CHAPTER 10

COMBINED EFFECTS OF INJECTION PRESSURE AND COMBUSTION CHAMBER GEOMETRY

10.1 INTRODUCTION

Improved thermal efficiency, reductions in fuel consumption and pollutant emissions from biodiesel fuelled diesel engines are important issues in engine research. To achieve these, rapid and better air-fuel mixing is the most important requirement. However, the use of biodiesel in an engine results in variation in engine performance and emissions due to variation in physical and chemical properties of the biodiesel. The effects of these physico-chemical properties on the air-fuel mixing and fuel supply system such as fuel pump have already been reported. The mixing quality of biodiesel spray with air can be generally improved by selecting the best injection parameters and better design of the combustion chamber.

The fuel injection system in a DI diesel engine is to achieve a high degree of atomization in order to enable sufficient evaporation in a very short time and to achieve sufficient penetration in order to utilize the full air charge. The performance and emission characteristics of CI engines are largely governed by fuel atomization and spray processes. When fuel injection pressure is low, fuel particle diameters will enlarge and the ignition delay period during the combustion will increase. This situation leads to decrease in engine performance since the combustion process goes to a bad condition. When the injection pressure is increased the fuel is well atomized and the fuel
particle diameters will become small. Efficient atomization increases the surface area of the fuel, as a result, high air-fuel mixture and evaporation rates can be attained (Lee et al. 2005, Ejim et al. 2007). Since the mixing of fuel with air becomes better during ignition delay period, engine performance will be increased (Hountalas et al. 2003, Cingur and Altiparmak 2003). If injection pressure is too high, that will result in smaller fuel droplet, which will have lesser momentum that will affect fuel distribution in the air. As a result the possibilities of homogeneous mixing decrease and combustion efficiency falls down (Celikten 2003). Hence to improve the performance and emission characteristics of the engine running with biodiesel a detailed investigation is required on the injection parameters particularly by varying the injection pressure. A high injection pressure is an effective method to improve DI diesel engine performance and decrease PM emissions levels due to improved spray atomization and fuel–air mixing.

10.2 AIM AND OBJECTIVES

The aim of the present phase of the research work was to optimize the injection pressure for POME20 fuelled engine that has been optimized in the last phase in terms of, injection timing and combustion chamber geometry to achieve improved performance and emission levels and to compare the results with that of standard engine and optimized engine (TRCC) operated at standard injection pressure of 200 bar and optimized injection timing of 21º bTDC. To achieve this aim, the following objectives were set:

- To investigate the effects of varying the injection pressure on the performance, emission and combustion characteristics of POME20 fuelled DI diesel engine having TRCC operated at an optimized injection timing of 21º bTDC.
To compare the engine performance, emission and combustion characteristics of modified injection pressure settings with that of standard injection pressure setting recommended by the engine manufacturer.

10.3 EXPERIMENTAL PROCEDURE

The injector opening pressure was varied by adjusting the spring tension of the injector by screwing or unscrewing the screw provided on the top of the injector. Then the experiments were carried out at different injection opening pressures of 185, 200, 210, 220, and 230 bar. To begin with the performance, emission and combustion tests were carried out using POME20 at various loads for standard engine having HCC with fuel injection pressure of 200 bar and standard fuel injection timing of 23º bTDC, following the experimental procedure explained in chapter-7. Then the performance, emission and combustion tests were carried out using POME20 at various loads for the modified engine having optimized combustion chamber i.e. TRCC with fuel injection pressure of 200 bar and optimized fuel injection timing of 21º bTDC. Hereafter the term ‘optimized engine’ represents engine piston having TRCC and operated at an injection timing of 21º bTDC. These performances, combustion and emission values were considered as baseline values throughout the experimentation in this phase for comparison with the results obtained from optimized engine with POME20 and PBDF operated at different injection pressures. Then the performance, emission and combustion tests were conducted for optimized engine with PBDF and POME20 at different injection pressures. The engine tests were carried out at 0%, 25%, 50%, 75% and 100% load. In order to have a meaningful comparison of emissions and engine performance, an investigation was carried out at same operating conditions i.e. ambient temperature, atmospheric pressure, engine speed and torque were maintained for all injection pressure settings. The
combined effects of injection pressure and already optimized injection timing and combustion chamber geometry on the performance, combustion and emission characteristics of the DI diesel engine operated with POME20 and PBDF at different loads of operation were investigated. The results were analysed and compared with the standard engine fuelled with POME20 and presented in the next section of this chapter.

