COMBUSTION CHARACTERISTICS OF AND BENCH TEST ON A MIXTURE OF GASOLINE AND ALTERNATIVE FUEL

by

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In this study, an evaporative premixed constant-volume combustion system was designed for the combustion of liquid fuels, compared with a traditional constant-volume firebomb. The effects of an alternative fuel to gasoline on the combustion characteristics of the laminar flame of gasoline were analyzed, and a bench test was subsequently carried out. The results showed that the addition of the alternative fuel made the maximum non-stretched flame propagation velocity of combusting gasoline increasingly close to that of combusting diluted mixed gas. The Markstein lengths of gasoline and a mixture of gasoline and an alternative fuel became shorter with a higher equivalence ratio, and flame combustion was increasingly unstable. The laminar combustion velocity of the mixture rose before declining as the equivalence ratio increased. According to the results of the bench test, adding 20% of the alternative fuel into gasoline had little impact on the power performance and fuel consumption of the engine, but it reduced HC emissions by 25% and CO emissions by 67%.

Key words: *constant-volume combustion, alternative fuel to gasoline, bench test, combustion characteristics, laminar combustion velocity*

Introduction

In response to the severe energy shortage and the strict emissions regulations, both Chinese and foreign scholars have been committed to the development and research of new technologies and models [1]. To some extent, the improvement in the structure of engines and the application of new energy and alternative fuels have alleviated energy scarcity and emission pollution [2].

A constant-volume firebomb works as an airtight container that simulates the combustion of fuels in the cylinder [3]. Recently, progress in its research has been made by Chinese and foreign scholars [4]. Bradley *et al.* [5] probed into the measurement of such combustion parameters as methane-air combustion velocity, the Markstein length, and flame quenching. Brandley *et al.* [6] delved into the laminar combustion velocities and Markstein lengths of iso-octane and n-Heptane at different levels of pressure and temperature. Kwon *et al.* [7] explored the cellular instability and self-acceleration nature of outward propagating flame. Bao *et al.* [8] probed into the formation mechanism of the unstable cellular structure of the hydrogen-air premixed laminar combustion flame. Jerzembeck *et al.* [9] studied the laminar combustion velocities of gasoline at different levels of pressure. Hamdan and Jubran [10] used an ATD34 engine to test the performance of ethanol gasoline of different blending ratios.

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Adopting the gas distribution of a traditional constant-volume firebomb, this work developed a new evaporative premixed constant-volume combustion system for liquid fuels like gasoline, delved into the combustion characteristics of the premixed laminar flame of a mixture of gasoline and alternative fuel (M), and carried out a bench test. This builds a foundation for the basic studies on gasoline combustion and for the selection and optimization of alternative fuels.

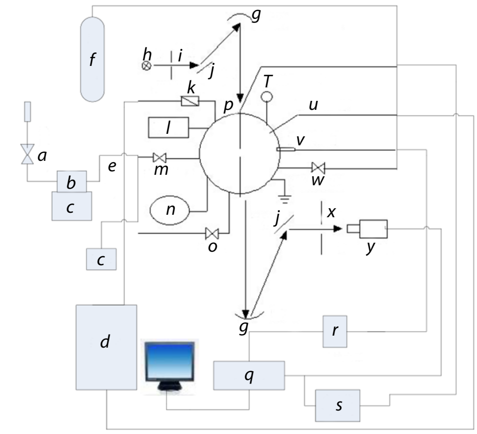


Figure 1. Constant-volume combustion system; *a – feed inlet valve, b – evaporator, c – temperature controller, d – control cabinet, e – outlet, f – compressed air, g – concave mirror, h – light source, i – slit, j – reflector, k – pressure transmitter, l – vacuum pump, m – flow control valve, n – scavenge pump, o – vent valve, p – electrode, q – IPC, r – charge amplifier, s – multifunctional controller, t – high precision pressure gauge, u – temperature sensor, v – steel pressure sensor, w – air inlet valve, x – knife edge, y – high speed camera*

