppm
	CO_2	± 0.1%
Pressure transducer	Pressure	± 0.1 MPa
Crank angle encoder	Crank angle	± 0.5° CA

Fig. 1. Experimental setup.

with gasoline to warm up condition which the temperature of the engine coolant went up to 80 °C. All the measured data were collected when the engine has run stably for more than one minute. The tests in this experiment were conducted at a fixed speed of 2000 rpm, the most frequently used speed for the test engine. For combustion characteristics, the engine loads of 20 Nm, 50 Nm and 100 Nm were selected to represent low, medium and high load for the test engine, respectively. To evaluate the effect of hydrous ethanol gasoline roundly, the tests were carried out at a wide load range. The engine load varies from 5 Nm to 100 Nm. The tests were repeated for two times which the measured values of the engine speed and torque remained within 2%, and finally, the values of the two readings were averaged.

3. Results and discussion

3.1. Combustion characteristics

3.1.1. In-cylinder pressure

Fig. 2 shows the in-cylinder with respect to crank angle for three various fuels at three typical load conditions. The

Table 3
Physical and chemical properties of gasoline, anhydrous ethanol and hydrous ethanol.

Fuel properties	Gasoline	Anhydrous ethanol [14]	Hydrous ethanol [15]
Density (15 °C, kg/m^3)	745	789	809
Kinematic viscosity (40 °C, cSt)	0.4–0.8	1.20	1.454
Lower heating value (kJ/kg)	42,900	26,800	25,235
Latent heat of evaporation (kJ/kg)	380–500	900	948
Boiling point (°C)	25–215	78	77

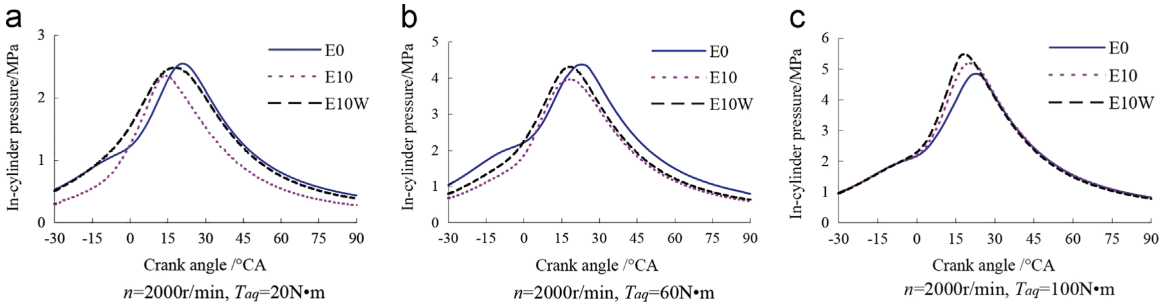

Fig. 2. In-cylinder pressures versus crank angle for three fuels at three operating conditions.

cylinder pressure curves appear similar among the three fuels. As shown in Fig. 2, the peak in-cylinder pressure of E0 was the highest at the low and medium loads, then E10W and E10. At high load, the peak in-cylinder pressure of E10W was the highest, while E10 and E0 came second and third, respectively.

At low and medium loads, gas temperature in the cylinder is lower than that at high loads. Higher latent heat of evaporation of blended fuels reduces the intake air temperature, which results in a worse fuel atomization and fuel–air mixture. In addition, the evaporation of ethanol or hydrous ethanol obviously decreases the gas temperature in the cylinder, leading to a lower peak in-cylinder pressure. This explains why the peak cylinder pressure of pure gasoline is higher than those of blended fuels for low and medium loads. Gas temperature in the cylinder increases with the increase of engine load. In the case of high load, the negative effect of higher latent heat of evaporation of blended fuels on peak in-cylinder pressure reduces, which results in high peak cylinder pressures of blended fuels. Meanwhile, on the premise of the same fuel–air equivalent ratio, the present oxygen of blended fuels accelerates the speed of flame propagation and combustion, thereby leading to high peak cylinder pressures.

