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Abstract Amongst alternative fuels for diesel-engine application, biodiesel is very attractive because it is biodegradable, an environmentally-friendly and sustainable source that can meet future energy demands. However, there are few published studies of the impact of biodiesel fuel and its blends on fuel injection pumps (FIPs). This study will investigate the influence of biodiesels derived from waste cooking oils with incremental blends of B10, B20, B30, B40 and B100. The FIP in this study is a rotary type attached to a four-cylinder, four-stroke direct injection, turbocharged diesel engine. Vibration and pressure measurements were made on the FIP. The results show the peak pressure close to the pump increases slightly the higher the proportion of biodiesel because of increased viscosity, density and bulk modulus of the fuel. Low frequency vibration increased as the proportion of biodiesel increased. These results demonstrate an increase in dynamic load on the pump components. However, high frequency vibration levels are lowest for the blends B10, B20 and B30, which may be helpful for improving the service life of the delivery.

Key words Vibration, Fuel injection pump, Injection pressure, Biodiesel, Diesel engine

1.0 Introduction

Stringent emission laws, depletion of fossil fuels and public pressure have forced the motor industry to find alternatives to fossil fuels. Biodiesel fuel blends are one promising option currently being researched as a pathway to energy diversity and reduced petroleum dependence of the transportation sector. As shown in the latest studies [1, 2] the majority of research efforts are into improving engine combustion, engine performance and reducing emissions. However, various researchers have studied the characteristics of high pressure fuel injection systems and the timing of injection for fuels containing biodiesel. The fuel injection system when

using biodiesel has an advancing injection timing and high injection pressure which can cause early combustion [2, 3-4-5-6]. However, despite being a critical mechanism, FIPs for diesel engines have received little attention in terms of the dynamics of their operation. Obviously the physical properties such as density and viscosity of biodiesel are different from normal diesel fuel and these differences will affect not only the fuel supply characteristics but also the dynamics of the FIP. The latter being one of the decisive factors influencing FIP service life.
In this study, a vibration based approach is used to study the dynamics of FIPs used with diesel and different biodiesel blends. It commences by describing possible vibration sources in a FIP and then a systematic test study based on a diesel engine equipped with a rotary FIP. Finally, both the vibration signals and injection pressure signals are examined with different biodiesel blends under the same engine operation conditions so that the dynamic changes due to different fuel blends can be extracted.

2.0 Dynamics Rotary Fuel Injection Pump

A rotary distributor diesel FIP has a single plunger and barrel, where the plunger combines rotary and reciprocating movements by rotating the cam plate [7], as shown in Figure 1. To achieve fuel injection, it must raise the pressure of the fuel sufficiently (several hundred bars) to rapidly open the delivery valve (microseconds). This allows the fuel to be forced into the injector nozzle at the correct time for fuel injection [9]. The valve impact may be reduced by the damping effect of the residual fuel between the seat and the valve body. The rotary and reciprocating movements will be accompanied by internal dynamic forces including that of fuel pressure in the barrel, the forces between the cam and roller, and also the recovery forces due to the spring. These forces will cause pump components and body to vibrate and possibly because of the high repetition rate may cause component resonance.

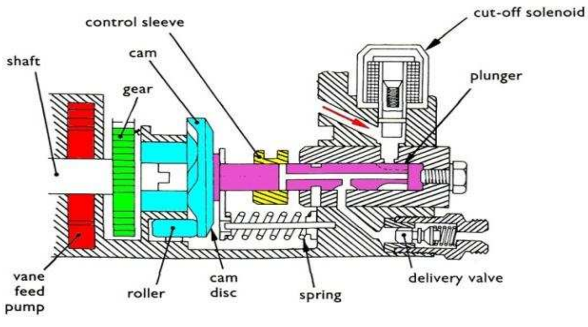

Fig. 1 Mechanical of a rotary distributor FIP of diesel engine [8]

The impact of the delivery valve on the valve seat will cause the pump body to vibrate. These vibrations become stronger at higher engine speeds because of a higher rate of fuel delivery and could mean the character of the vibrations may change with different types of fuel and delivery rates. In particular, biodiesel has a high density and viscosity which will change the vibration excitation and system response [10, 11-12]. Thus, it could be possible to use the vibration response to evaluate the changes of the internal dynamic effects due to different fuels.