### 10.4 RESULTS AND DISCUSSION

The performance, emission and combustion characteristics of the standard engine with HCC and optimized engine with TRCC at 21° bTDC and at different injection pressures were determined, compared and analysed in terms of BSFC, BTE, UBHC, CO, NOₓ, smoke emissions and combustion parameters such as ignition delay, cylinder peak pressure, exhaust gas temperature and heat release rate.

#### 10.4.1 Combustion Characteristics

Figure 10.1 shows the variation of ignition delay for standard engine and optimized engine operated with different injection pressures. At high injection pressures the ignition delay decreased as a result of increased in cylinder temperature due to improved air-fuel mixing and enhanced pre-combustion reactions. It was observed that the ignition delay decreased with increasing injection pressure from the standard injection pressure of 200 bar (5.9° CA) to 210 bar (5.7° CA) and 220 bar (5.5° CA) at full load operation. This performance can be reasoned to better atomization, vaporization of the fuel and air-fuel mixing. It was observed that increasing the injection pressure above 220 bar increased the delay period to 6° CA due to poor air fuel mixing. Further, it was found that the ignition delay substantially increased by lowering the injection pressure to 185 bar (8° CA) from 200 bar. This was caused by poor atomization, vaporization and air fuel mixing of POME20.
The comparison of the HRR curves for standard and optimized engines with PBDF and POME20 at different injection pressures is shown in Figure 10.2. It can be seen from the Figure 10.2 that with increase in injection pressure from 200 bar to 210 bar and 220 bar, the maximum heat release rate increased due to improved premixed combustion phase. This was because of improved combustion as a result of better atomization and improved air fuel mixing. It was observed that the highest maximum heat release rate of 89.4 J/°CA was recorded for optimized engine operated with 220 bar injection pressure at 10°CA bTDC, while with 200 bar injection pressure the maximum heat release rate was recorded as 85.2 J/°CA at 8°CA bTDC. As the injection pressure was further increased to 230 bar, the maximum heat release rate decreased. This was attributed to the relatively poor combustion due to poor air fuel mixing as a result of the lesser momentum of smaller fuel droplet with respect to air. In addition lowering the injection pressure to 185 bar from 200 bar, the maximum heat release rate decreased to 68.7 J/°CA at 6°CA bTDC. This was caused by the incomplete combustion due to poor atomization, vaporization and air fuel mixing.

The comparison of the CHRR curves for standard and optimized engines with PBDF and POME20 at different injection pressures is shown in Figure 10.3. The cumulative heat release rate increased with increase in injection pressure from 200 bar to 210 bar and 220 bar. This was because of improved combustion as a result of better atomization and improved air fuel mixing. However with further increase in injection pressure to 230 bar, the cumulative heat release rate decreased. This can be reasoned to the relatively poor combustion due to poor air fuel mixing as a result of the lesser momentum of smaller fuel droplet with respect to air. In addition it was observed that decreasing the injection pressure to 185 bar from 200 bar, the cumulative heat release rate decreased. This was because of poor combustion of POME20 due to poor atomization, poor vaporization and air fuel mixing. The cumulative heat release rate for increased injection pressure of 210 bar,
Figure 10.1 Variation of ignition delay at different injection pressures

Figure 10.2 Comparison of HRR at full load at different injection pressures
220 bar and 230 bar were recorded as 692 J, 703 J and 669 J respectively at 10° aTDC compared to 653 J at standard injection pressure of 200 bar for optimized engine fuelled with POME20. However for decreased injection pressure of 185 bar the cumulative heat release rate was to 569 J at 10°CA aTDC at full load.

The cylinder pressure variations with crank angle for standard engine and optimized engine with POME20 and PBDF at different injection pressures is shown in Figure 10.4. The results indicate that the cylinder pressure variations were increased initially, while increasing the fuel injection pressure above standard injection pressure i.e. increasing the injection pressure from 200 bar to 210 bar and 220 bar and then decreased with further increase in pressure to 230 bar. It was also observed that the best results were associated with an injection pressure of 220 bar for the optimized engine with POME20. This performance can be reasoned to better combustion due to better atomization, vaporization of the fuel and air-fuel mixing.