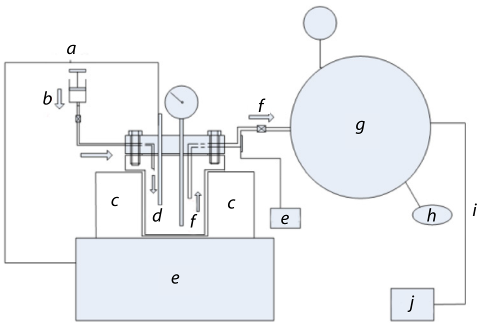


Figure 2. Evaporative premixed gas distribution system for liquid fuels; *a – acquire temperature, b – liquid fuel, c – heat, d – evaporator, e – heat for a constant temperature, f – gas fuel, g – combust, h – pump out, i – control ignition, j – control system*

Testing Equipment and method

Experiment equipment

Building on a traditional constant-volume firebomb, we developed a new evaporative premixed constant-volume system for liquid fuels like gasoline and diesel, as is shown in fig. 1. This system consists of five parts, namely, a constant-volume combustion system, an evaporative gas distribution system, an ignition system, a schlieren photographing system, and a control and acquisition system [11].

The constant-volume firebomb is a sphere with a 350 mm internal diameter, with a maximum operating pressure of 4 MPa and a maximum heating temperature of 600 K. There are four perspective windows around it, and each window has a diameter of 140 mm. The heating elements are evenly distributed outside the constant-volume firebomb, with a heat preservation layer [12]. The ignition system can be extended to the center of the constant-volume firebomb, safe and reliable [13]. The high-speed camera features a photographing rate of 10000 fps and an exposure time of 50 μs.

The gas distribution system of the constant-volume firebomb was utilized to design the evaporative premixed gas distribution system for liquid fuels like gasoline and diesel, as shown in fig. 2. The main structure was a steel evaporator, in which there was a cylindrical cavity with a volume of 500 ml. Besides, there was a conical airtight space between the upper cover and the container. It could withstand a pressure of 20 MPa and a high temperature of 600 K. When the evaporator was heated to the designated temperature, the liquid fuel inside would evaporate completely, and the experiment would be carried out if this temperature was maintained [14]. The flow control valve was opened according to the designated partial pressure ratio and the steam of the liquid fuel was put into it until the designated pressure was reached. In this way, an accurate ratio of the liquid fuel to air could be obtained [15].

Experiment materials

This paper probed into the effects of an alternative fuel to gasoline on the combustion characteristics of premixed laminar flame. In this study, the gasoline was 93-octane gasoline for commercial use. The alternative fuel was an oxygen-containing alternative fuel supplied by an enterprise, and its oxygen content was high and its physical and chemical properties were similar to those of gasoline [16]. The information about the gasoline and the alternative fuel (M) is presented in tabs. 1 and 2, respectively.

Table 1. Parameters of the commercial gasoline

Name	Content of carbon	Content of hydrogen	Content of oxygen	Others
Commercial 93-octane	87.3%	12.1%	0.3%	0.3%

Table 2. Parameters of the alternative fuel (M)

Name	Content of carbon	Content of hydrogen	Content of oxygen	Others
Oxygen-containing alternative fuel	47.4%	10.4%	42.1%	0.1%

Experiment method

An improved constant-volume firebomb and the new evaporative premixed gas distribution system were used to generate the mixed gas from gasoline or the mixture of gasoline and the alternative fuel (according to the blending proportions of the domestic ethanol gasoline and a foreign alternative fuel). The gasoline was mixed with 10% and 20% of the alternative fuel, respectively, and the resulting mixtures were named B10 and B20. One of them was to be chosen for the bench test depending on the analysis of constant-volume combustion [11].

According to the spherical diffusion flame theory by Badley *et al.* [6] the combustion characteristic parameters during the combustion of gasoline or the mixture of gasoline and the alternative fuel, including the propagation velocity, stretch ratio, and laminar combustion velocity, could be calculated. Based on the findings by Badley *et al.* [5], the electrode-based ignition energy in a firebomb affects the initial development of flame. That's the reason that a flame radius of 6 mm to 30 mm was used to explore the combustion characteristics in this experiment.