3.0 Experimental Facilities and Test Procedures

3.1 Test rig setup

To identify the effects of biodiesel blends on the FIP, a four-cylinder, four-stroke, turbocharged, direct injection diesel engine was used for the experimental study. The test layout is shown in Figure 2 and the specification of the diesel engine shown in Table 1.

Table. 1 Specification of diesel engine and FIP

Diesel Engine Type	JCB 444 TCA74kW
Number of cylinders	4
Compression ratio	18.3:1
Number of valves	16
Injection system	Direct Injection
Displacement	4.399 Litre
Engine firing sequence	1-3-4-2
Maximum engine speed	@ 2200 rpm
FIP Type Delphi	DES / 10130DEG
Number of injections	4
Pressure range of FIP	100-500 bar
Maximum speed of FIP	@ 1100 rpm

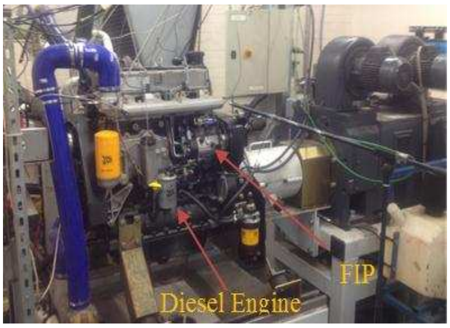

Fig. 2 Test rig (diesel engine JCB 444 TCA)

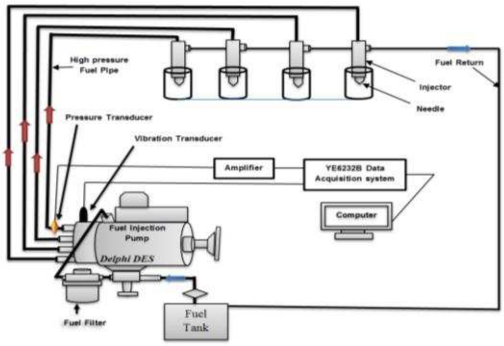

Fig. 3 Schematic diagram of the engine FIP

The FIP on the engine is a rotary fuel injection pump. Its key specification is also provided in Table 1. The engine test rig is fully instrumented for in-cylinder pressure measurement, emission measurements and vibro-acoustics measurement. For this study, a dynamic pressure sensor is mounted on the fuel line close to the pump, as shown in Figure 3, for measuring the pressure changes of the FIP. An accelerometer is mounted on the body of the FIP body to obtain the desired vibration signal non-intrusively. For the experiments, the engine operated at two speeds: 1200 rpm and 1600 rpm, each of which was under four increment loads: 100 Nm, 200 Nm, and 300 Nm and to 400 Nm. These settings were kept constant for different fuel blends to ensure accurate comparisons and hence obtain quantitative results of changes due to the use of different fuel blends.

3.2 Biodiesel Fuel Physical-Chemical Properties

To perform the experimental study, a typical biodiesel from waste cooking oils was used as the base fuel and for creating different blends when mixed with standard diesel

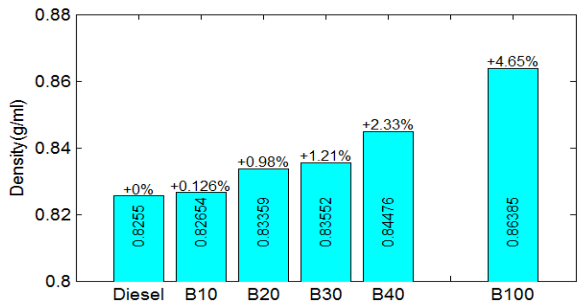

Fig. 4 Density measurement results

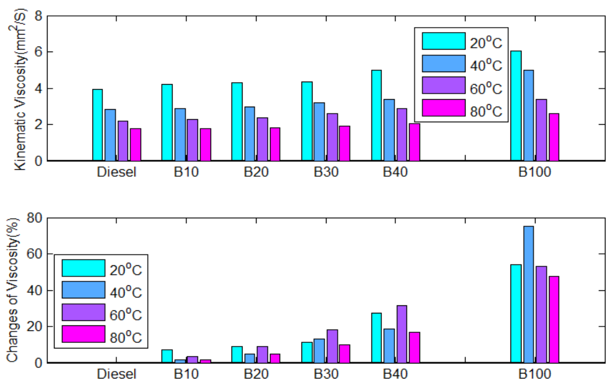

Fig. 5 Viscosity measurement results

To obtain a better understanding of the effects of incremental increases in the relative volume of biodiesel blends B10, B20, B30 and B40 were also tested under the same engine operating conditions. Before the actual tests the density and viscosity of these blends are measured for more accurate comparison.
Figure 4 shows the measured densities increase with increase in proportion of biodiesel, which agrees with previously published literature [2, 12], however Figure 5 shows that the percentage changes in viscosity are significantly greater, which may be a major factor influencing the fuel injection characteristics. Figure 5 also shows that the relative changes are greater the higher the amount of biodiesel in the blend. These results agree with previously published literature [13, 14].

