CHAPTER 6

NANO-HYBRID COMPOSITE LINER TESTING IN COMPRESSION IGNITION ENGINE

6.1 INTRODUCTION

The NL fabricated using the selected nano-hybrid composite material was tested under real-time environment in a single cylinder engine with diesel as a fuel in a test bed setup in laboratory at room temperature. The parameter of BTE, combustion parameters of cylinder pressure and heat release rate using computerized data acquisition system and emission parameters of CO, HC, NOx, smoke using the exhaust gas analyzer were carried out and compared with the present CL.

6.2 EXPERIMENTAL ENGINE TEST RIG

The performance, combustion, and emission characteristics of the engine were tested using the present CL and the newly fabricated NL. A four stroke, direct-injection, water-cooled Kirloskar AV1 (3.75kW) engine was used as the test engine for this study. It has a cylinder bore of 80 mm and stroke length of 110 mm, and a runs at constant speed of 1500 rpm. The schematic diagram of the engine test setup used for this study is shown in Figure 6.1. Eddy current dynamometer was used to vary load on the engine. The time taken to consume 50 cc of fuel was noted using burette setup.

The engine was started with pure diesel and warmed up for 20 min. After the warm up period, the engine was run until steady state was reached, at each load. The fuel consumption, exhaust gas temperature, engine cooling water temperature, and emission values were recorded for different loads. The readings were noted continuously for 5 mins to minimize the experimental uncertainties.
Each test was performed three times and the average values were noted. A similar procedure was repeated for both CL and NL with diesel engine.

![Figure 6.1 Schematic diagram of the engine test setup](image)

**6.3 COMPARATIVE EXPERIMENTAL OBSERVATIONS FOR CL AND NL IN DIESEL ENGINE**

**6.3.1 Brake Thermal Efficiency (Performance Parameter)**

The variation of BTE with brake power (BP) for different loads is shown in Figure 6.2 for both conventional and composite liners. The BTE indicates the ability of combustion system to accept the newly developed liner and provides a comparable means of assessing how efficiently heat energy was converted into mechanical output by using new the NL.

It can be seen from Figure 6.2 that the BTE of the engine with NL is higher than that of engine with CL at all-loads. At the maximum load, the BTE of the engine with NL was found to be 5.74% higher than that of the engine with CL. This increase in efficiency could be attributed to the LHR by the hybrid liner and also due to reduction in in-cylinder heat transfer and lower heat flux.
This enables better combustion inside the combustion chamber, resulting in increased efficiency (Patali et al. 2014).

Figure 6.2 BTE versus BP for CL and NL

The results show that the nano- and micro-reinforcements play a major role because of their exceptionally high surface-to-volume ratio of the reinforcing phase with Al6061 matrix material. High temperature is maintained inside the combustion area so that the possibility of complete fuel burning is high.

Thus, the suitability of the new liner for operating at different BPs has been established, with reduced fuel consumption. Figure 6.2 also shows that at up to 80% of the full-load, BTE increased and beyond that load BTE decreased in both CL and NL. This could be due to increase in the fuel conversion up to 80% of full-load; beyond which air/fuel ratio is reduced as oxygen has been completely used up (Patali et al. 2014, Domakonda and Puli 2012). It was clearly proved that the economic load of the engine was 80%.
6.3.2 **Combustion Analysis**

Combustion is the conversion of a substance called a fuel into chemical compounds known as products of combustion by combination with an oxidizer (air). The combustion process is an exothermic chemical reaction, i.e., a reaction that releases energy as it occurs. Thus combustion may be represented symbolically by:

\[
\text{Fuel} + \text{Oxidizer} \rightarrow \text{Products of combustion} + \text{Energy} \quad (6.1)
\]

Oxygen (O₂) is one of the most common elements on earth making up 20.9% of air. Rapid fuel oxidation results in large amounts of heat. In diesel engines, air alone is taken in during suction stroke and compressed during compression stroke to a compression ratio of 14 to 18. Then the temperature and pressure of in-cylinder air increases, at the end of compression, the fuel is injected into the combustion chamber. The hot air ignites the fuel and hence combustion takes place inside the cylinder. The objective of good combustion is to release all the heat in the fuel. This is accomplished by controlling the temperature high enough to ignite and maintain ignition of the fuel, turbulence or intimate mixing of the fuel and oxygen, and sufficient time for complete combustion.