Results and discussion

Effects of the alternative fuel to gasoline on the laminar combustion velocity

Figure 3 shows the correlation between flame radius and time during combustion of the gas mixing air and the blend of gasoline and the alternative fuel. Figure 3(a) reveals the correlation between flame radius and time during gasoline combustion with different equivalence ratios. As is presented in fig. 3, the relation between the flame radius and time in the gasoline combustion was similar to a linear one regardless of the equivalence ratio. As the equivalence ratio rose, the flame radius was progressively longer before swiftly shortening, and the time-based increase in flame radius with an equivalence ratio staying between 1.1 and 1.4 was remarkably greater than that with other equivalence ratios.

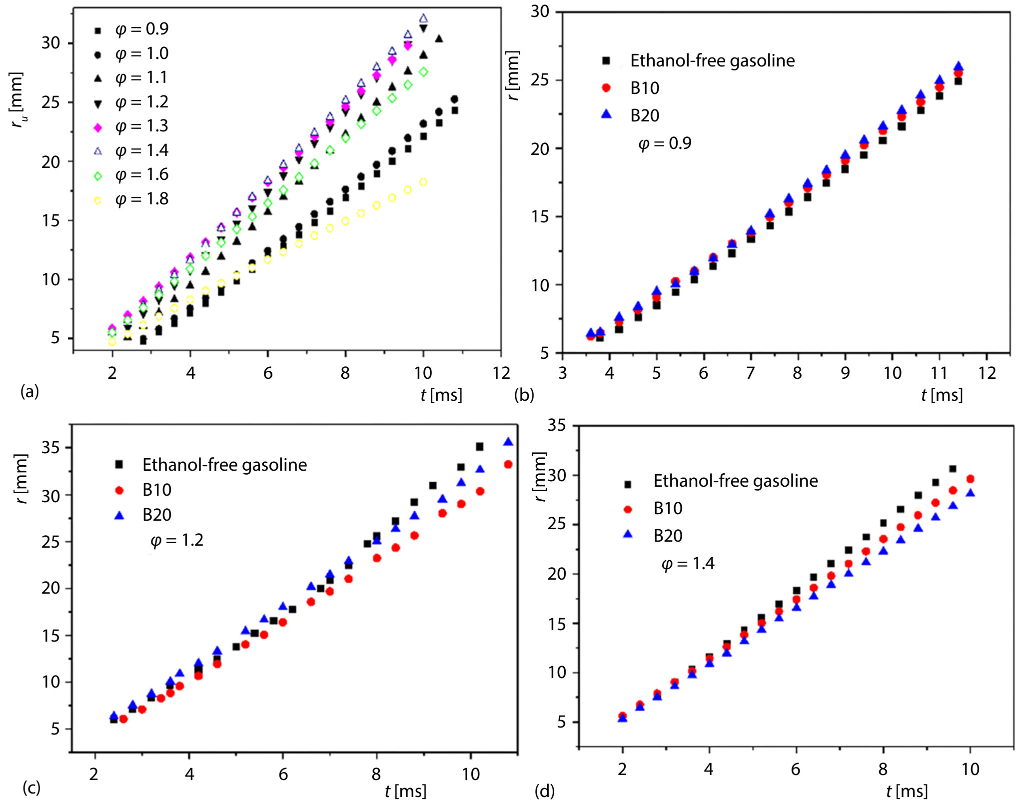


Figure 3. Effects of gasoline or the mixture of gasoline and the alternative fuel on the combustion radius

