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Research paper

Experimental study of the spray characteristics of biodiesel based on inedible oil

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ABSTRACT

We studied the spray characteristics of inedible oil using experimental and simulation methods. Spray penetration, spray cone angle and spray tip speed were measured at different biodiesel ratios in a constant volume vessel with wide visualization and high back pressure, using a high-speed camera. The characteristics of biodiesel spray were simulated under the same conditions using Star-CD software. The experimental results showed that, as the ratio of biodiesel in the blends increased, spray penetration and spray speed increased, but the spray cone angle decreased. Throughout the spray injection period, the region at 0.05–0.475*S* (spray tip penetration) was a key area affecting spray cone angle. From 0.8 ms after injection, the spray penetration deviation ratios started to increase with increasing biodiesel blend ratios. Simulation results showed similar macroscopic spray characteristics to the experimental results for jatropha oil. The results also showed that the Sauter mean diameter of blend fuels was greater than that of diesel, and spray was more concentrated, due to the higher viscosity and surface tension of the biodiesel, compared with conventional diesel fuel. The macroscopic and microscopic spray properties of blended fuels containing 5%, 10% and 20% biodiesel were similar to diesel.

1. Introduction

Biodiesel is a renewable, biodegradable, and oxygenous fuel, with similar physical and chemical characteristics to diesel. Moreover, it produces lower combustion emissions and fewer greenhouse gas emissions than fossil diesel. As a result, biodiesel has become a focus of alternative fuel research and applications in recent years (Dong and Liu, 2007).

However, there are some differences in physical parameters between biodiesel and diesel, and it is therefore necessary to study the spray characteristics of biodiesel in relation to its application in internal combustion engines. Senatore et al. (2005) investigated the influence of different back pressures on spray penetration of three different biodiesels, using a high-pressure, common-rail injection system in a constant volume vessel. Zhao et al. (2008) studied the influence of injection duration and back pressure on spray penetration and spray cone angle using an electronic unit pump, and found that the spray penetration and spray cone angle of biodiesel were larger than those of diesel. An increase in back pressure led to a simultaneous reduction in spray penetration and increase in spray cone angle. Lee et al. (2005) studied the atomization characteristics of biodiesel-blended fuels, including spray tip penetration, Sauter mean diameter (SMD), and mean velocity distribution, using a spray visualization system and phase Doppler particle analyzer. The authors concluded that the biodiesel blended fuels had similar spray tip penetrations to conventional diesel, but higher SMD, because the viscosity and surface tension of the biodiesel were higher than those of the conventional diesel fuel. Grimaldi and Postrioti (2000) compared the spray characteristics in terms of tip penetration and cone angles using fuel spray generated by common-rail pressures ranging from 60 to 120 MPa, developed in an atmospheric chamber. Shao et al. (2003) and Delacourta et al. (2005) applied digital imaging techniques to study the characteristics of diesel spray. Weber et al. (2005) investigated the processes of fuel evaporation and mixture formation in dense atomized spray using the Mie/Shadow imaging technique and a 1D-linear Raman scattering technique. Postrioti et al. (2004) used a laser sheet technique to obtain global spray data suitable for tuning direct injection systems to different fuels, and for numerical code validation. Desantes et al. (2005) studied the effects of parameters such as injection pressure, nozzle hole diameter and environment gas density on spray tip penetration.

In this study, we investigated the spray characteristics of three different biodiesels. The test rig was composed of a constant-volume vessel with wide visualization and high back pressure, an oil pump test bed, a high-speed video camera, image-processing software and a data acquisition system. Using this test rig, we investigated spray penetration, spray cone angle and spray tip speed of three biodiesels of different blends sourced from inedible oils and analyzed the changes in spray penetration and spray cone angle throughout the entire spray process.

2. Spray test system

2.1. Spray visualization experimental test rig

A diagram of the biodiesel spray test rig is shown in Fig. 1.

The constant volume vessel was charged with high-pressure nitrogen gas, and a manual exhaust valve was connected to the

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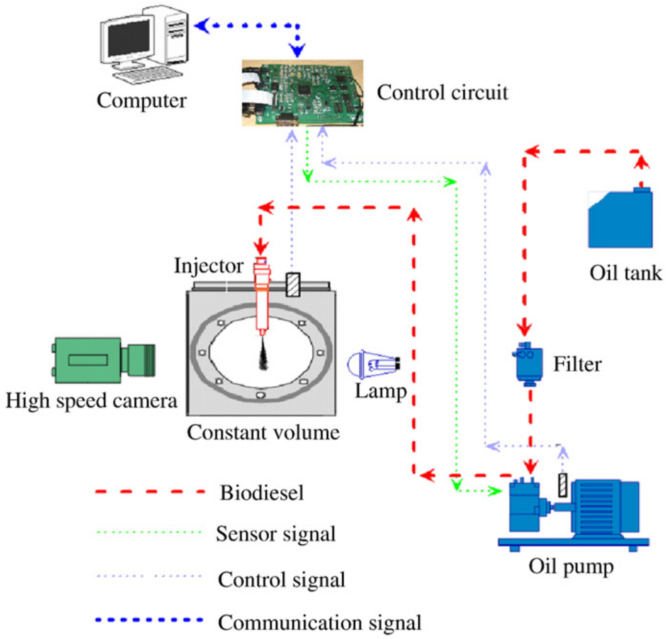

Fig. 1. Diagram of the biodiesel spray test rig.