4.0 Results and Discussion

4.1 FIP Pressure Characteristics

Figure 6 shows the comparison of pressure waveforms obtained after 60 readings of pressure measured in the high pressure FIP under different operating conditions. It can be seen that the amplitude and duration of FIP pressure increases with both the load and the speed. However, when comparing biodiesel (B100) with standard diesel, the results show a clear increase in the amplitude and more advanced injection. In contrast, the changes for other blends cannot be observed as clearly.

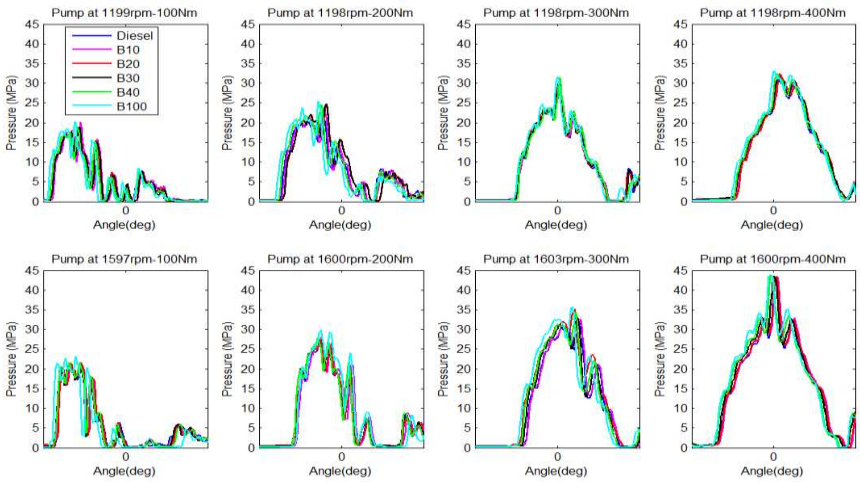

Fig. 6 Engine FIP pressures under different operating conditions

In order to see the changes more accurately, three key fuel injection parameters maximum pressure, injection timing and injection duration are extracted from the waveform. Figure 7 presents the comparison of these parameters under different load and two speeds.

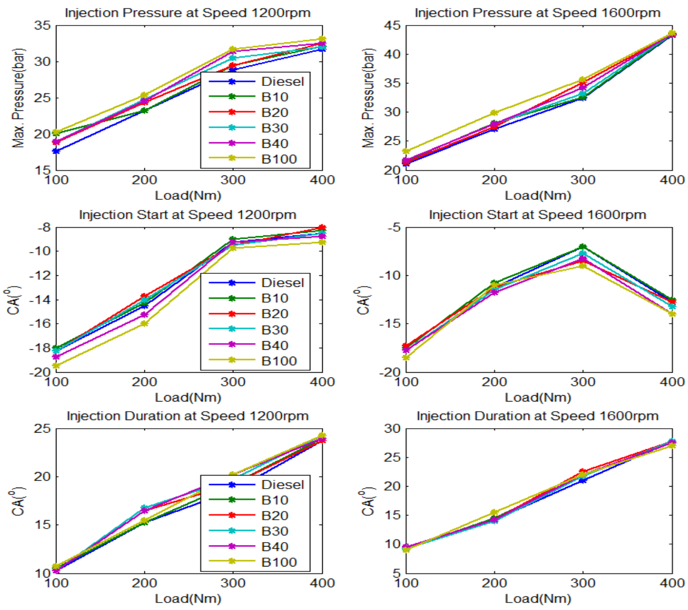

Fig. 7 Characteristics of key fuel injection parameters

The results show that the peak pressure gets higher for all blends and is more significant at the lower speed due to the effect of the high viscosity under the interactions of prolonged time and at a low pressure. However, the increase is not proportional to the mixed proportions of biodiesel. This may be due to the nonlinear effects of the fluid dynamics. For similar reasons, only higher proportions of biodiesel including B30, B40 and B100 show clearly the advanced injection whereas B10 and B20 show little change in the injection timing. In addition, the duration of the injection shows little change when compared to that of normal diesel. In general, it can be concluded that the higher proportion (B30, B40) of biodiesel alters the pressure supply characteristics, thereby influencing fuel injection quality and combustion. However, these changes are not as significant as shown in previous studies. Nevertheless, the increase in the peak pressure indicates a higher dynamic load applying to the pump and supplies lines, which may lead to the effects these components.