Figures 3(b)-3(d) manifest the correlation between flame radius and time during the combustion of gasoline, B10, and B20 when the equivalence ratio was 0.9, 1.0, 1.1, 1.2 and 1.4, respectively. According to fig. 3(b), the flame radius did not change much with time when the equivalence ratio was 0.9. It, however, became slightly longer as the alternative fuel increased proportionately. When the equivalence ratio was 1.0 or 1.1, there was little difference in the flame radius between B10 and B20. But the flame radii of the two were significantly longer than that of gasoline, so it was with the growth rate of the flame radius. As the equivalence ratio went higher, the growth rate slowed down. When the equivalence ratio was 1.2, there was little difference in flame radius in the initial stage. But as the combustion continued, the flame radius of ethanol-free gasoline combustion progressively became longer than that of the gasoline with the alternative fuel. When the equivalence ratio was 1.4, the gasoline, B10 and B20 ranked in a descending way in terms of the combustion radius of flame and the growth rate of combustion radius.

Figure 4 reflects the correlation between the stretched flame propagation velocities (Sn) and flame radius during combustion of gasoline and the mixture of gasoline and the alternative fuel. According to fig. 4(a), the stretched flame propagation velocity of gasoline was the highest when the equivalence ratio was 1.2. According to figs. 4(b) and 4(c), as the proportion of the alternative fuel increased, the equivalence ratio of the maximum flame propagation velocity fell gradually (the equivalence ratio of the 10% alternative fuel was 1.1, and that of the 20%

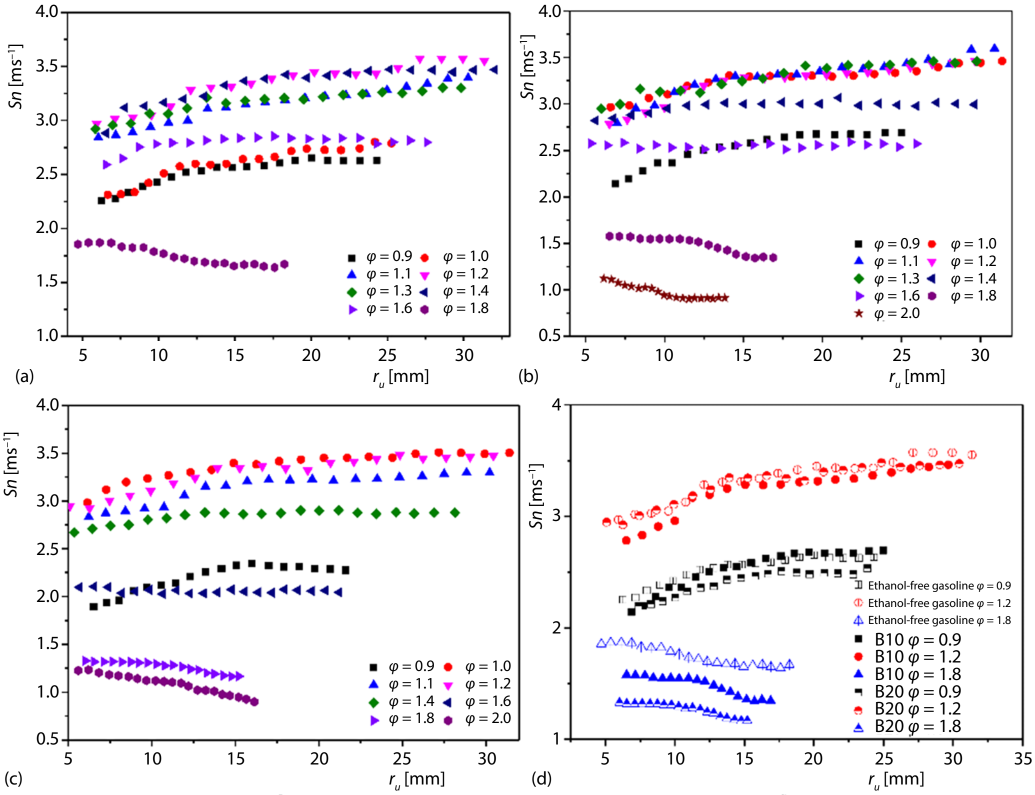


Figure 4. Correlation between the stretched flame propagation velocity and flame radius of of gasoline and the mixture of gasoline and the alternative fuel

alternative fuel was 1.0). As indicated by it, the alternative fuel could accelerate the combustion of gasoline in diluted mixed gas, and a higher proportion of the alternative fuel made the acceleration more noticeable. Figure 4(d) reveals the correlation between the stretched flame propagation velocity and the flame radius of gasoline, B10 and B20 with different equivalence ratios.