Accordingly, there is a need to study the in-cylinder pressure of compressed air and heat release rate to know the combustion characteristic of newly developed NL. In the present experimental setup, an attached pressure transducer (AVL/GM12D air-cooled), a combustion analyzer (AVL619 Indimeter), and IndWin software, version 2.2, were used to measure combustion parameters with data acquisition system, which will provide instantaneous evaluation of the combustion event allowing the effects of changes in the in-cylinder thermodynamic processes like in-cylinder pressure and heat release rate. Cylinder pressure for 90 continuous cycles has been measured at each operating point, and an average of
these cycles is used for heat release analysis. All the measured data from the engine operated with CL and NL were calculated and results are stored in appropriate files in order to retrieve and superimpose data on the plotter for comparison. The measured parameters were used to compute maximum cylinder pressure and heat release rate as discussed further down.

### 6.3.2.1 Cylinder pressure

Figure 6.3 shows the variations in cylinder pressure with crank angle for CL and NL at a maximum load of 3.75 kW. The highest peak pressures are found to be 72.15 bar and 70.61 bar for NL and CL, respectively. The reasons for slightly higher peak cylinder pressure are better burning of diesel inside the combustion chamber and reduction of heat lost using NL. This is also due to the higher temperature of the engine cycle maintained by nano- and micro-reinforcement particles present in the NL.

![Cylinder Pressure Diagram](image)

**Figure 6.3 Cylinder pressure versus crank angle for CL and NL**

Further, Al6061 matrix material has a low thermal coefficient of expansion, which also aids in achieving higher temperature. Solid lubricant graphite
micro-particles present in the NL make the operation of the engine cycle smooth. Although tensile strength and elastic modulus of the NL are comparatively lower than those of CL, it can easily withstand the in-cylinder pressure generated during the engine cycle. This may be due to the fact that ZrO₂ and SiC ceramic particles have high tensile strength and elastic modulus than CL.

6.3.2.2 Heat release rate

Figure 6.4 shows the variations in the rate of heat release with crank angle for CL and NL at a maximum load of 3.75 kW. The highest heat release rate of 76.77 kJ/m³ degrees for CL and 80.53 kJ/m³ degrees for NL could be observed from the plot. The slight increase in heat release rate is due to increased burning rate during the burning phase of diesel engine cycle, which is maintained by matrix and nano- and micro-reinforcement particles present in the NL. Generally, highest peak pressure is observed for LHR diesel operation due to the higher and early heat release (Abedin et al. 2014). This could be achieved because the thermal conductivity of NL is higher than that of CL material.

![Figure 6.4 Heat release rate versus crank angle for CL and NL](image-url)
6.3.3 Exhaust Gas Temperature

In the experimental test setup, iron and iron-constant thermocouples were used to measure the exhaust gas temperature. Figure 6.5 shows that the exhaust gas temperature of the engine operated with NL and CL. One could observe from the plot that the exhaust gas temperature is higher at all-loads in the engine fitted with NL compared to that in the engine fitted with CL. This indicate that the higher in-cylinder temperature also leads to an increase in the exhaust gas temperature (Zheng et al. 2014). The amount of the energy released during combustion affects the combustion temperature, which can be determined by exhaust gas temperature (Jaichandar et al. 2013).

The exhaust gas temperature indicates that the NL-operated engine has better combustion than CL-operated engine. Higher combustion gas temperature could destroy the lubricating film between piston body and liner, increasing local metal temperature (Espadafor et al. 2010).

