CHAPTER 6

RESULTS AND DISCUSSION

CASE (I) CATALYTIC CRACKED WASTE TRANSFORMER OIL AND TRANSESTERIFIED WASTE TRANSFORMER OIL IN A STANDARD DIESEL ENGINE

Initially, the engine is made to run with diesel for 30 minutes to attain warm up condition which is ensured by the cooling water and lubrication oil temperature. Subsequently, the engine is tested using different blends of CCWTO such as CCWTO25, CCWTO50, CCWTO75 and CCWTO100 without any modifications. Before testing the engine with respective fuel blends, the previously used fuel was completely drained from the fuel lines, filters, pumps, injector and other associated equipment’s. During the engine testing, load is varied through an eddy current dynamometer in steps of 20% from 20% to 100% load. Each time, the speed and required power output are maintained constant by adjusting the fuel pump rack position. The engine parameters such as BSFC, TFC, BTE, heat release rate and emissions parameters such as CO, smoke and NO\textsubscript{x} were recorded then. Variation of all these parameters with respect to brake power for different blends of CCWTO was examined at standard engine operating and design conditions. All the reported measurement with regards to engine and emission parameters, which were realized at ambient condition, was noted for three times to improve the accuracy of the measured readings. The above said methodology is repeated for the engine test using different blends of TWTO such as TWTO25, TWTO50, TWTO75 and TWTO100 without any modifications.
In order to figure out the total uncertainty of the intended experiment using CCWTO and TWTO in the diesel engine associated with various instruments, an error analysis was conducted in the right earnest. The accuracy and uncertainty of the equipment’s and measured parameters are listed in Table 6.1. From the uncertainty of individual parameters, the total uncertainty of the experiment was computed by method of propagation of errors, as described in Holman [40], and was noted to be ±2.0%

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Measurement</th>
<th>Accuracy</th>
<th>Uncertainty (%)</th>
</tr>
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<tr>
<td>Burette</td>
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</tr>
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<td>Loading device</td>
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<td>Speed Sensor</td>
<td>Speed</td>
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<td>Temperature indicator</td>
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</tr>
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<td>Exhaust gas analyzer</td>
<td>CO, % by volume</td>
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</tr>
<tr>
<td></td>
<td>HC, ppm</td>
<td>±10 ppm</td>
<td>0.1</td>
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<td>±12 ppm</td>
<td>0.2</td>
</tr>
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<td>Cylinder pressure</td>
<td>±0.3 kg</td>
<td>0.3</td>
</tr>
<tr>
<td>Crank angle encoder</td>
<td>Crank angle</td>
<td>± 1°</td>
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**6.1 COMBUSTION ANALYSIS**

The combustion in compression ignition engine is influenced by various parameters such as the properties of fuel, design of the combustion chamber, fuel injection timing and engine operating conditions [41]. The two parameters which play a vital role in determining the combustion process are heat release rate and in-cylinder pressure, which are analysed in the present study for the operation of CCWTO blends in a diesel engine. Figure 6.1 and 6.2 depicts the in cylinder pressure and heat release rate curve, respectively, for diesel and various blends of CCWTO – diesel at part load.
condition, respectively. It could be inferred from figure 6.1 that CCWTO50 exhibit higher heat release rate and the calorific value of CCWTO50 (10,690 kcal/kg) which is much closer to that of diesel (10,738 kcal/kg). The pointed out increase in peak heat release rate and in-cylinder pressure for CCWTO50 blend are due to promotion in the combustion process, induced by the comparable calorific value of CCWTO50 and viscosity of CCWTO with diesel. Normally, when vegetable oil based fuels are used in a diesel engine, the heat release rate and in-cylinder pressure drops on account of reduced calorific value of the fuel used in [42,43]. However, since CCWTO possess comparable calorific value with diesel, there isn’t any compromise in the amount of energy being released and therefore, they are reported to be higher than diesel. In a comparison with diesel, the peak heat release rate of CCWTO50 was found to be 11% higher than diesel at part load condition. Part load refers to 2.6 kW of the maximum brake power produced. The heat release was calculated from the pressure data recorded for 100 cycles. The in-cylinder pressure signals, measured for each crank angle position using the pressure transducer and crank angle encoder, are processed to calculate the heat release rate. The following formula is used in Indwin software for measurement of heat release rate.

\[
\frac{dQ}{d\theta} = \frac{\gamma}{\gamma - 1} P \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dp}{d\theta}
\]

Where, \( Q \) is the heat release rate per crank angle, \( P \) is the in-cylinder pressure, \( V \) is the cylinder volume and \( \gamma \) is the specific heat ratio.