Figure 5 shows the correlation between the stretched flame propagation velocity and the stretch rates of gasoline and the mixture of gasoline and the alternative fuel. According to Figures 5(a)-5(c), as the equivalence ratio became higher, the negative value of the *Sn-α* slope (Markstein length) declined gradually in the combustion of the three types of gasoline. As is shown in these figures, the negative value of the *Sn-α* slope approached zero, suggesting the combustion became less stable when the equivalence ratio was 1.6 during the combustion of ethanol-free gasoline. But in the case of the mixture of gasoline and the alternative fuel, the equivalence ratio was 1.4. In addition, when the equivalence ratio was 2.0, gasoline could not be burned, but the gasoline with the alternative fuel was combustible. Figures 5(d)-5(f) reveal the *Sn-α* of the three types of gasoline in the combustion with different equivalence ratios. As shown in the figures, when the equivalence ratio was either 0.9 or 1.2, the combustion was stable, and a higher proportion of the alternative fuel undermined combustion stability. When the equivalence was 1.8, neither the combustion of gasoline nor that of the mixture of gasoline and the alternative fuel was stable.

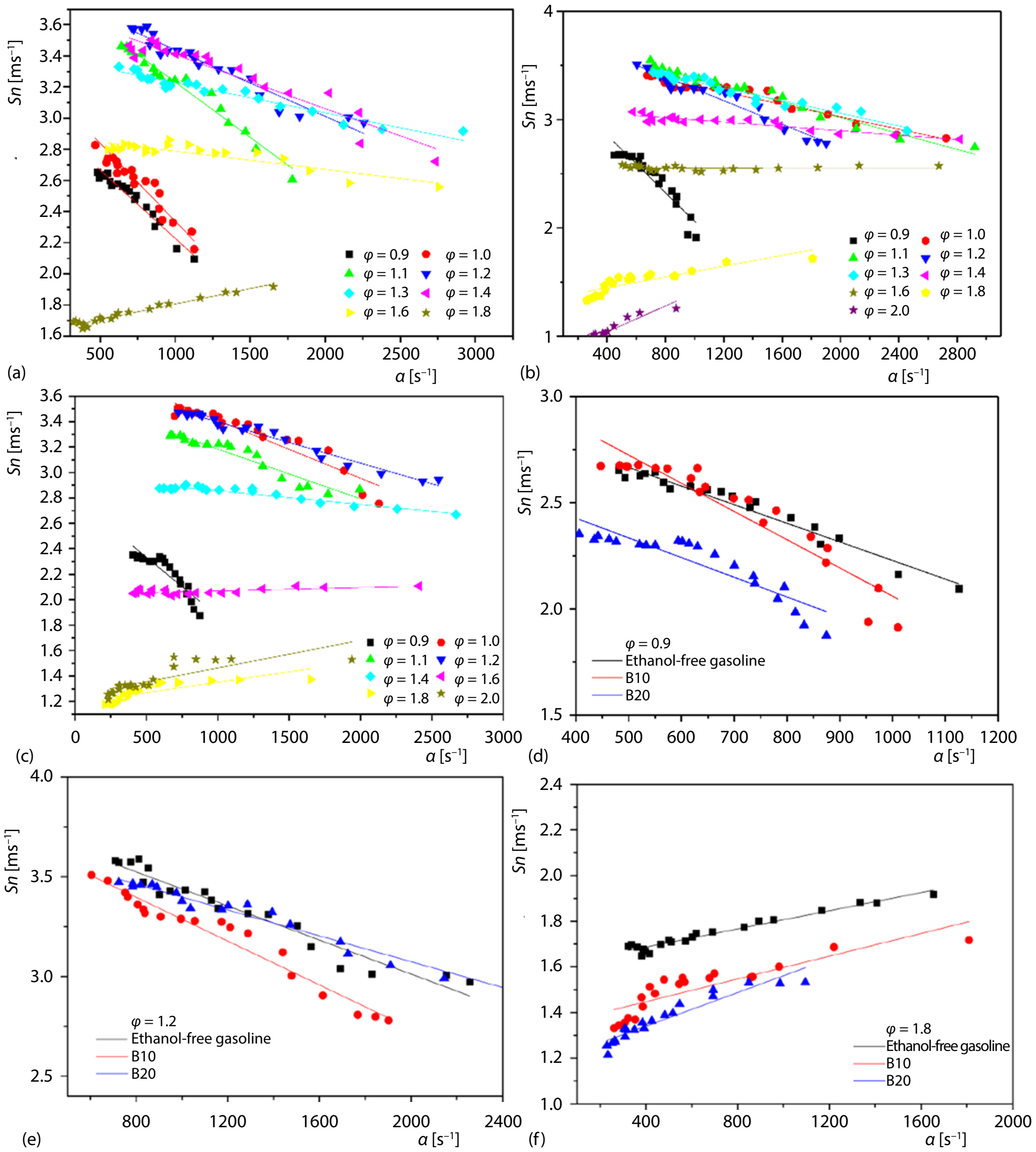