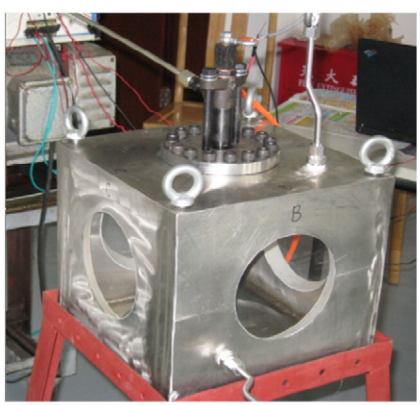

Fig. 2. Constant volume vessel.

constant-volume vessel to adjust the back pressure of the spray. There was a T-joint connected to a mechanical pressure gauge and pressure sensor on the top of the constant volume vessel, to monitor the back pressure. The constant volume vessel is shown in Fig. 2. In this study, the back pressure was kept at 1.1 MPa.

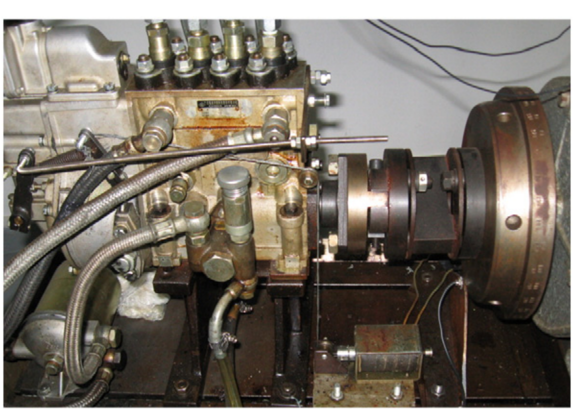

Fig. 3. Oil pump test bed.

Table 1
Physico-chemical characteristics of samples.

List	0# diesel	jatropha oil	Palm oil	Used fried oil
Density (20 °C)/g/L	853.8	875	873	880
Viscosity (40 °C)/(mm^{2}s^{-1})	3.4	4.27	4.41	4.35
Flash point/°C	>60	77	144	146
Sulfur content (m/m)/%	≤0.2	0.008	0.006	0.007
Cold filter clogging temperature/°C	4	1	10	3
90% Recovery temperature/°C	<355	336	332	336
10% Remnant carbon after evaporation (m/m)/%	≤0.3	0.15	0.80	0.34

A DC motor was used as the power source to drive the in-line high-pressure P-type pump (Weifu Company, Wuxi, P.R.China) at the oil pump test bed. The rotation speed range of the pump was in the range of 400–1100 rpm. The oil pump rotation speed could be adjusted by regulating the operating voltage of the DC motor with a speed controller. The maximum injection pressure was proportional to the oil pump rotating speed. The single-injection was achieved using a microcomputer to drive a powerful high-speed solenoid valve to control the fuel supply and cut off (Zhang et al., 2007). The oil pump test bed is shown in Fig. 3.

2.2. Selection of biodiesel and its physico-chemical properties

The main ingredients of biodiesel are fatty acid methyl esters, which provide a very effective alternative to diesel fuel. They can be obtained by the esterification of triglycerides and methanol. Vegetable oil, animal fat and used, fried oil are the main raw materials used to produce biodiesel.

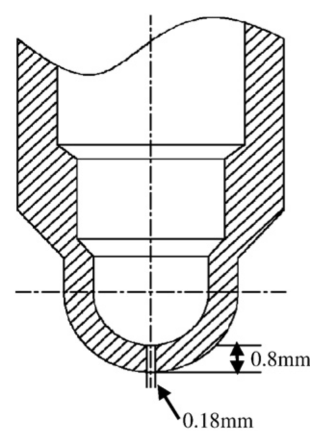

Fig. 4. Top structure of injector nozzle.

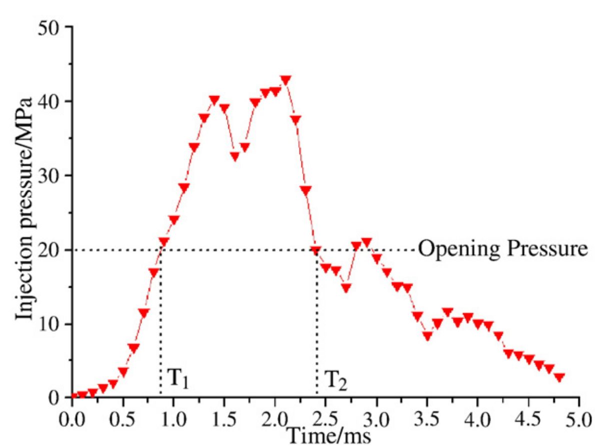

Fig. 5. Injection pressure curve.

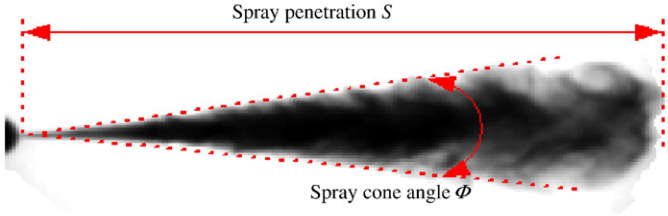

Fig. 6. Spray macroscopic characteristics.

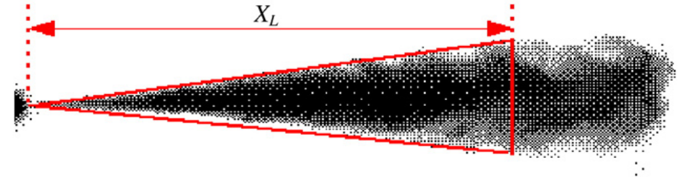

Fig. 8. Schematic diagram of spray cone angle calculation.