At all the operating conditions, E10W exhibits higher peak in-cylinder pressures than E10 does. The reason behind it is water in hydrous ethanol expedites the fuel mixing with air, and leading to a faster flame propagation and combustion [16]. Additionally, water in hydrous ethanol promotes the formation of free radicals H, O, OH and HO_2, which enhances the combustion process [17].

3.1.2. Heat release rate

The heat release rate was analyzed in order to figure out the actual process of combustion in the cylinder. Fig. 3 presents heat release rate with respect to crank angle for three various fuels at three typical load conditions. We can see from Fig. 3 that the peak heat release rates of E0 are higher than those of E10 while lower than those of E10W at low and medium loads. At high load, both of peak heat release rates of E10 and E10W are higher than that of E0. It can be observed from Fig. 2 and Fig. 3 that peak heat release rate and peak in-cylinder pressure increases with the increase in engine load. This behavior may be explained by the reduction of excess air coefficient with the increase in engine load, thereby leading to an increase of fuel density within the reaction zone due to richer fuel–air mixture. Thus, a faster flame propagation and combustion process decreases heat transfer loss, resulting in a higher combustion temperature, peak in-cylinder pressure and heat release rate.

At low and medium loads, the peak heat release rates of E10 are higher than those of E0. When the engine is operating at low and medium loads, lean mixture is injected into the cylinder, resulting in both the heat release and the temperature of the combustion low. Thus, the higher talent heat of evaporation of ethanol reduces the combustion temperature of mixture obviously, leading to lower peak heat release rates. With the increase of the engine load, E10 presents an increase in the peak heat release rate and ultimately, shows a higher peak heat release rate at high load. This may be due to the fact that the negative impact of latent heat of evaporation of ethanol on burning temperature reduces [18]. In addition, the presence of ethanol which makes fuel–air mixture more homogeneous at high load and subsequently reduces local heterogeneous

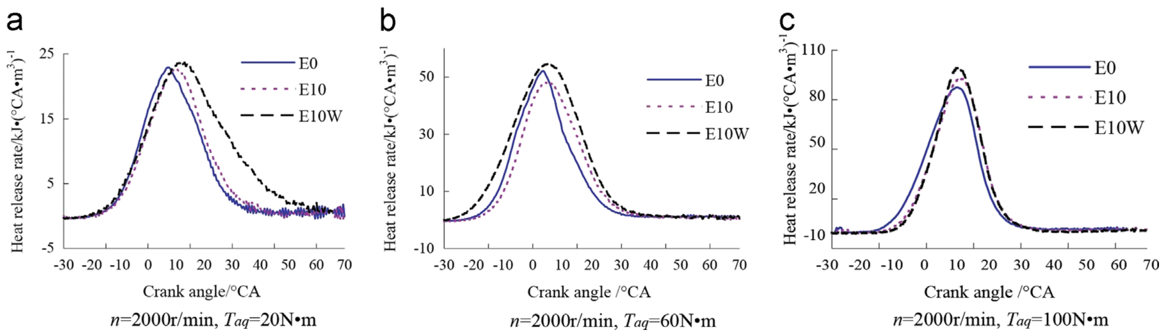

Fig. 3. Heat release rates versus crank angle for three fuels at three operating conditions.

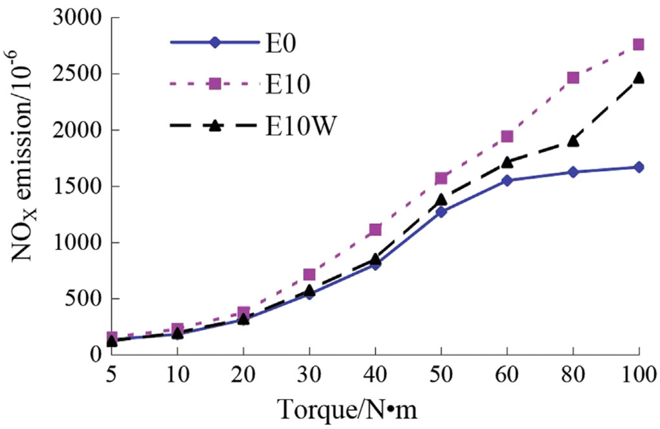

Fig. 4. Comparison of NO_x emissions for three fuels at various load conditions.