The cylinder pressure and heat release rate are influenced by the ignition delay, which obviously depends on the ignition properties of fuel being combusted. The higher cetane number of CCWTO (52.7) leads to marginally shorter ignition delay period when compared to that of diesel and in light of this, the start of
combustion is noticed to be slightly shifted for CCWTO – diesel blends. However, this slight advancement in start of combustion (SOC) has not deterred the combustion process and the increase in magnitude of premixed combustion for CCWTO – diesel blends are evidence to this fact. In a comparison with diesel, the cylinder pressure of CCWTO50 was found to be 6% higher than diesel at part load condition. In the past, reports in advancement of combustion process when using higher cetane fuels have been traversed [44], which is akin to the results drawn in the present work.
Figure 6.3 Variation of heat release rate with respect to crank angle at part load condition for transesterified waste transformer oil – diesel blends

Figure 6.4 Variation of cylinder pressure with respect to crank angle at part load condition for transesterified waste transformer oil – diesel blends
Figure 6.3 and Figure 6.4 depicts the heat release rate and cylinder pressure, respectively, for TWTO – diesel blends at part load condition. With the increase in proportion of TWTO in the blend, the magnitude of heat release rate decreases and so does is the trend with the diffusion combustion phase too. Primarily, due to higher cetane number of TWTO, SOC has been advanced with the increase in proportion of TWTO in the blend. Since TWTO is more viscous than diesel, the atomization and evaporation of it is anticipated to be poor, hindering the preparation of homogenous fuel-air mixture during the shorter ignition delay period. Therefore, the amount of fuel being burnt in premixed combustion phase is decreased, reducing the magnitude of heat release rate with the increase of TWTO in the blend. Normally, biodiesel tend to possess lower calorific value than diesel and this is deemed to decrease the heat release rate for them. However, unlike biodiesel, TWTO doesn’t suffer much drop in calorific value than that of diesel and therefore, there is no reduction in magnitude of peak heat release rate for TWTO. Also, the accumulated heat release rate has been observed to decrease with the increase in proportion of TWTO in the blend due to its poor combustion, caused by the higher viscosity and boiling point of TWTO. With the already reduced amount of fuel being burnt in premixed combustion phase, the less pronounced diffusion combustion is expected to make the combustion incomplete for higher blends of TWTO with diesel.

When comparing the combustion characteristics of different TWTO blends with diesel, TWTO25 is scrutinized to show comparable peak heat release rate with diesel, while all other blends showed reduced peak heat release rate. Notably, almost all the properties of TWTO25 were found to be closer to diesel and hence, the combustion characteristics were observed to be akin to that of diesel. However, peak heat release rate for higher blends of TWTO decreased, with TWTO100 evincing a
decrease of 32% than diesel due to the reasons as elucidated above. In the same note, the diffusion combustion phase happens to be in par with diesel for TWTO25 and happens to get less pronounced with the increase in proportion of TWTO in the blend. Inferences on the reduction in peak heat release for fuel having higher viscosity and boiling point, similar to TWTO, complies with the results portrayed in the current study.

The variation of in-cylinder pressure trace with respect to crank angle at full load condition has been shown in figure 6.4. The in-cylinder pressure trace increases progressively until fuel injection and then rises rapidly after start of ignition, to attain maximum pressure inside the cylinder. It is clearly perceivable from the plot that the peak in-cylinder pressure decreased with the increase in proportion of TWTO in the blend; however, for TWTO25, the peak pressure is in par with diesel. For higher blends, the increased viscosity of TWTO has had affected the fuel atomization, affecting the evaporation and fuel/air mixing process so as to decrease the peak pressure on the whole.

6.2 PERFORMANCE ANALYSIS

The BTE for TWTO blends and CCWTO blends are compared with diesel at part load conditions are shown in figure 6.5. It is a well-known fact that BTE of the engine relies on fuel consumption and calorific value of the fuel [45]. Notably, due to comparable calorific value of CCWTO with diesel, there is no increase in fuel consumption. In further introspection, the viscosity of CCWTO – diesel blends are brought marginally closer to diesel as the intended cracking process has improved the fuel viscosity and the calorific value of the fuel. The reduced fuel consumption for CCWTO – diesel blends, due to the above mentioned reasons, clearly reflects on the improvement in BTE of the engine. Substantially, the comparable flash point of
CCWTO – diesel blends with diesel has had improved the fuel evaporation and the ensuing fuel-air mixing process so as to enhance the combustion holistically. Accompanied by this, the reduction in fuel viscosity after cracking process has triggered more active combustion for CCWTO – diesel blends, resulting in an increased BTE for CCWTO – diesel blends than diesel. Categorically, the increase in BTE was found to be 2% higher for CCWTO50 at part load condition when compared to diesel fuel.