Figure 5. Correlation between the non-stretched flame propagation velocity and flame radius of gasoline and the mixture of gasoline and the alternative fuel

Figure 6 reflects the correlation among the Markstein length (Lb), non-stretched flame propagation velocity (Sl) and equivalence ratio of gasoline and the mixture of gasoline and the alternative fuel. Figure 6(a) shows that as the equivalence ratio increased, the Markstein lengths of all the three types of gasoline reduced and the flame combustion became increasingly unstable. According to fig. 6(b), as the equivalence ratio went up, the non-stretched flame propagation velocities of the three types of gasoline rose before dropping after reaching the maximum when the equivalence ratio was 1.2. If the equivalence ratio of 1.2 was taken as the tipping point, then when the ratio was lower than 1.2, an increase in the proportion of the alternative fuel would lead to a higher non-stretched flame propagation velocity, and; when the ratio was higher than 1.2, the velocity would decline as the proportion of the alternative fuel went up.

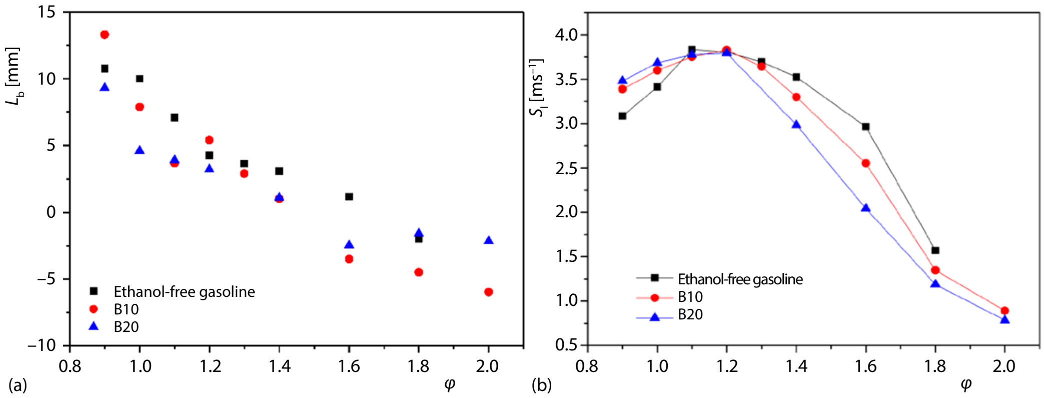


Figure 6. Correlation among the Markstein length, non-stretched flame propagation velocity and equivalence ratio of gasoline and the mixture of gasoline and the alternative fuel