oxygen, results in a complete combustion. Further, ethanol in blended fuel promotes the formation of free radicals at high temperatures, which accelerates the reaction speed and improves the peak heat release rate. As can be also seen from Fig.3, E10W exhibits higher peak heat release rate than E10 does at all the operating conditions. The reasons behind it are similar with the explanations for peak in-cylinder pressure as mentioned before.

3.2. Emission characteristics

3.2.1. NO_x emissions

For three various fuels, NO_x emissions for varying engine loads at the speed of 2000 rpm are illustrated in Fig. 4. It can be observed from Fig. 4 that NO_x emission for three fuels increases with the increasing engine load. Formation of NO_x depends on a higher combustion temperature, a longer residence time at that temperature and oxygen-enrichment in the reaction regions [19]. Obviously, with the increasing engine load, the combustion temperature could be higher, resulting in higher NO_x emissions.

At all operating conditions, a higher NO_x emission level is observed for the blended fuels. Due to higher latent heat of evaporation and lower heating value of the blended fuels, their cooling effect could reduce the combustion temperature and thereby reduce the formation of nitrogen oxides. However, the presence of oxygen in blended fuels provides relative oxygen-enrichment in the reaction regions, which promotes the oxidation of N_2 and the formation of the NO_x. In addition, a faster flame propagation and combustion process caused by ethanol increases the combustion temperature in the cylinder, thereby leading to an increase of the NO_x emission. For the blended fuels, the combination effect of these factors results in the overall reduction of NO_x emission. Compared with E10, for E10W, a slight drop of NO_x emission can be observed at all the operating conditions. This can be explained by the presence of water in hydrous ethanol which absorbs heat to evaporate, reducing the combustion temperature in the cylinder, and hence, NO_x emission reduces slightly.

3.2.2. HC emissions

Fig. 5 shows HC emission for three fuels with respect to engine load at the speed of 2000 rpm. At the speed of 2000 rpm and the torque of 20 Nm condition, compared with pure gasoline, HC emissions of the tested engine powered by E10W and

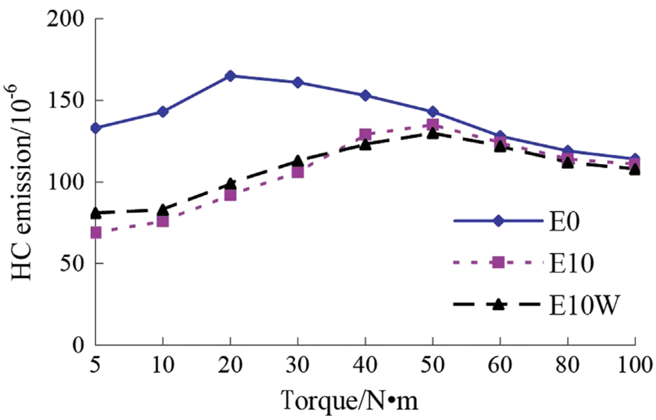

Fig. 5. Comparison of HC emissions for three fuels at various load conditions.

E10 decrease by 40% and 44.24%, respectively. When the engine is operating at high load conditions, HC emissions for three fuels decrease.

HC productions, primarily caused by unburned mixtures, are located around the periphery of the reaction regions [14]. At low loads, leaner mixture and lower combustion temperature increase HC emission caused by flame quenching on the chamber walls. With the addition of ethanol (or hydrous ethanol), the presence of oxygen reduces the zone of 'lean outer flame', which results in a reduction of HC formation. This explains why a significant drop of HC emissions can be observed for E10W and E10 at low load conditions. Turbulence intensity of gas in the cylinder increases with the increasing engine load, which makes fuel–air mixture more homogenous. Hence, engine load increases, leading to a higher combustion temperature and efficiency. When the engine is operating at high load conditions, air–fuel equivalence ratios for three fuels are slightly higher than 1. The excess air in the cylinder reduces the residual gas coefficient, leading to a more efficient combustion and lower HC emission.