Three inedible-source biodiesels, palm oil, used fried oil, and jatropha oil, were selected. The main physico-chemical characteristics of these biodiesels and of 0 # diesel are shown in Table 1.

2.3. Characteristics of nozzle and spray

A single-hole injector with a nozzle diameter of 0.18 mm and nozzle orifice length of 0.8 mm was employed, as shown in Fig. 4.

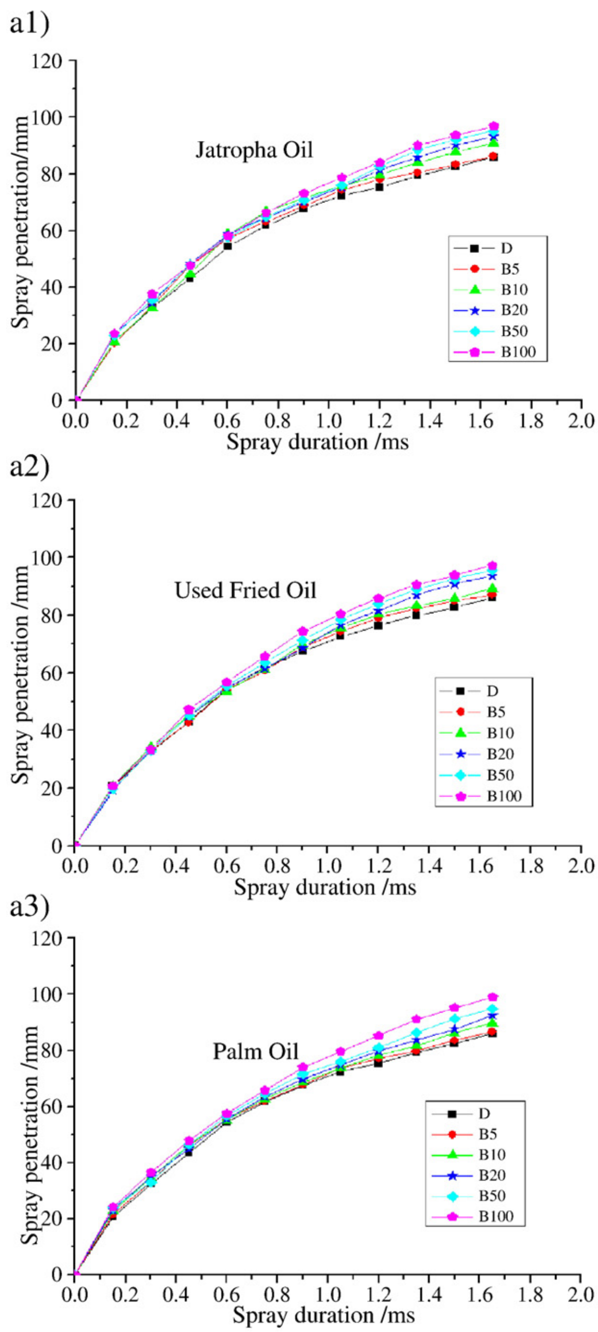

Fig. 7. Spray penetration of biodiesel at different blend ratios. D means diesel, B means biodiesel, and the X in BX is the volume percentage of biodiesel in the diesel mixture.

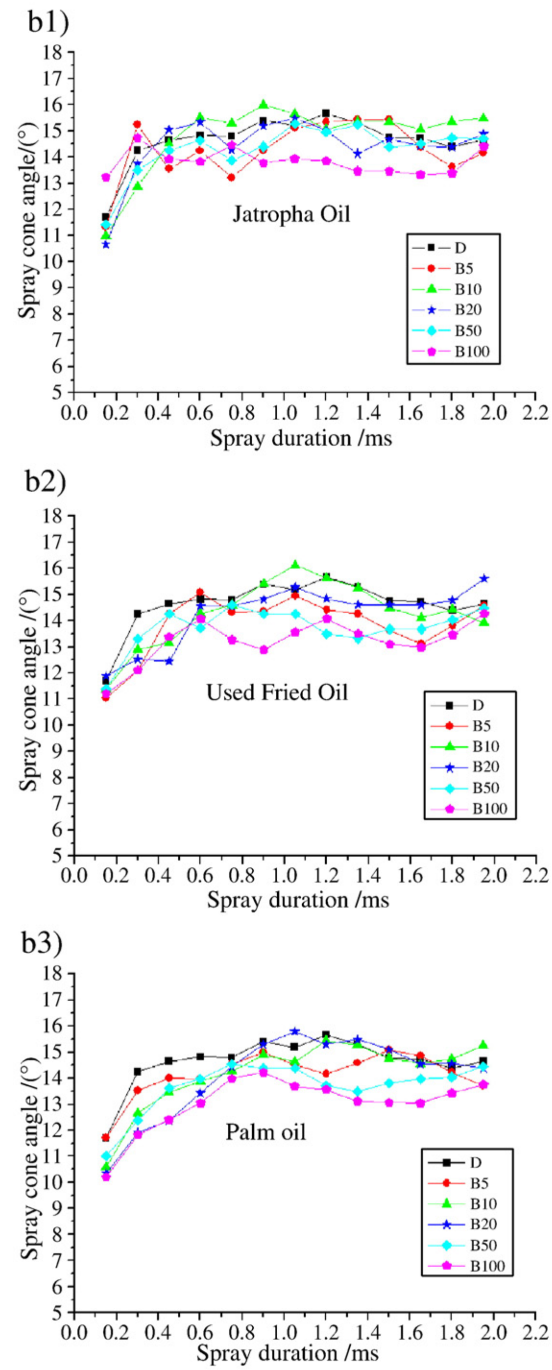

Fig. 9. Spray cone angle of biodiesel at different blend ratios.