It was also noticed that the cylinder pressure variations and peak cylinder pressure were decreased with lowering the injection pressure to 185 bar from 200 bar. This was as a result of poor combustion of POME20 due to poor atomization, vaporization and air fuel mixing. However the cylinder pressure variations and peak cylinder pressure of the optimized engine operated with POME20 at 220 bar were lower than the PBDF at all loads of operation owing to the lower calorific value of biodiesel fuel. Another reason for this was higher viscosity, which results in slightly poor atomization and poor combustion.

The variation of peak pressures with respect to brake power for the optimized engine and the standard engine at different injection pressures with PBDF and POME20 is shown Figure 10.5. It was noticed that the in-cylinder
Figure 10.3  Comparison of CHRR at full load at different injection pressures

Figure 10.4  Comparison of cylinder pressure at full load at different injection pressures
peak pressure for optimized engine increased with higher injection pressure due to large amount of heat release in the premixed combustion phase as a result of better atomization, air-fuel mixing and enhanced combustion. It was also observed that the peak pressure increased with increasing injection pressure from the standard injection pressure of 200 bar (75.8 bar) to 210 bar (77.6 bar) and 220 bar (78.7 bar) at full load. This can be reasoned to better combustion due to better atomization, vaporization of the fuel and air-fuel mixing. It was also witnessed that increasing the injection pressure above 220 bar to 230 bar decreased peak pressure to 74.6 bar.

Further, it was found that the peak pressure substantially decreased by lowering the injection pressure to 185 bar (68 bar) from 200 bar. This was because of poor combustion of POME20 due to poor atomization, poor vaporization and air fuel mixing. It can also be seen that the peak pressure was slightly lower for POME20 when compared to PBDF operation in the optimized engine. This was attributable to the lower calorific value for POME20, and improper mixing of POME20 with air due to higher viscosity and lower vaporization.

Figure 10.6 shows the variation of EGT for standard engine and optimized engine with PBDF and POME20 at different injection pressures. It was found that the EGT increased initially and then decreased with increased injection pressures. The EGT increased with increase in injection pressure due to improved premixed combustion and prolonged diffusion combustion. This was attributable to better atomization, air-fuel mixing and vaporization of the fuel droplets. The EGT for increased injection pressures of 210 bar, 220 bar and 230 bar were measured as 568°C, 583°C and 551°C respectively at full load compared to 556°C at the standard injection pressure of 200 bar for the optimized engine, fuelled with POME20. However lowering the injection pressure to 185 bar from 200 bar, the EGT was decreased to 472°C.
Figure 10.5 Variation of peak pressures at different injection pressures

Figure 10.6 Comparison of EGT at different injection pressures
10.4.2 Performance characteristics

The BSFC variations for standard engine and optimized engine with PBDF and POME20, at different injection pressures of 185, 200, 210, 220, and 230 bar are shown in Figure 10.7. It was found that the BSFC for optimized engine decreased with increasing the injection pressure. It was observed that the BSFC decreased marginally with increasing injection pressure from the standard injection pressure of 200 bar (0.249 kg/ kW-hr) to 210 bar (0.247 kg/ kW-hr) and 220 bar (0.243 kg/ kW-hr). This behaviour was attributable to much improved mixing due to better atomization and vaporization of the fuel that led to better combustion. However it was noticed that the BSFC increased when the injection pressure was increased beyond 220 bar. This outcome could be attributed to poor combustion due to Oxygen starvation as a result of lower penetration, poor dispersion of the fuel and weak air entrainment. Further, it was found that the BSFC increased with lowering the injection pressure to 185 bar (0.302 kg/ kW-hr) from 200 bar. This was caused by poor combustion of POME20 due to poor atomization, vaporization and air fuel mixing.

Figure 10.8 shows the comparison of BTE of standard engine and optimized engine with PBDF and POME20 at different injection pressures. BTE for the optimized engine having TRCC with POME20 increased with increasing the injection pressure due to better air fuel mixing and complete combustion. It was observed that the BTE increased with increasing injection pressure from the standard injection pressure of 200 bar (33.09% at full load) to 210 bar (33.77% at full load) and 220 bar (34.31% at full load). It was also observed that increasing the injection pressure above 220 bar decreased the BTE. This may be due to decrease in droplet size of the fuel. A smaller fuel droplet will have lesser momentum that will affect the fuel distribution in air.
Figure 10.7 Variation of BSFC at different injection pressures

Figure 10.8 Comparison of BTE at different injection pressures
The decrease in the relative velocity of fuel corresponding to the air will result in partial suffocation of fuel by its own products of combustion leading to incomplete combustion. Further, it was found that the BTE decreased with lowering the injection pressure to 185 bar (27.67% at full load) from 200 bar. This was due to poor combustion of POME20 as a result of poor atomization and air fuel mixing.