Compared with E10, the addition of water in E10W absorbs heat to evaporate, reducing the combustion temperature in the cylinder. At low loads, on the basis of a lower combustion temperature, the level of HC emissions for E10 is lower than that of E10W. However, at high temperature conditions, the breakdown of water in E10W into the hydroxy radical (–OH) and the hydrogen radical (–H) promotes the oxidation of unburned hydrocarbons [20].

3.2.3. CO emissions

When the engine is operating at the speed of 2000 rpm and various engine load conditions, CO emission of the engine powered by three fuels is shown in Fig. 6. For blended fuels, a significant drop of CO emission can be observed from Fig. 6. Specifically operating at the torque of 10 Nm condition, a highlighted reduction in CO emission can be seen for E10W compared to that of pure gasoline.

Carbon monoxide, the product of incomplete combustion, is mainly produced in flame quenching regions. CO emissions are extremely influenced by the combustion temperature in the cylinder and the homogenization of fuel–air mixture. At all the operating conditions, CO emissions of the engine powered by pure gasoline are more than those of blended fuels. The addition of oxygen content of ethanol improves the oxidation of CO, thereby resulting in a reduction of CO production. The lower activation energy and ignition temperature of blended fuels accelerate the combustion and flame propagation velocity, thereby contributing to a more complete combustion and a reduction of CO formation. Due to the lower volatility, blended fuels have leaner fuel–air mixture than pure gasoline does in the process of intake stroke, promoting complete combustion and thus reducing CO formation [21].

At low loads, CO emissions of E10W are more than those of E10. This can be explained by the addition of water reduces the combustion temperature, restraining the oxidation of CO, and hence, CO emission increases. At medium and high loads, the breakdown of water in E10W into the hydroxy radical (–OH) and the hydrogen radical (–H) promotes the oxidation of CO at high temperature conditions. In addition, according to chemical kinetics, moderate addition of water promotes the oxidation of CO on the condition of sufficient reaction [17]. These two reasons explain why E10W has fewer CO emissions at medium and high loads.

3.2.4. CO_2 emissions

Fig. 7 presents CO_2 emission for three fuels with respect to engine load at the speed of 2000 rpm. When the engine is operating at load range varying from 5 Nm to 50 Nm, a significant reduction of CO_2 emission can be observed for E10 and E10W compared to pure gasoline. Specifically at the torque of 20 Nm, compared to pure gasoline, CO_2 emission of E10W decreases by 39.50%. When the engine is operating at high load conditions, CO_2 emissions for three fuels are comparable.

Generally, CO_2 production is mainly influenced by carbon–hydrogen ratio of the fuel [22]. Compared to pure gasoline, the addition of ethanol reduces carbon–hydrogen ratio of the blended fuels, resulting in a lower CO_2 production for E10 and

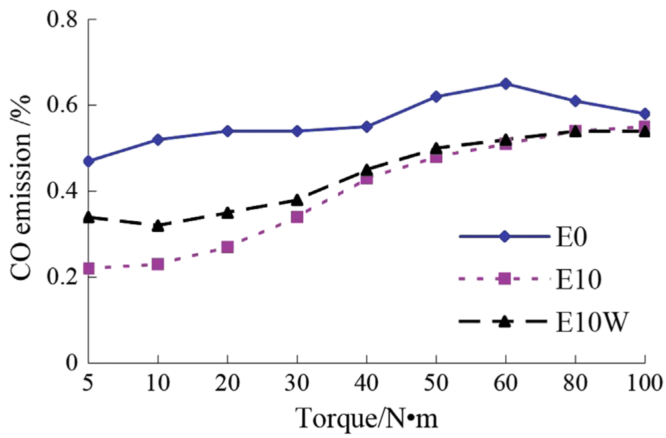

Fig. 6. Comparison of CO emissions for three fuels at various load conditions.