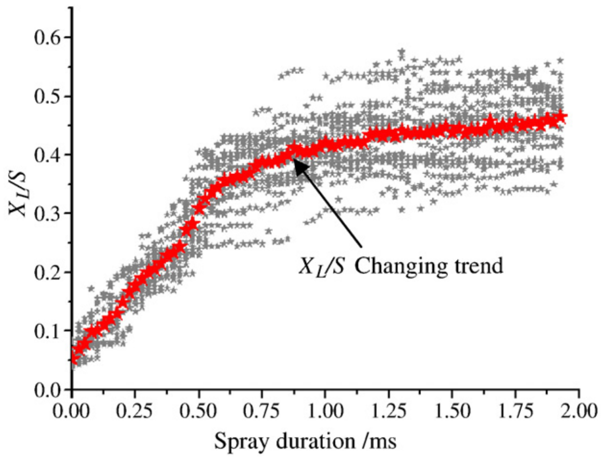

Fig. 10. Trend in X_L/S throughout the entire spraying process.

The rotating speed of the oil pump was set at 850 rpm, and the injection pressure measured under these conditions is shown in Fig. 5. It can be seen that the maximum injection pressure throughout the entire spray process was 43 MPa. The initial injection pressure was 20 MPa, and the duration of injection ΔT_2T_1 was about 1.6 ms.

The macroscopic characteristics, such as spray penetration, spray cone angle, and spray tip speed were studied. The definitions of these characteristics are shown in Fig. 6.

3. Experimental results and discussion

We studied biodiesel derived from three inedible oils at five blend ratios, containing 5% (B5), 10% (B10), 20% (B20), 50% (B50), and 100% (B100) biodiesel, as well as 0# diesel.

3.1. Spray penetration

From Fig. 7, it can be seen that viscosity and spray penetration increased with increasing blend ratio of biodiesel in the fuel. This was mainly because the increase in fuel viscosity prevented the breaking of the spray jet, resulting in an increase in the size of the spray droplets. The larger the size of the spray droplets, the higher their momentum and the smaller the resistance preventing forward movement (Cao, 2005; Hiroyasu and Arai, 1990).

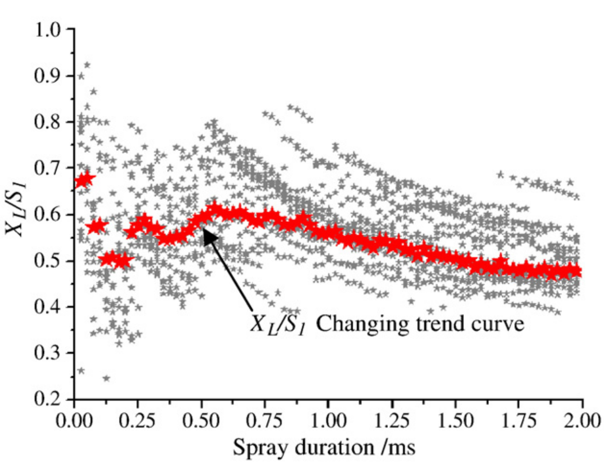

Fig. 11. Trend in X_L/S_1 throughout the entire spraying process.

3.2. Spray cone angle

In order to simplify the algorithm for calculating the spray cone angle Φ in the experiment, an alternative method was employed, as shown in Fig. 8. During the process of spraying, X_L was the distance between the bottom edge of the triangle and the nozzle, which ranged from 0 to S. The maximum angle was calculated as the spray cone angle.

From Fig. 9, it can be seen that the spray cone angle decreased as the blend ratio of the biodiesel increased. The spray cone angles for different fuels followed a trend of an initial increase, followed by a decrease, and then remained stable. This was mainly because an increase in injection pressure caused the spray to spread around, leading to a gradual increase in the cone angle. As the spray continued, droplets around the border became smaller and diffused easily,