![Figure 6.5 Exhaust gas temperature with BP for CL and NL](image)

Figure 6.5 Exhaust gas temperature with BP for CL and NL
6.3.4  Engine Emission Measurements

The demand for emission regulations has strongly increased in recent years to achieve green environment globally. In view of the ever shrinking requirements, it is important for engineers and researchers to reduce emissions of exhaust air pollutants. In this experimental investigations, AVL-444 DI gas analyzer was used to measure the carbon monoxide (CO), hydrocarbon (HC) and oxides of hydrogen (NOx) contents present in the exhaust gas of the test engine. An AVL-437 smoke meter was used to detect the amount of smoke emitted by the test engine.

6.3.4.1  Carbon Monoxide (CO)

CO is the product of incomplete combustion due to insufficient oxygen available to convert all the carbon atoms to carbon dioxide. It is mainly dependent on the air/fuel ratio relative to the chemically correct proportion and increases when the air/fuel ratio becomes greater than stoichiometric air and fuel requirements. Figure 6.6 shows the variations of CO emission levels against BP for CL and NL.

![Figure 6.6 CO versus BP for CL and NL](image_url)
At maximum load, the CO emission levels were found to reduce by 12.5% with the use of NL compared to CL, as shown in the Figure 6.6. It is also clear that in the NL-operated engine, CO emission is lower than the CL-operated engine at all-loads. This is mainly due to the higher surrounding wall temperature of NL, maintained the presence of nano- and micro-reinforcement particles, which helped in complete burning of oxygen content inside the combustion chamber.

6.3.4.2 Hydrocarbon (HC)

HC is an intermediate product of incomplete combustion. The variation in HC emission with BP for CL and NL is shown in Figure 6.7. The plots show a reduction in the values of HC in the engine with NL for all BPs. The percentage reduction obtained with NL at maximum load was 10.95%. The heat loss due to the coolant use reduced (when the engine was operated with NL), leading to good flammability of fuel inside the combustion chamber, which results in reduction of HC at all-loads.

Figure 6.7 HC versus BP for CL and NL
6.3.5 Oxides of nitrogen (NO\textsubscript{x})

The 79% of air is nitrogen, with traces of other elements. Nitrogen reduces combustion efficiency by absorbing heat from the combustion of fuels, diluting the flue gases and increases the volume of combustion by-products. It also can combined with oxygen at high flame temperatures to produce oxides of nitrogen (NO\textsubscript{x}), which are toxic pollutants. As per the combustion theory, the formation of NO\textsubscript{x} is merely a function of in-cylinder combustion temperature (Imtenan et al. 2014, Desantes et al. 2014) and the amount of oxygen.

Figure 6.8 shows the variation in NO\textsubscript{x} for engines operated with CL and NL. A comparison of the NO\textsubscript{x} emission values showed that there is a marginal increase in NO\textsubscript{x} emission with the use of NL than with the use of CL. The increase in the levels was found to be 2.7% at maximum load.

![Figure 6.8 NO\textsubscript{x} versus BP for CL and NL](image)

Several factors such as fuel properties, engine type, and engine-operating condition affect the engine NO\textsubscript{x} emissions. Although the higher
overall cylinder temperature is an indicator of higher NO\textsubscript{x}. Combustion that takes place over a short period of time allows less cooling time for heat transfer and dilution, which results in higher NO\textsubscript{x} formation (Ashraful et al. 2014a,b, Rajasekar et al. 2010, Senthilkumar et al. 2012, Savva et al. 2014, Vedharaj et al. 2014).

Since the nano-ZrO\textsubscript{2}, micro-SiC\textsubscript{2}, and micro-Gr reinforcements can withstand high temperature and Al6061 matrix material has lower thermal expansion coefficient, the temperature inside the combustion chamber is high. In-cylinder NO\textsubscript{x} reduction technique like exhaust gas recirculation is an effective way to reduce NO\textsubscript{x} emission from diesel engine (Zheng et al. 2014). It can be attached to reduce NO\textsubscript{x} when the engine is operating with NL.