Figure 10.9 shows the variation of BSEC of the standard engine and optimized engine with PBDF and POME20 at different injection pressures. The results indicate that the BSEC was decreased initially with increasing the injection pressure from standard injection pressure i.e. increasing the injection pressure from 200 bar (10.73 MJ/ kW-hr at full load) to 210 bar (10.66 MJ/ kW-hr at full load) and 220 bar (10.49 MJ/ kW-hr at full load) and then increased with further increase in pressure to 230 bar (11.34 MJ/ kW-hr at full load). It was also observed that the best results were associated with an injection pressure of 220 bar for optimized engine with the POME20. It was noticed that the BSEC increased with lowering the injection pressure to 185 bar (13.01 MJ/ kW-hr at full load) from 200 bar. This was on account of poor combustion of POME20 due to poor atomization, vaporization and air fuel mixing. However BSEC of the optimized engine operated with POME20 at 220 bar was marginally higher than the PBDF operation at all loads of operation. This was attributable to the lower calorific value and higher viscosity of POME20, which resulted in slightly poorer atomization and poorer combustion, compared to PBDF.

10.4.3 Emission Characteristics

The comparison of UBHC emissions for both the standard engine and the optimized engine with POME20 and PBDF at different injection pressures is shown in Figure 10.10. It was noticed that the UBHC emissions decreased with increasing injection pressure from the standard injection pressure of 200 bar (48 ppm) to 210 bar (46.2 ppm) and 220 bar (44.6 ppm).
Figure 10.9 Variation of BSEC at different injection pressures

Figure 10.10 Variation of UBHC emissions at different injection pressure
This performance can be endorsed to improved combustion due to better atomization, vaporization of the fuel and air-fuel mixing. It was also observed that increasing the injection pressure above 220 bar marginally increased UBHC emissions. Further it was found that the UBHC emissions substantially increased with lowering the injection pressure to 185 bar (57.6 ppm) from 200 bar. This was caused by poor combustion of POME20 due to poor atomization, vaporization and air fuel mixing.

Figure 10.11 shows the comparison of CO emissions with brake power for the optimized engine at different injection pressures. Reduction in CO emissions were observed with increased injection pressure operation mainly due to better atomization, evaporation and complete combustion. It was observed that the CO emissions decreased marginally with increasing the injection pressure from 200 bar to 220 bar. Compared to standard injection pressure, the CO emissions for optimized engine with increased injection pressure of 210 bar and 220 bar were lower by 3.6% and 9% respectively at full load. However further increase in injection pressure was found not so advantageous; furthermore, a decrease in injection pressure was also observed as not desirable as it led to increase in CO emissions from the engine. There was a reduction of 38.4% of CO emissions for the optimized engine compared to standard engine when tests were carried out with POME20 at an increased injection pressure of 220 bar.

Figure 10.12 compares the CO₂ emissions for both standard engine and optimized engine with POME20 and PBDF at different injection pressures. It was noticed that the CO₂ emissions increased with increasing injection pressure from the standard injection pressure of 200 bar (8.1%) to 210 bar (8.3%) and 220 bar (8.7%). This can be endorsed to improved combustion due to better atomization and air-fuel mixing. It was also observed that increasing the injection pressure above 220 bar marginally decreased CO₂ emissions (8%). Further it was found that the CO₂ emissions
greatly decreased with lowering the injection pressure to 185 bar (6.2%) from 200 bar. This was caused by poor combustion of POME20 due to poor atomization, vaporization and air fuel mixing. It was also noticed that for the

![Figure 10.11  Variation of CO emissions at different injection pressures](image1)

![Figure 10.12  Variation of CO\textsubscript{2} emissions at different injection pressures](image2)
optimized engine operated at an injection pressure of 220 bar the CO₂ emissions vary from 3.8% at low load to 8.7% at full load with POME20 and from 2.2% at low load to 7.2% at full load with PBDF.