Figure 7 reveals the correlation between the laminar combustion velocities (ul) and equivalence ratio of gasoline and the mixture of gasoline and the alternative fuel. According to fig. 7, as the equivalence ratio of the three types of gasoline increased, the laminar combustion velocity rose before declining, and both of them reached the maximum when the equivalence ratio was 1.2. If the equivalence ratio of 1.2 was taken as the tipping point, then when the ratio was below 1.2, a higher proportion of the alternative fuel led to a higher laminar combustion velocity, but there was little difference in the effect of the proportion of the alternative fuel on the laminar combustion velocity. When the equivalence ratio was above 1.2, the laminar combustion velocity dropped as the proportion of alternative fuel increased. In the case of the same equivalence ratio, a higher proportion of the alternative fuel would lead to a lower laminar combustion velocity.

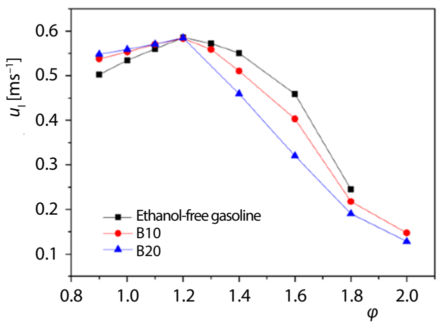
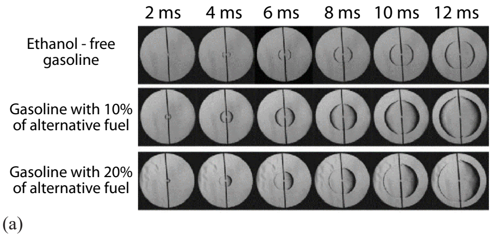
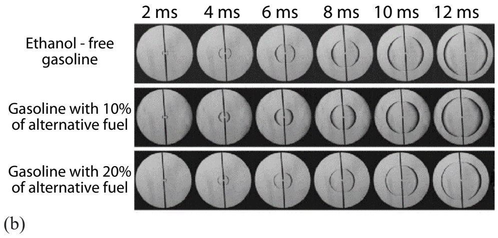


Figure 7. Correlation between laminar combustion velocity and equivalence ratio of gasoline and the mixture of gasoline and the alternative fuel

Analysis of combustion characteristics

Figure 8 compares combustion conditions between gasoline and the mixture of gasoline and the alternative fuel under different equivalence ratios. Figure 8(a) shows that, when the equivalence ratio was 1.0, the combustion radius of gasoline was shorter than that of the gasoline with the alternative fuel at the same combustion time, and the combustion velocity of the former was lower than that of the latter. According to fig. 8(b), when the equivalence ratio was 1.2, the combustion radius of gasoline was slightly larger than that of the gasoline with the alternative fuel at the same combustion time, and the combustion velocity of the former was slightly higher than that of the latter but the difference was insignificant, and the combustion of the three types of gasoline was stable. As fig. 8(c) shows, when the equivalence ratio was 1.6, the combustion radius of gasoline was larger than that of the gasoline with the alternative fuel at the same combustion time, and the combustion velocity went higher, as the proportion of the alternative fuel increased, the combustion velocity declined. These results shown in fig. 8 were compatible with the laminar combustion velocities. But according to the comparison, an encircled structure began to appear at t = 10 ms in the combustion of the ethanol-free gasoline, but it took form at t = 8 ms in the combustion of the gasoline with the alternative fuel. This demonstrates that adding the alternative fuel into the concentrated mixed gas made the gasoline combustion more unstable.