### 6.3.5.1 Smoke

Smoke is a collection of tiny unburned gas particles which hold hundreds of different chemicals and fumes. Visible smoke is mostly carbon. It occurs when there is incomplete combustion (not enough oxygen to burn the fuel completely) inside the combustion chamber during engine operation. Figure 6.9 shows the variation of smoke emission in Hartridge smoke unit (HSU) for the CL and NL. Smoke has reduced by 4.76% for NL at maximum load. This was due to better vaporization and quick combustion of fuel supplied inside the combustion chamber (NL cylinder wall), which were maintained by the natural properties of reinforcements and matrix material.

Lower level of unburned HC in the engine exhaust could have occurred due to the complete combustion with the help of fuel–burn oxygen. This could have been the reason for reduction in smoke emission. Since the high temperature maintained by NL in the combustion chamber, where the piston squishes or squeezes part of the fuel-air mixture at the end of the compression stroke, the mixture is pushed out of the squish area and this
promotes turbulence, further mixing of the fuel-air mixture and more efficient combustion leads to reduction of smoke. However, there is always a trade-off between NO\textsubscript{x} and smoke emission in a diesel engine fuelled by any kind of fuel (Banapurmath et al. 2015).

![Figure 6.9 Smoke versus BP for CL and NL](image)

6.4 TEARDOWN ANALYSIS

In order to study the degree of damage and wear in the NL fitted engine, a teardown analysis was also carried out. After running for 2000 h at frequent intervals for a period of 1 year, at various load conditions, the new NL was dismantled from the engine and is shown in Figure 6.10. The internal parts were inspected and evaluated to investigate wear characteristics, breakage, and other damage as well as the accumulation of dirt, sludge, and carbon.
6.4.1 Visual Examination of Developed NL

No cracks were found both inside and outside of the NL, which indicates that the NL is capable of running for a long service life, and no need of any dimensional changes to improve the strength of newly developed NL. During visual inspection, very small quantities of carbon deposits were found at the top of the piston which was lesser than that found in the engine with CL, which shows that more complete combustion has taken place in the engine fitted with NL.

During the testing period, outer wall of the NL was continually placed in cooling water. After dismantling the NL, no corrosion effect was found outside the surface of the NL on visual inspection. This is due to good corrosive resistance property of the hybrid composites.

6.4.2 Monitoring Engine Oil Condition

At the time of NL assembly, the oil in the sump was completely cleaned and filled with new Castrol Agri MP Plus 20W-40 engine oil. After 2000 h of running under various load conditions at frequent intervals, the engine oil was completely removed from the oil sump and was kept undisturbed for 20 h and filtered with less than 100 nm muslin cloth.
No foreign particles or Al matrix debris or reinforcement debris were observed in the oil. At the same time, the bottom portion of the engine oil sump was also cleaned with neat cloth and fine brushes, which also showed absence of foreign particles. This inspection proved that there was no material loss in the developed nano-hybrid composite liner under different load operating condition during the period of study. The frictional coefficient of Al MMC was 25% more than that of cast iron while sliding under identical conditions (Natarajan et al. 2006).

6.5 SUMMARY

The effect of a newly developed NL on diesel engine performance, combustion, emission characteristics, and suitability to replace the CL in the engine cylinder was studied and the results observed in this study are summarized as follows.

- The NL enhanced BTE, in-cylinder pressure, heat release rate, and exhaust temperature.
- The NL has resulted in reduced CO, HC, and smoke emissions,
- The NL has increased NOx emission.

Thus, this investigation has shown that the newly developed NL has good potential to replace the presently used conventional CL for achieving greater fuel economy and green environment. The fact that it can be used without any modification of the engine structure with weight saving of 43.75% is an added advantage.