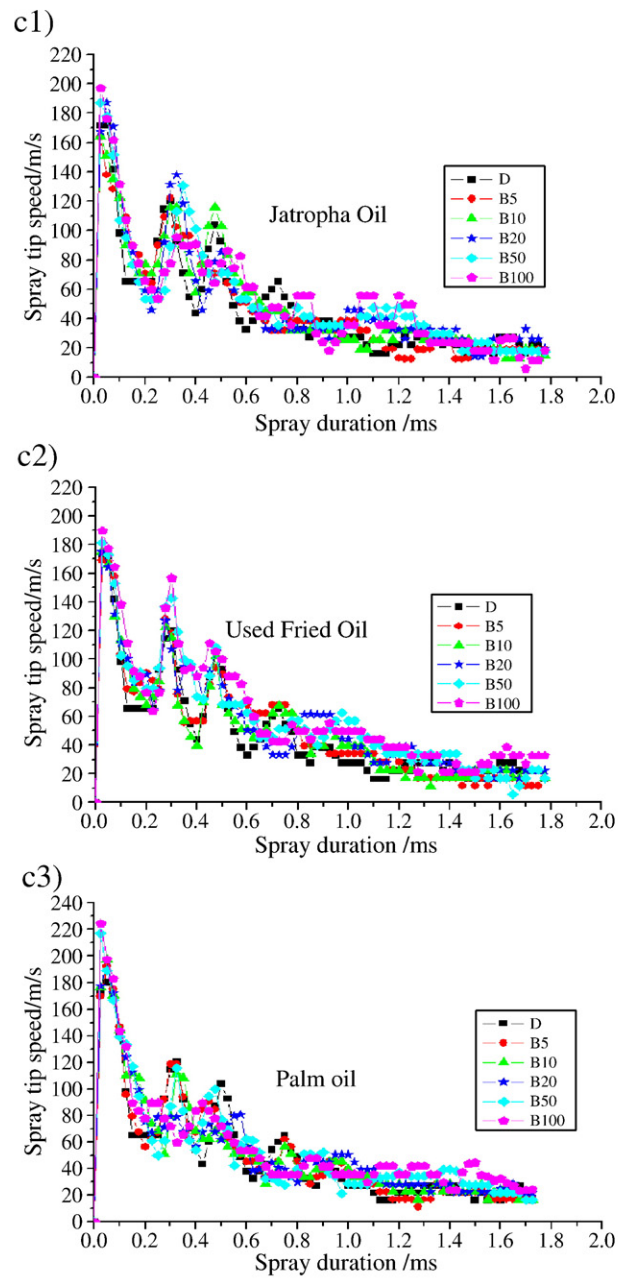

Fig. 12. Spray tip speed of biodiesel at different blends.

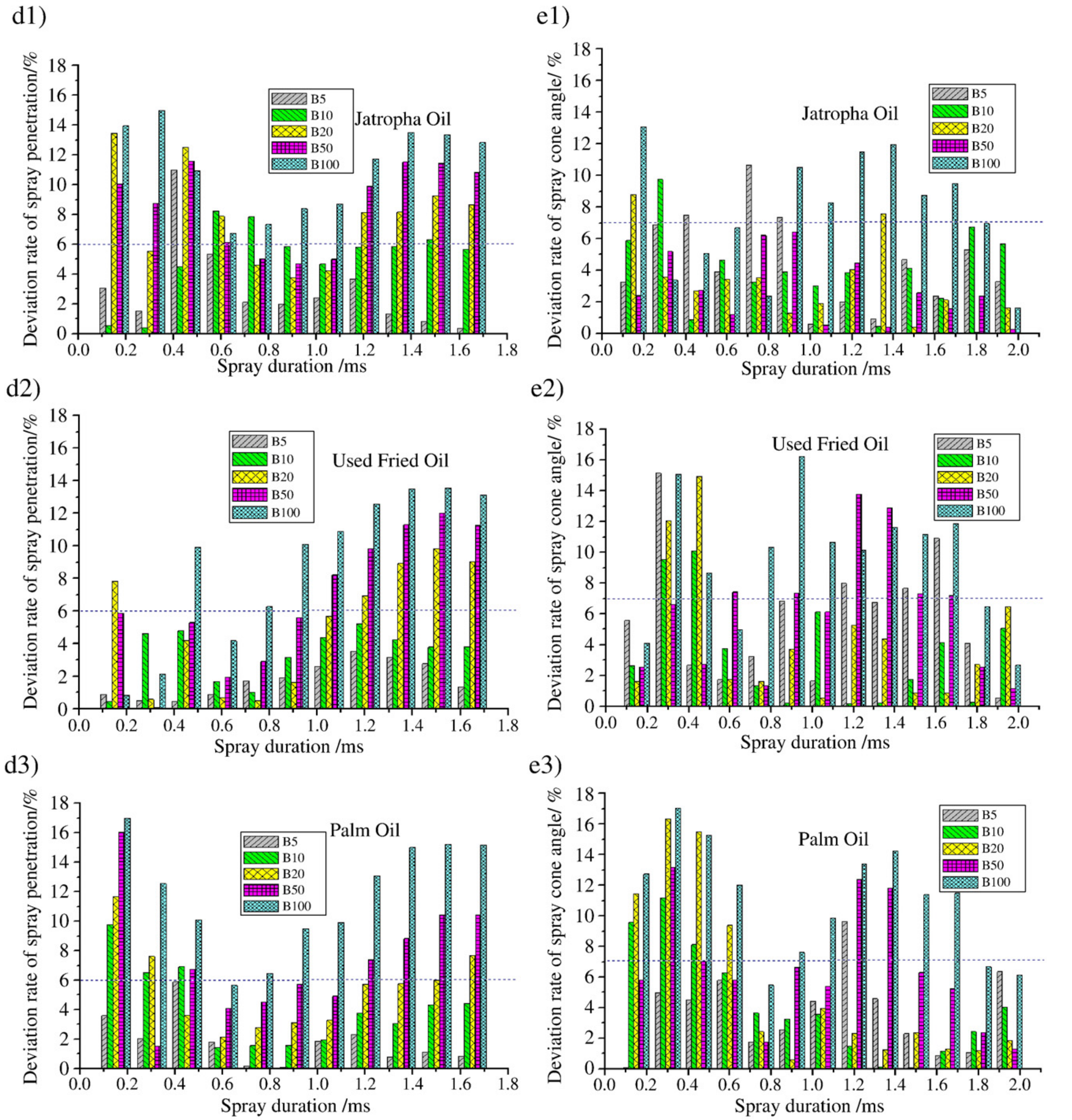

Fig. 13. Deviation ratio of spray penetration and spray cone angle during the entire spray process.

leading to a reduction in the spray angle. At the same time, the decreasing injection pressure led to a decrease in the spray angle. Finally, the volatilized and non-volatilized fuel reached a dynamic balance, and the cone angle then stabilized.

The variation in X_L with time throughout the whole spray process was studied, as shown in Fig. 10. X_L increased linearly and rapidly within 0.6 ms, and then continued to increase slowly. From Fig. 10, it can be seen that the value of X_L was about 0.05S at the beginning of spraying, and had increased to about 0.475S by the end of spraying.