4.2 Engine FIP Vibration Characteristics

As mentioned in section 2, the high-pressure impulses associated with the reciprocating forces of the plunger motion and the impacts due to opening and closing of the deliver valve may be the main causes of pump vibrations. These dynamic forces that generate the reciprocating motion also apply to the pump housing that generates vibration [8, 9]. Therefore, to see the influence of the fuel blends, the vibration signals are examined under different conditions as shown in Figure 8.

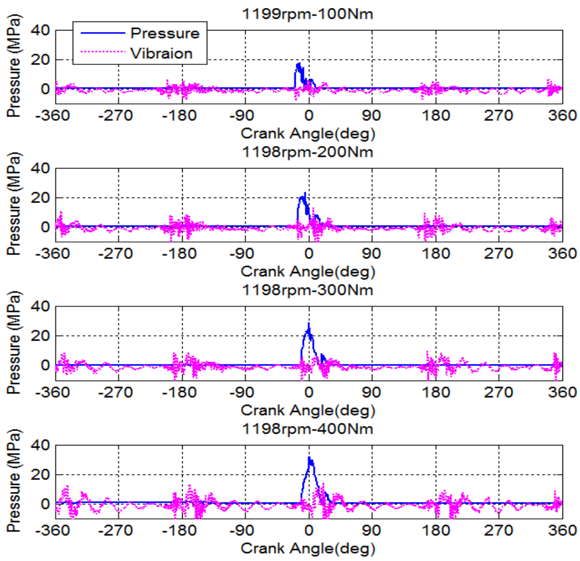

Fig. 8 FIP vibration signals under different load at 1200 rpm

Figure 8 shows vibration signals in association with the pump pressure. It can be seen that the vibration responses closely correlate with the pressure variations. Firstly, the high rate oscillations appear in the same period of the pressure pulse. In particular, there are two clusters of transient responses which correspond to the two impacts caused by the opening and closing of the delivery valve. Secondly, the amplitudes of the transient responses increase consistently with the pressure amplitude, showing that these vibrations could be an accurate indication of the amplitude of the pressure. Moreover, there are clear low frequency transient responses between two high frequency transients and their amplitude also increase with the pressure. These low frequency transients mainly come from the reciprocating forces due to the plunger, cam ring motions and associated transmissions. To gain a better understanding of the vibration, the signals are converted into the frequency domain. Figure.9 (a) shows typical spectra for two different loads at the same speed. It shows that there are a string of harmonics in the spectrum due to the injection frequency which are calculated by

$$f_i = \frac{n}{2 \times 60} \times 4 \qquad (1)$$

Where (n) is the engine speed in rpm. In addition, the amplitude increases clearly with the load. As these discrete components mainly relate to the reciprocating excision and its associated transmissions, their amplitude may be an effective indicator of the interaction between the mechanical motion and the fluid flow. Moreover, the spectrum also shows distinctive continuous contents in the high frequency range that also increase with load. As these contents relate more to the impulsive responses due to the impacts of the delivery valve, it can be a base for evaluating the valve motions. In addition, the spectrum comparison between the normal diesel and the biodiesel in Figure.8 (b) also shows clear differences. The spectral content of biodiesel at the injection frequency and its high order harmonics show visible increases due to high resistive loads caused by high density and high viscosity of biodiesel. The continuous contents also exhibit an increase for similar reasons. Although these changes are much smaller compared with that of the load effects in Figure 9(a), they show that the effect of density and viscosity on the FIP dynamics is similar to that of the load. Thus, the spectrum changes could be used to evaluate fuel quality.

As discussed above, there are two main sources of FIP vibration which exhibit in different frequency ranges. To show the effect of these two sources, the frequency contents below 400 Hz are averaged to obtain spectral amplitudes to represent the effects of the interaction due to reciprocating forces, whereas amplitudes are averaged between 400 Hz-2000 Hz to illustrate the effects of the impact on the delivery valves.