Figure 6.5 Variation of brake thermal efficiency for catalytic cracked waste transformer oil and transesterified waste transformer oil – diesel blends at part load condition

Figure 6.5, depicting the variation of BTE for TWTO – diesel blends with respect to part load and a decreasing trend with increase in proportion of TWTO in the blend was observed. However, among all the blends, TWTO25 shows a comparable BTE with diesel, while it was observed to be lower for TWTO100. Comparatively, TWTO is a heavier molecule than diesel, ascertained based on its higher viscosity and boiling point, rendering the dispersion of fuel jet into finer
droplet very difficult and thereby affecting the combustion process. Despite higher viscosity of biodiesel, certain researchers have acceded to the improvement in BTE in wake of inherent presence of oxygen within the fuel, which has had duly promoted the combustion process. Nonetheless, herein, TWTO is not an oxygenated fuel as opposed to biodiesel and since it a derivative of mineral oil, it could be categorically regarded as diesel like fuel, which is bound to encompass mostly alkanes and alkenes. As such, the promotion in combustion is not favoured, reducing the BTE with the increase in proportion of TWTO in the blend.

6.3 EMISSION ANALYSIS

6.3.1 NO\textsubscript{X} emission

Figure 6.6 shows the variation of NO\textsubscript{X} emission for various CCWTO and TWTO – diesel blends at part load conditions. Reportedly, NO\textsubscript{X} emission significantly depends on the factors such as in-cylinder gas temperature, prevalence of excess oxygen in the combustion chamber and residence time [46,47]. From the figure it clearly depicts, a higher NO\textsubscript{X} emission was found for CCWTO50 than diesel at part load condition and the reason is due to higher in-cylinder temperature, caused by improved combustion. An increase of about 9% was observed for CCWTO50 when compared to that of diesel at part load condition. Substantially, the heat release curve, as described above, also exhibits a higher magnitude of premixed combustion phase, supporting the cause of increased in-cylinder temperature. The past reports on increase in NO\textsubscript{X} emission for oxygenated fuels due to the phenomenon [48, 49], as elucidated in the present work, justifies the results drawn in the current work.

With the general token that much pronounced premixed combustion phase would elevate in-cylinder temperature to promote NO\textsubscript{X} formation, it is appropriate to note a reduction in NO\textsubscript{X} emission for TWTO100, as it exhibits much lower peak heat
release rate than all other blends. Evidently, the much lower in-cylinder temperature has forbidden active combustion and therefore, NO\textsubscript{X} emission is deemed to be reduced by 27% for TWTO100 when compared to diesel, as evinced in figure 6.6.

![Graph showing NO\textsubscript{X} emission for catalytic cracked waste transformer oil and transesterified waste transformer oil – diesel blends at part load condition.]

Figure 6.6 Variation of NO\textsubscript{X} emission for catalytic cracked waste transformer oil and transesterified waste transformer oil – diesel blends at part load condition

### 6.3.2 Smoke emission

Figure 6.7 shows the variation of smoke emission for various CCWTO and TWTO – diesel blends at part load condition. It is observed from the figure that smoke emission is marginally lower with CCWTO – diesel blends. Conceptually, increase in NO\textsubscript{X} emission is expected to decrease smoke emission in respect of widely reported NO\textsubscript{X}-smoke trade off in a diesel engine [50] and this has been observed in the current study too. The decrease in smoke emission for CCWTO – diesel blends is due to proper oxidation of soot in the flame region, supported by the improvement in fuel properties of CCWTO after cracking process. Also, soot precursors, which are formed during the premixed combustion phase, is well oxidised on account of more
pronounced premixed combustion of CCWTO-diesel blends, thereby decreasing the smoke emission. From the figure, a 13% decrease in smoke emission for CCWTO50 than that of diesel has been deduced at part load condition.