The relationship between X_L and S_1 was also analyzed, where S_1 is spray tip penetration at different X_L calculation times. As shown in Fig. 11, the trend was not obvious within 0.6 ms, but after 0.6 ms, X_L decreased slowly and ultimately converged around 0.475S_1.

3.3. Spray tip speed

As shown in Fig. 12, the spray tip speed fluctuated due to the fluctuating injection pressure inside the high-pressure pipeline, and then decreased gradually. The previous pulsive process of the spray droplets caused the pressure in this region to be lower than back pressure, and the subsequent spray droplets were then able to move forward at high speed and collide with the previous spray droplets,

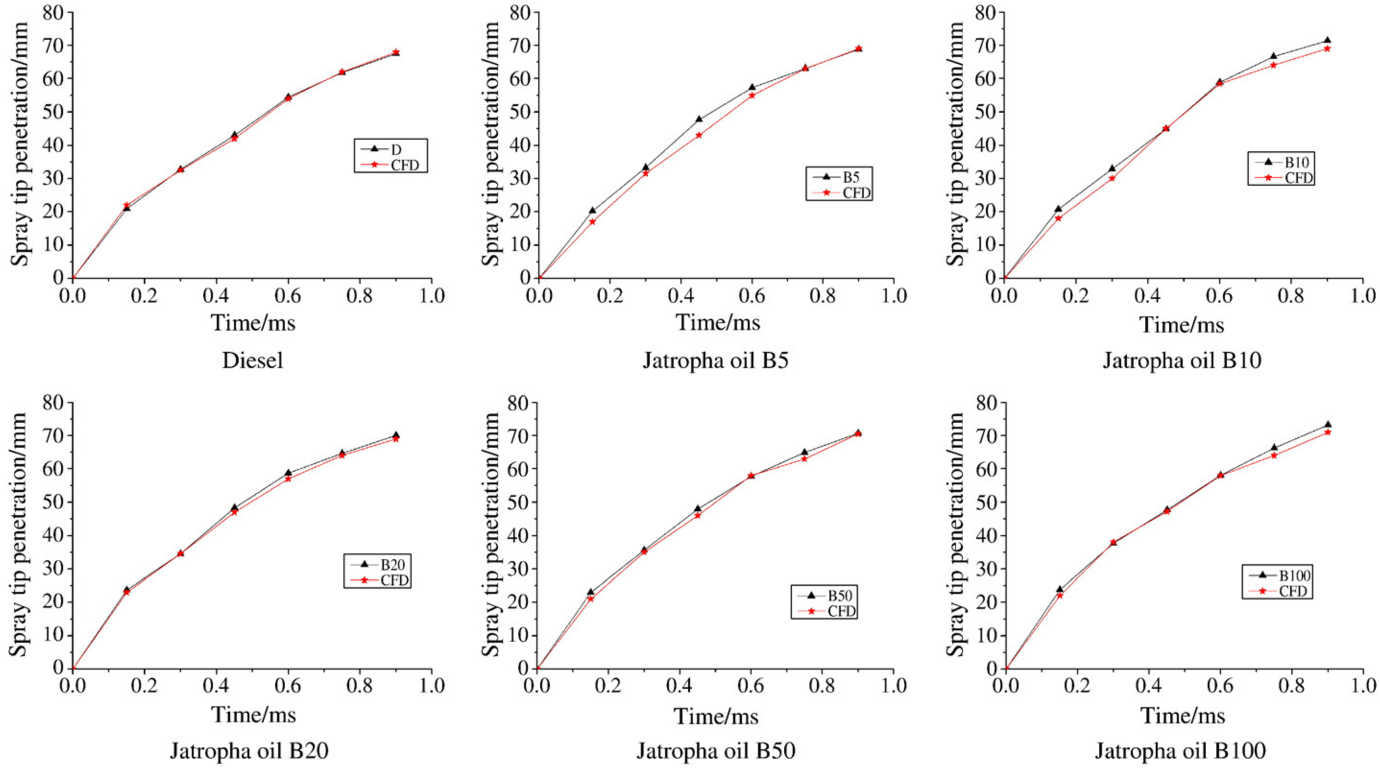

Fig. 14. Comparisons of spray tip penetration between simulation results and experimental data.

which may also have contributed to spray tip speed fluctuations. From Fig. 12, it can be seen that the maximum spray tip speed was about 200 m s^{-1}. Spray tip speed then decreased to 20–40 m s^{-1} and remained stable at 1.2 ms after injection.

3.4. Difference between biodiesel and diesel

The differences between biodiesel at different blend ratios and diesel were also investigated, as shown in Fig. 13. The differences in spray penetration between diesel and the three biodiesels at blend ratios of B5, B10 and B20 remained within 6%, and the differences in spray cone angle remained within 7% throughout most of the whole spray process, as shown by the dashed-line in the figures. It can also be seen that the differences in spray penetration between diesel and different biodiesel blends were small during the first 0.6–0.8 ms after the injection. After 0.8 ms, differences in spray penetration increased with increases in the biodiesel blend ratios.

4. Computational fluid dynamics (CFD) simulation

We used Star-CD CFD software to simulate the spray characteristics of jatropha oil biodiesel and diesel. Spray tip penetration was compared between the numerical simulation data and the experimental data. The simulation results for spray tip penetration were in good agreement with the experimental data (Fig. 14).

The speed, concentration and SMD of different blends of jatropha oil and diesel were calculated during the injection. From Fig. 15, it can be seen that spray speed increased with the incremental blend ratios of jatropha oil. The viscosity of the blend fuel was the main cause of increasing spray speed. At the same time, the area demonstrating the highest speed moved gradually from the spray tip to near the spray nozzle throughout the spray process.