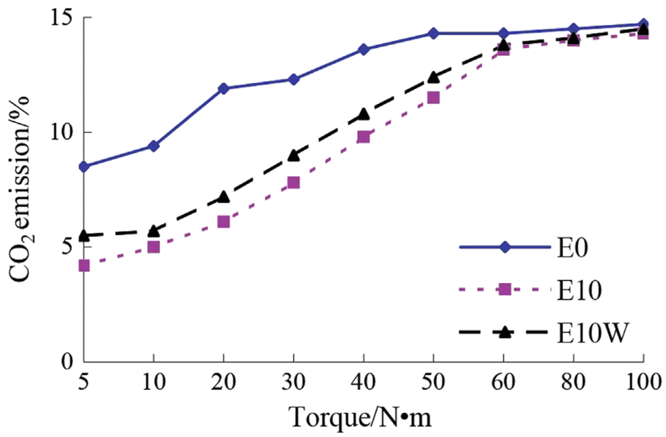

Fig. 7. Comparison of CO_2 emissions for three fuels at various load conditions.

E10W at low and medium loads. At high loads, to export comparable power, more blended fuels are injected into the cylinder, which increases the formation of CO_2. Thus, CO_2 emissions for three fuels are comparable under high load conditions.

4. Conclusions

The focus of this study was to evaluate the effects of hydrous ethanol gasoline on the combustion and emission characteristics on a port injection gasoline engine. Based on the experimental results, the conclusions are as follows:

(1) Compared with E0, E10W showed higher peak in-cylinder pressure at high load. Increases in peak heat rise rates were observed for E10W fuel at all the operating conditions. Besides, the usage of E10W increased NO_X emissions at a wide load range. However, at low load conditions, E10W reduced HC, CO and CO_2 emissions significantly and thus could be an environmental benefit. E10W also produced slightly less HC and CO emissions, while CO_2 emissions were not significantly affected at higher operating points.
(2) Compared with E10, E10W showed higher peak in-cylinder pressures and peak heat release rates at the tested operating conditions. In addition, decreases in NO_X emissions were observed for E10W from 5 Nm to 100 Nm, while HC, CO and CO_2 emissions were slightly higher at low and medium load conditions.
(3) The practical consequence of burning E10W fuel showed a better combustion process, especially at higher loads. In addition, E10W fuel had lower NO_X emissions than E10 at all operating conditions and lower HC, CO and CO_2 emissions significantly and simultaneously than E0 at low load conditions. From the above, it can be concluded that E10W fuel can be regarded as a potential alternative fuel for gasoline engine applications.

Acknowledgments

This work was supported by the key discipline construction of the Midwest Plan of Hainan University (No. ZXBJH-XK015).

References

[1] M.A. Costagliola, L.D. Simio, S. Iannaccone, M.V. Prati, Combustion efficiency and engine out emissions of a SI engine fueled with alcohol/gasoline blends, Appl. Energy 111 (2013) 1162–1171.
[2] I. Schifter, L. Diaz, R. Rodriguez, J.P. Gómez, U. Gonzalez, Combustion and emissions behavior for ethanol–gasoline blends in a single cylinder engine, Fuel 90 (2011) 3586–3592.
[3] C. Dardiotis, G. Fontaras, A. Marotta, G. Martini, U. Manfredi, Emissions of modern light duty ethanol flex-fuel vehicles over different operating and environmental conditions, Fuel 140 (2015) 531–540.
[4] R. Leng, C.T. Wang, C. Zhang, D. Dai, G.Q. Pu, Life cycle inventory and energy analysis of cassava-based fuel ethanol in China, J. Clean. Prod. 16 (3) (2008) 374–384.
[5] D. Dong, D. Zhao, C. Liao, Energy consumption analysis in life cycle of cassava fuel ethanol production and the advantages of the new technology in energy consumption, Trans. Chin. Soc. Agric. Eng. 24 (7) (2008) 160–164.
[6] S.H. Liu, L.Z. Shen, N.Y. Ye, Y.H. Bi, X. Luo, et al., Research on effects of E10 hydrous ethanol gasoline blend on performance and emissions of gasoline engine, Chin. Intern. Combust. Engine Eng. 33 (5) (2012) 46–51.
[7] A. Kyriakides, V. Dimas, E. Lymperopoulou, D. Karonis, E. Lois, Evaluation of gasoline–ethanol–water ternary mixtures used as a fuel for an Otto engine, Fuel 108 (2013) 208–215.