Figure 6.7 Variation of smoke emission for catalytic cracked waste transformer oil and transesterified waste transformer oil – diesel blends at part load condition

The smoke emission for various blend fuels, which is understood to have been formed during diffusion combustion zone, has been exhibited in figure 6.7. As evident from the heat release rate, the accumulated heat release rate is figured out to be lower with the increase in proportion of TWTO in the blend, indicating much less pronounced diffusion combustion phase. As such, the soot precursors formed during the premixed combustion phase are not duly oxidized in the rather less active diffusion combustion phase. In addition, poor fuel atomization would not pave way for the invasion of oxygen molecules into the bigger droplets and thereby, inhibiting the soot oxidation process. Finally, besides the disregard in the diffusion combustion phase, the premixed combustion is also noted to be less pronounced for higher blends.
of TWTO and this reduces the in-cylinder temperature so as to prohibit the oxidation of soot in the fuel rich regions of spray to some extent. In view of all these substantiations for the improper oxidation of soot, smoke emission for TWTO100 is elucidated to be higher than diesel by 17%. On the other hand, the smoke emission for TWTO25 is duly noted to be comparable to that of diesel for the justifications as accounted above.

6.3.3 HC emission

Compression ignition engine are capable of converting the fuel-air mixture into the products of combustion by 98% when compared to Spark ignited engines [41]. With such high fuel conversion efficiency obtained for diesel fuel, it would be interesting to study the effect of CCWTO blends on incomplete products of combustion such as HC and CO. Figure 6.8 shows the variation of unburned hydrocarbon emission for CCWTO and TWTO – diesel blends at part load condition. As inferred from the figure, CCWTO – diesel blends were noticed to liberate lower unburned hydrocarbon when compared to that of diesel. Understandably, the slight advancement in combustion process, coupled by the enhanced fuel properties of CCWTO, has led to complete combustion and thereby, decreasing HC emission by 9% for CCWTO50 than diesel at part load condition.

In the other hand, as inferred from the figure, TWTO – diesel blends were noticed to liberate higher unburned hydrocarbon when compared to that of diesel. Understandably, the combustion process, coupled by the fuel properties of TWTO, has led to incomplete combustion and thereby, increasing HC emission by 5% for TWTO100 than diesel at part load condition.
6.3.4 CO emission

Diesel engines generally produce lower emissions of CO as they always run at lean mixture, which favourably promotes the oxidation of it at a desired temperature of the combustion zone [51]. Figure 6.9 shows the variation of CO emission for CCWTO and TWTO – diesel blends and diesel at part load conditions. It could be inferred from the figure that the CCWTO – diesel blends shows a reduction in CO emission due to the promotion in combustion process. Notably, the reduction in fuel viscosity is deemed to facilitate better oxidation of CO. In addition, due to the increased heat release rate, the in-cylinder temperature is believed to be higher, which has had promoted the better oxidation of CO and thereby, reducing the CO emission. Considering that the two reasons for the formation of CO emission such as dearth of oxygen and decrease in-cylinder temperature haven’t had much role to play in our context to affect combustion process, the CO emission has been ably reduced for
CCWTO-diesel blends. In particular, the CO emission for CCWTO50 were noted to be reduced by 33% than that of diesel at part load condition.

Figure 6.9 Variation of CO emission for catalytic cracked waste transformer oil and transesterified waste transformer oil – diesel blends at part load condition

With the increase in proportion of TWTO in the blend, the CO emission increases as the oxidation of TWTO blends in the confines of combustion chamber is affected and this culminates in incomplete combustion. In reflection, the amount of fuel being injected is higher for higher TWTO blends in order to maintain the required power output and this increases the fuel to air equivalence ratio, decreasing the prevalence of oxygen that is required for the proper oxidation of CO. Further, the in-cylinder temperature for the higher blends of TWTO is believed to be lower on the grounds of reduction in magnitude of heat release rate, as detailed above. The increased fuel to air equivalence ratio, coupled by the lowered in-cylinder temperature, impedes CO oxidation and as a result, CO emission was noted to be increased for higher blends of TWTO than lower blends. In respect of better fuel
properties for TWTO 25, CO emission are evinced to be in the closer vicinity of diesel at low and full load conditions, respectively.

6.4 CLOSURE

It has been inferred from the engine study that the CCWTO 50 shows better results in terms of performance, emission and combustion characteristics of the engine without any modification in the design parameters whereas trans-esterified waste transformer oil and its blends (TWTO) shows decreased engine characteristics with increase in proportion of TWTO in the blend due to the nature of its properties. In order to effectively operate high viscous oils and their blends in diesel engine few researchers have made an attempt to modify the combustion chamber design. The engine design, particularly the combustion chamber design in a direct injection diesel engine has to achieve a high degree of air movement inside the cylinder in terms of swirl, squish and turbulence, in order to prepare better air-fuel mixture to promote the evaporation in a very short time and to achieve higher efficiency. With this background, in order to achieve improved performance and reduction in emissions with higher blends of TWTO operated diesel engine, combustion chamber modification is mandatory.