SMD of the sprays were calculated from spray axis cross-sections at different time points. From Fig. 16, it can be seen that SMD gradually increased with increasing blend ratio of jatropha oil in the fuel, mainly due to differences in the viscosity and surface tension of the different blends. The differences in SMD between the B5, B10 and B20 jatropha oil blends were small, compared with diesel spray, indicating that low blend ratios of jatropha oil in fuel will have little impact on combustion and emissions.

The concentration of blend fuels in the central region of the spray was stronger than that of diesel (Fig. 17). This was mainly because the volatility of blended biodiesel fuels is less than that of diesel. As biodiesel is an oxygenous fuel (oxygen content 10%), a high concentration of blended fuels in the central region would not necessarily lead to more soot generation. Engines burning blended biodiesel fuels should increase their fuel injection pressure appropriately in order to improve fuel atomization and to reduce the concentration in the central region.

5. Conclusions

Based on the results of this study, we concluded that:

(1) Although the three biodiesel fuels were produced from different inedible oils, their viscosities and densities, and therefore their macroscopic spray characteristics, were similar. Spray penetration and spray tip speed increased with increasing blend ratios of biodiesel, but the spray cone angle decreased, indicating a reduction in spray atomization quality with increasing biodiesel blend ratios of the fuel.
(2) At 0.8 ms after injection, spray penetration deviation ratios started to increase with the increasing blend ratio of the biodiesel. During injection, the region of 0.05–0.475*S* was a key factor affecting spray cone angle.

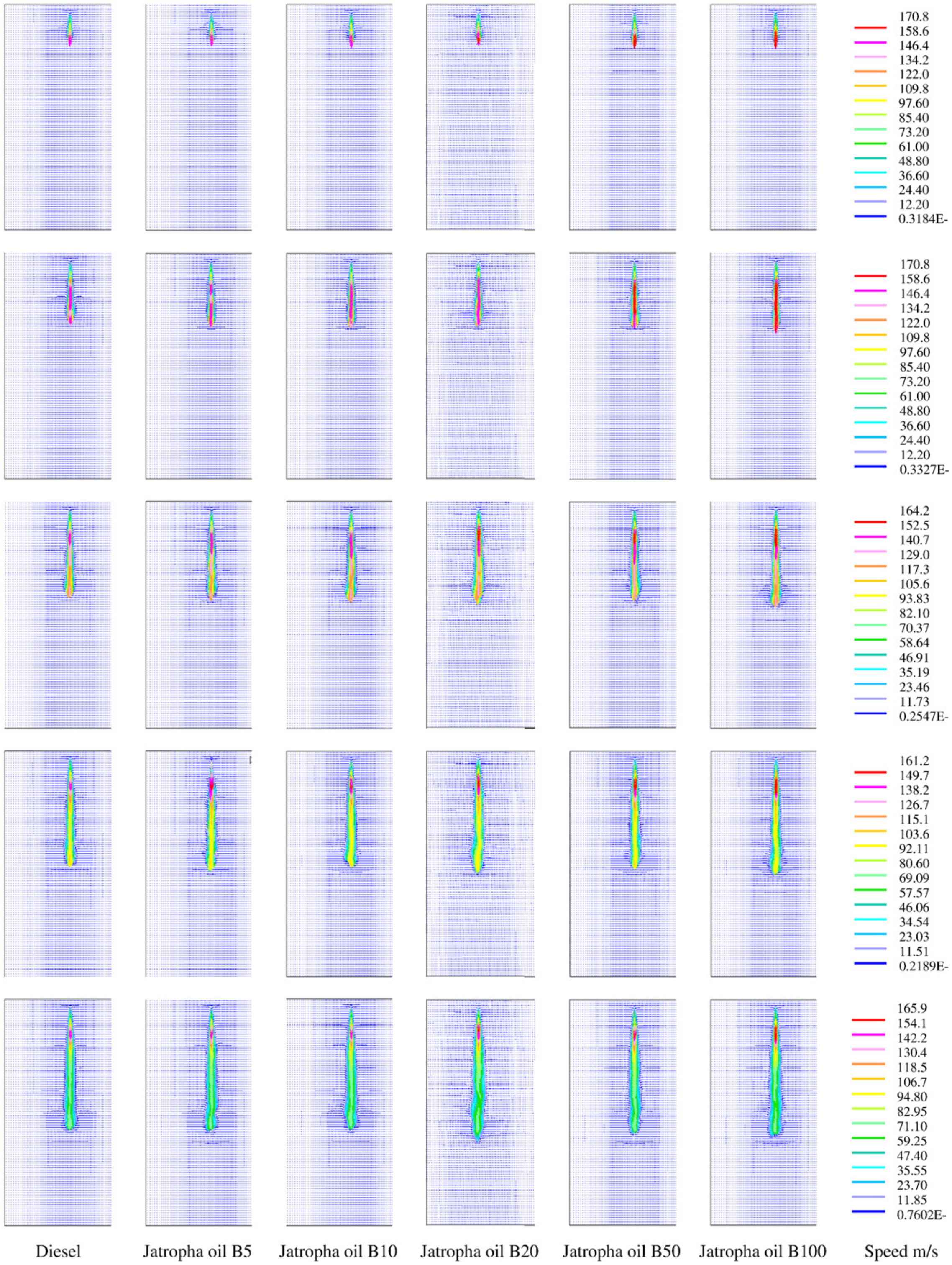

Fig. 15. Speed comparison between fuels with different jatropha oil blend ratios.