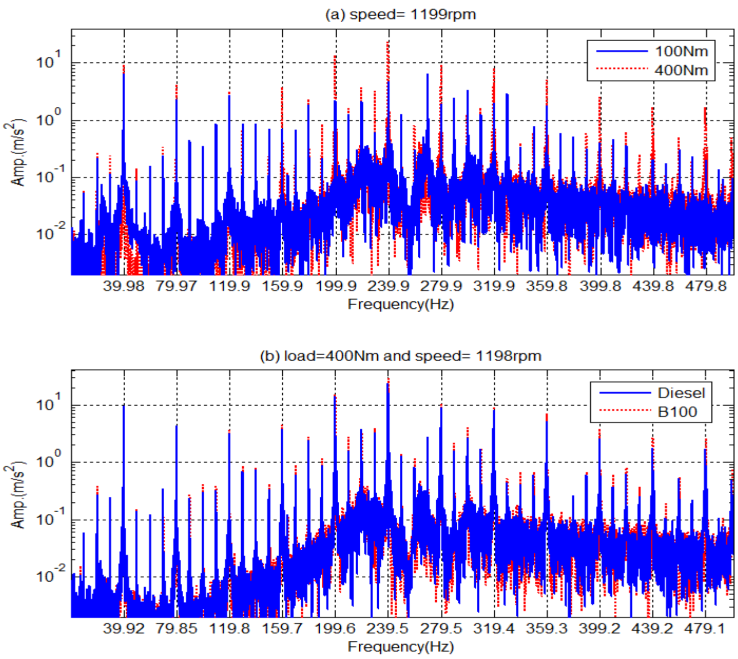

Fig. 9 Comparison of vibration spectrum between different cases

Figure 10 shows the results of these two spectral values at two different speeds for the different fuel blends. It can be seen that for most load conditions the low frequency amplitudes for the biodiesel and its blends show a slight increase, compared with that of diesel. This shows that due to the additional load caused by the high viscosity and density of the biodiesel, more power is needed to drive the plunger and hence more dynamic loading to the system. For the high frequency amplitudes it shows that B20 and B30 have the lowest values. This means that high viscosity will reduce the impacts of the delivery valve and the vibration responses. However, as the viscosity becomes too high (such as B40 and B100), the effect of higher dynamic forces is more significant. This then results in a higher value of the high frequency amplitude. In general, it shows that lower proportions of biodiesel (B10, B20 and B30) will reduce the impact excitation and help maintain the contact surfaces of the delivery valve and potentially the nozzle valve in the injector.

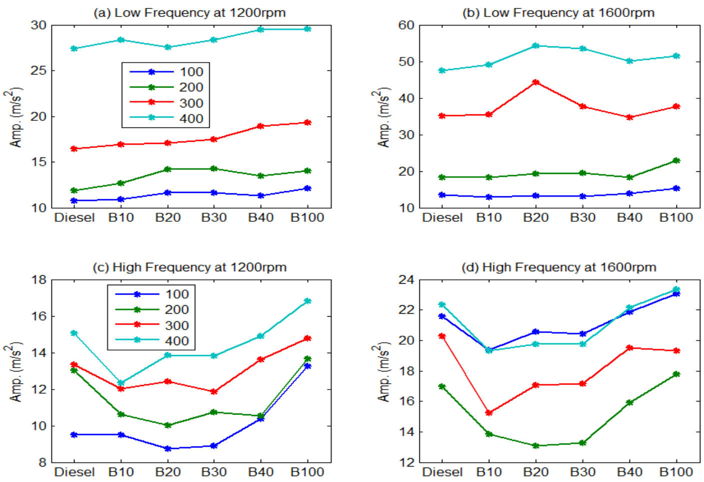

Fig. 10 Comparison of Vibrations FIP between different biodiesel blends

5.0 Conclusion

This experimental study has confirmed that the injection pressure waveforms show higher peak value and advanced injection for higher proportions (B40 and B100) of biodiesels due to the effects of high density, high viscosity and bulk modulus. The high amplitude, especially, may indicate high dynamic loads upon the pump systems, which may in turn influence the service life of the pump. Furthermore, the vibration responses in the low frequency range also show higher amplitude for different biodiesel blends, which is consistent with the results from the pressure analysis. However, the high frequency vibrations due to the impacts of the delivery valves show a clear decrease in the smaller proportion biodiesel blends (B10, B20 and B30). This shows that these blends can be helpful for sustaining the contact surfaces of delivery valve with the high viscosity value.

6.0 Acknowledgement

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