Figure 10.13 shows the variation of NOₓ emissions for the standard engine and the optimized engine with PBDF and POME20 at different injection pressures. It was observed that at high injection pressures, NOₓ emissions were increased. With POME20 as fuel, the NOₓ emissions at full load increased from 722 ppm to 736 ppm and 745 ppm on increasing the injection pressure by 10 bar and 20 bar from the standard injection pressure of 200 bar respectively. This was attributed to higher combustion temperatures arising from improved combustion due to better mixture formation in TRCC due to improved atomization. However on lowering the injection pressure to 185 bar, the NOₓ emissions were dropped to 702 ppm, similarly on increasing the injection pressure to 230 bar, the NOₓ emissions were declined to 716 ppm. For the optimized engine with POME20 as fuel and at 220 bar, the NOₓ emissions were higher by about 15%, compared to the standard engine (648 ppm) with PBDF at full load.

The smoke opacity comparison for the optimized engine and the standard engine with PBDF and POME20 at different injection pressures is shown in Figure 10.14. It was observed that the lower injection pressure operation resulted in higher smoke emissions than high injection pressure. At lower injection pressure, the atomization process was very poor. This results in bigger droplets and hence bigger core. It was found that smoke emissions are formed in the core region (Greeves and Meehan 1975). Hence, at a lower injection pressure of 185 bar (63%) higher smoke emissions were formed due to bigger droplet. However at a higher injection pressures of 210 bar (53.4%) and 220 bar (52.1%), it was observed that lower smoke emissions were formed compared to standard injection pressure of 200 bar (54.2%) due to
Figure 10.13 Comparison of NO$_x$ emissions at different injection pressures

Figure 10.14 Comparison of smoke emissions at different injection pressures
small size fuel droplets, better air-fuel mixing and complete combustion. TRCC with POME20 operated at 220 bar gave a 28% reduction of smoke opacity when compared with standard engine fueled with PBDF.

10.5 SUMMARY

In this experimental phase, experiments were carried out to study the influences of injection pressure on the optimized engine having TRCC operated at injection timing of 21° bTDC. Two fuels PBDF and POME20 were used. The tests were carried out at different injection opening pressures of 185, 200, 210, 220, and 230 bar. The results were compared with that of POME20 operated standard engine to decide on the proper injection pressure for biodiesel fuelled optimized engine and PBDF operated optimized engine for validation. From the experimental results the following conclusions can be drawn.

1. It was observed that the performance of the engine initially improved and then decreased with increasing injection pressure i.e. BTE increased marginally and BSEC and BSFC were slightly decreased with increasing injection pressure from 200 bar to 220 bar due to better atomization and air fuel mixing and complete combustion. Further increase in injection pressure to 230 bar was not found so favorable due to lower penetration, poor dispersion of the fuel and weak air entrainment. In addition, decrease in injection pressure to 185 bar was also found not desirable as it led to drop in BTE and increase in BSFC and BSEC of the engine due to poor atomization, vaporization and air fuel mixing.

2. CO, UBHC and smoke emission levels were decreased with increasing injection pressure from 200 bar to 220 bar due to
better atomization and air fuel mixing and complete combustion.

3. NO\textsubscript{x} levels were increased with increasing injection pressure from 200 bar to 220 bar due to high in-cylinder temperature as a result of better atomization, air fuel mixing and complete combustion.

4. Ignition delay decreased with increasing injection pressure from 200 bar to 220 bar due to high in-cylinder temperature as a result of better atomization and air fuel mixing and complete combustion. However for the same reasons peak in-cylinder temperature and maximum heat release rate were increased.

The present phase of investigation showed that the performance, combustion and emission characteristics of biodiesel fuelled previously optimized engine in terms of combustion chamber design and injection timing can be, further improved by suitably adjusting the injection pressure. In general, the engine having TRCC operated with retarded injection timing (21° bTDC) and increased injection pressure of 220 bar was observed to be better in terms of performance, combustion and exhaust emissions. Compared to the optimized engine operated at standard injection pressure of 200 bar, the engine operated with increased injection pressure of 220 bar provided a better performance by about 2.48%, 2.24% and 2.23% in terms of BTE, BSFC and BSEC respectively and an emission level improvement of 9%, 7.1% and 3.9% in terms of CO, UBHC and smoke opacity respectively. However the NO\textsubscript{x} emission level was deteriorated by about 3.2%. Hence the use of TRCC in biodiesel fuelled DI diesel engine was found effective. In addition, to gain the maximum benefit from biodiesel fuelled DI diesel engine it was learnt that injection parameters such as fuel injection timing and fuel injection pressure have to be matched with the combustion chamber design.