[8] R. Munsin, Y. Laoonual, S. Jugjai, Y. Imai, An experimental study on performance and emissions of a small SI engine generator set fuelled by hydrous ethanol with high water contents up to 40%, Fuel 106 (2013) 586–592.
[9] I. Schifter, L. Diaz, R. Rodriguez, J.P. Gómez, U. Gonzalez, Combustion characterization in a single cylinder engine with mid-levels hydrated ethanol–gasoline blended fuels, Fuel 103 (2013) 292–298.
[10] R.C. Clemente, E. Werninghaus, E.P.D. Coelho, L.A.S. Ferraz, Development of an internal combustion alcohol fueled engine, SAE technical paper, 2001-01-3917, 2001.
[11] R.C. Costa, J.R. Sodré, Hydrous ethanol vs. gasoline ethanol blend: engine performance and emissions, Fuel 89 (2010) 287–293.
[12] T.C. Cordeiro de Melo, G.B. Machado, C.R.P. Belchior, M.J. Cola, J.E.M. Barros, E. Oliveira, et al., Hydrous ethanol–gasoline blends – combustion and emission investigations on a flex-fuel engine, Fuel 97 (2012) 796–804.
[13] R.S. Figliola, D.E. Beasley, Theory and Design for Mechanical Measurements, John Wiley & Sons, New York, 2000.
[14] E.G. Giakoumis, C.D. Rakopoulos, A.M. Dimaratos, D.C. Rakopoulos, Exhaust emissions with ethanol or n-butanol diesel fuel blends during transient operation: a review, Renew. Sustain. Energy Rev. 17 (2013) 170–190.
[15] A.F. Lopez, M. Cadrazco, A.F. Agudelo, L.A. Corredor, J.A. Vélez, J.R. Agudelo, Impact of n-butanol and hydrous ethanol fumigation on the performance and pollutant emissions of an automotive diesel engine, Fuel 153 (2015) 483–491.
[16] Alam Ebna, M. Fahd, W.M. Yang, P.S. Lee, S.K. Chou, C.R. Yap, Experimental investigation of the performance and emission characteristics of direct injection diesel engine by water emulsion diesel under varying engine load condition, Appl. Energy 102 (2013) 1042–1049.
[17] W. Zhang, G.Q. Shu, Z.H. Chen, Y.G. Shen, J.Q. Weng, et al., Chemical kinetics of ignition timing of diesel engine fueled with water emulsion diesel, Trans. Chin. Soc. Agric. Eng. 28 (13) (2012) 59–66. (in Chinese).
[18] M. Eyidogan, A.N. Ozsezen, M. Canakci, A. Turkcan, Impact of alcohol gasoline fuel blends on the performance and combustion characteristics of an SI engine, Fuel 89 (10) (2010) 2713–2720.
[19] J. Warnatz, U. Maas, R.W. Dibble, Combustion, 4th ed. Springer, New York, 2010.
[20] A. Alahmer, Influence of using emulsified diesel fuel on the performance and pollutants emitted from diesel engine, Energy Convers. Manag. 73 (2013) 361–369.
[21] H.Q. Wei, D.Q. Feng, G.Q. Shu, M.Z. Pan, Y.B. Guo, D.Z. Gao, et al., Experimental investigation on the combustion and emissions characteristics of 2-methylfuran gasoline blend fuel in spark-ignition engine, Appl. Energy 132 (2014) 292–298.
[22] S.R. Turns, An Introduction to Combustion Concepts and Applications, McGraw-Hill, New York, 2000.