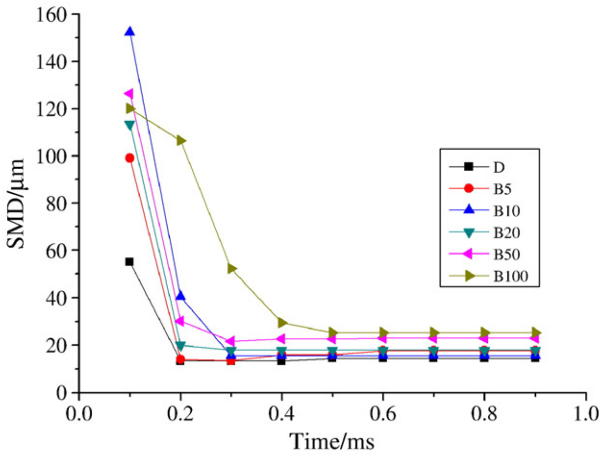

Fig. 16. SMD comparison between fuels with different jatropha oil blend ratios.

(3) Although the viscosity and surface tension of the biodiesel were higher than those of the conventional diesel fuel, the macroscopic and microscopic spray properties of B5, B10 and B20 blended fuels were similar to diesel. However, the SMD of biodiesel blends markedly increased when the ratio of biodiesel was >20% (B20). This implies that fuel atomization characteristics will be different in blends with higher ratios of biodiesel.

Symbols

S	spray penetration
Φ	spray cone angle
S_1	spray tip penetration at different X_L calculation time
X_L	the distance between bottom edge of the triangle and the nozzle

Acknowledgments

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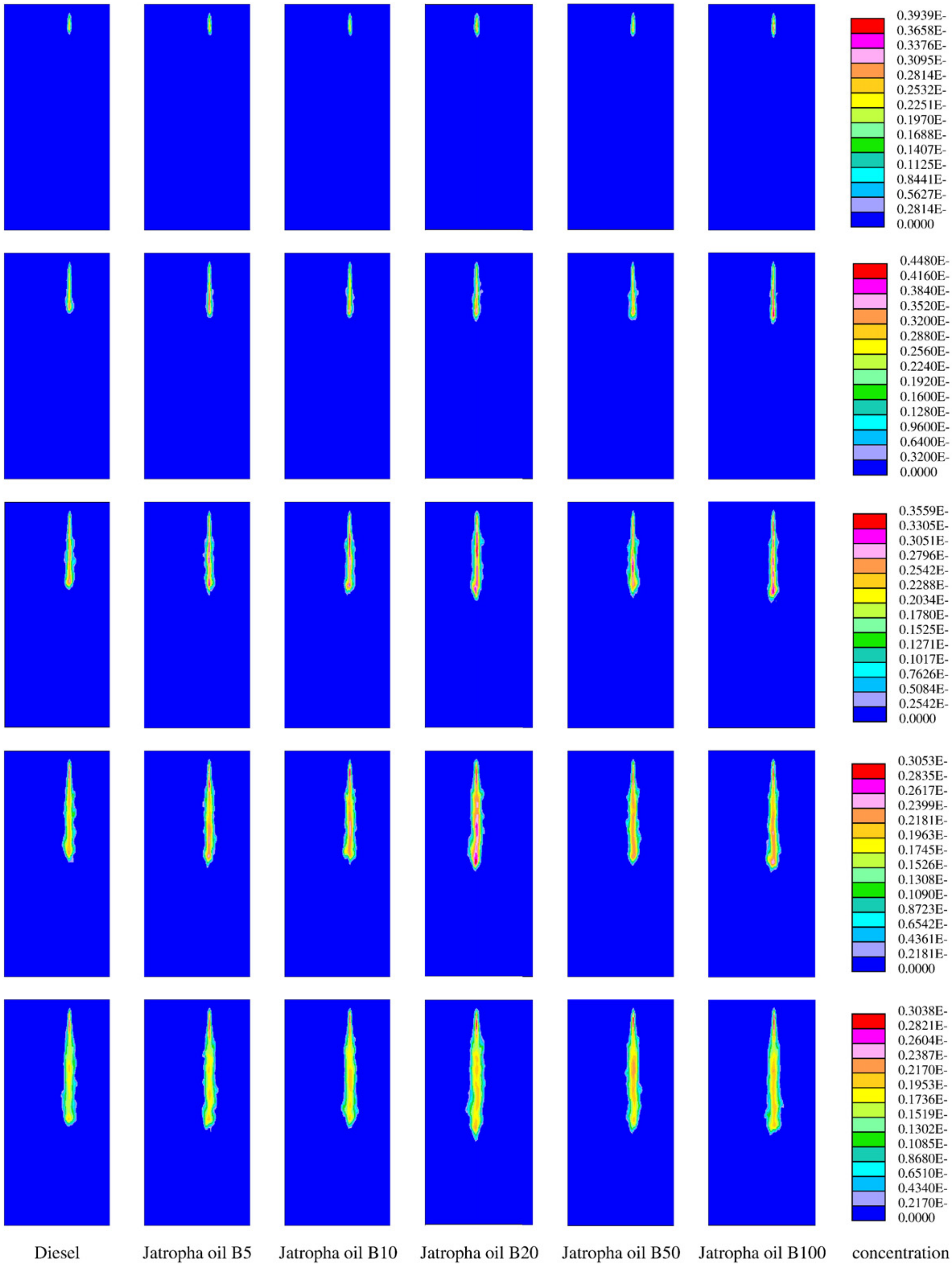

Fig. 17. Fuel concentration comparison between fuels with different jatropha oil blend ratios.