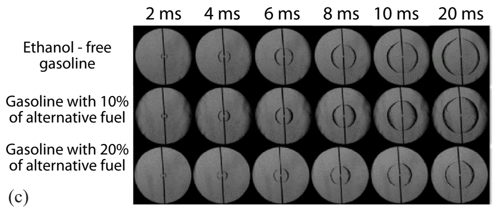


Figure 8. Comparison of combustion with different equivalence ratios between gasoline and the mixture of gasoline and the alternative fuel; (a) equivalence ratio = 1.2, (b) equivalence ratio = 1.2, and (c) equivalence ratio = 1.6

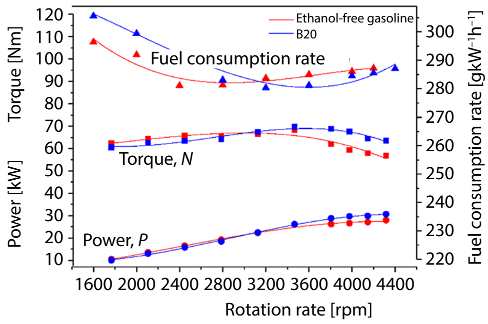


Figure 9. Comparison of the external characteristic curves between ethanol-free gasoline and gasoline

Analysis of the bench test results

Figure 9 is the external characteristics curves of ethanol-free gasoline and the B20 gasoline. According to fig. 9, there was little difference in the power and torque of the engine between B20 and ethanol-free gasoline. At a high rotation rate, the power and torque of the engine of B20 were slightly higher than that of ethanol-free gasoline. At a low rotation rate, the fuel consumption rate of B20 was greater than that of ethanol-free gasoline. Figure 10 shows the emissions of HC and CO of B20 and ethanol-free gasoline with the external characteristics of the engine. It is obvious that the emissions of HC and CO were significantly reduced after 20% of the alternative fuel was added into the gasoline, with HC emissions decreased by 25% and CO emissions 67%.

Conclusions

In this study, we developed an evaporative premixed gas distribution system applicable to explore the laminar flame combustion characteristics of gasoline and the mixture of gasoline and the alternative fuel and carried out a bench test. The following conclusions were drawn:

- An alternative fuel to gasoline made the maximum non-stretched flame propagation velocity of combusting gasoline increasingly close to that of combusting diluted mixed gas.

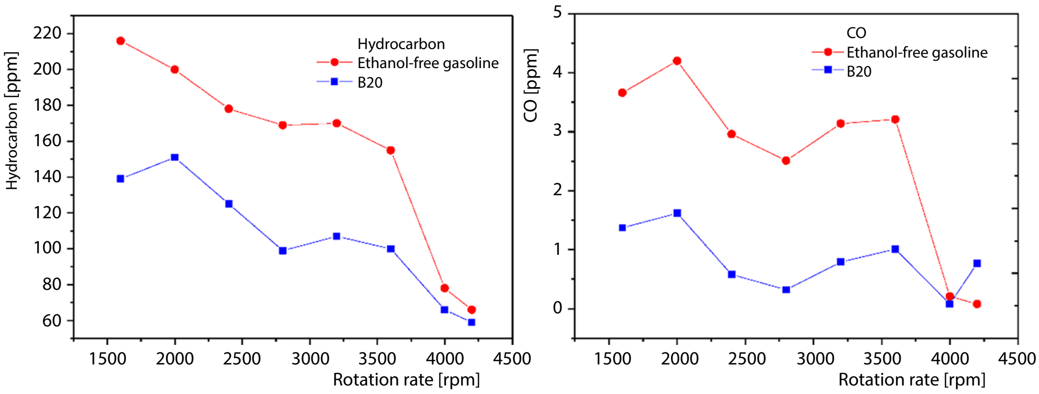


Figure 10. Comparison of the HC and CO emissions with the external characteristics of the engine between ethanol-free gasoline and B20 gasoline

- As the equivalence ratio increased, the Markstein lengths of gasoline and the mixture of gasoline and the alternative fuel became shorter and the flame combustion less stable.
- As the equivalence ratio increased, the laminar combustion velocity of the mixture of gasoline and the alternative fuel would increase before declining.
- If 20% of the *alternative fuel* (M) was added to gasoline, the power performance and fuel consumption of the engine were rarely affected, but HC and CO emissions were significantly reduced, with HC emissions decreased by 25% and CO emissions 67%.
- According to the analysis of the combustion characteristics and the bench test results, the *alternative fuel* (M) was highly effective gasoline with alternative fuel.

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