CHAPTER III

DIESEL FUEL, DRIVING PERFORMANCE AND COMBUSTION

3.1 GENERAL

Several operating characteristics influence engine performance, and their relative importance depend on engine type and duty cycle (for example, truck, passenger car, Stationary generator, marine vessel, etc.). These characteristics are:

- Starting ease
- Low noise
- Low wear (high lubricity)
- Long filter life (stability and fuel cleanliness)
- Sufficient power
- Good fuel economy
- Low temperature operability
- Low emissions

Engine design has the greatest impact on most of these characteristics. However, because the focus of this research is oxygen enriched combustion of fuel, this chapter discusses how these characteristics are affected by OECT.
3.1.1 Starting

Leaks and heat loss reduce the pressure and temperature of the fuel/air mixture at the end of the compression stroke. Thus, a cold diesel engine is more difficult to start and the mixture more difficult to ignite when compared to a hot diesel engine. When Engines are equipped with start-assist systems, they increase the air temperature to aid ignition. These controls in the diesel engine can also decrease starting engine noise, white smoke, and cranking time. Diesel fuel that readily burns, or has good ignition quality, improves cold start performance. The cetane number of the fuel defines its ignition quality. Masound Miyamoto et al experimented the effect of oxygenated fuel with biodiesel to improve combustion and emission characteristics, reduced cold starting problems were resulted. A cold diesel engine is more difficult to start and the mixture more difficult to ignite when compared to a hot diesel engine. Robert Bosch et al (1999).


3.1.2 Power

Power is determined by the engine design. Diesel engines are rated at the brake horsepower developed at the smoke limit. For a given engine, varying fuel properties within the standard specification range does not alter power significantly.

However, fuel viscosity outside of the standard specification range causes poor atomization, leading to poor combustion, which leads to loss of power and fuel economy. In the present study, varies injection pressure with different levels of oxygen enrichment were tested in 4 stroke single cylinder engine. Power increases considerably with respect to oxygen
enrichment. Cylinder brake power increases considerably when the intake oxygen increases from 21% to 23% Stated by Ramesh poola et al (1996).

3.1.3 Noise

The noise produced by a diesel engine is a combination of combustion and mechanical noise. Fuel properties can affect combustion noise directly.

In a diesel engine, fuel ignites spontaneously shortly after injection begins. During this delay, the fuel is vaporized and mixing with the air in the combustion chamber. Combustion causes a rapid heat release and a rapid rise of combustion chamber pressure. The rapid rise in pressure is responsible for the knock that is very audible in some diesel engines. By increasing the cetane number of the fuel, the knock intensity is decreased by the shortened ignition delay. Fuels with high cetane numbers ignite before most of the fuel is injected into the combustion chamber. The rates of heat release and pressure rise are then controlled primarily by the rate of injection and fuel-air mixing, and smoother engine operation results. Khair et al. Oxygen enriched combustion reduces combustion noise stated by gong li et al (2006)

3.1.4 Fuel economy

Here again, engine design is more important than fuel properties. However, for a given engine used for a particular duty, fuel economy is related to the heating value of the fuel. Moon and Joon (2008) experimented the effects of oxygen enrichment for internal combustion engine. Savings in fuel consumption was resulted. Combustion catalyst may be the most vigorously promoted diesel fuel aftermarket additive. However, the southwest Research Institute, under the auspices of the US Transportation Research Board, ran back to back test of fuel with and without a verity of combustion

In general fuel economy is customarily expressed as output per unit volume, e.g., Km per liter. Oxygen enriched combustion decreases specific fuel consumption.

3.1.5 Wear and Lubricity

Some moving parts of diesel fuel pumps and injectors are protected from wear by the fuel. To avoid excessive wear, the fuel must have some minimum level of lubricity. Lubricity is the ability to reduce friction between solid surfaces in relative motion. The lubrication mechanism is a combination of hydrodynamic lubrication and boundary lubrication. In hydrodynamic lubrication, a layer of liquid prevents contact between the opposing surfaces. For diesel fuel pumps and injectors, the liquid is the fuel itself and viscosity is the key fuel property. Fuels with higher viscosities will provide better hydrodynamic lubrication. Diesel fuels with viscosities within the standard specification range provide adequate hydrodynamic lubrication.

Boundary lubrication becomes important when high load and/or low speed have squeezed out much of the liquid that provides hydrodynamic lubrication, leaving small areas of the opposing surfaces in contact. Boundary lubricants are compounds that form a protective anti-wear layer by adhering to the solid surfaces The less-processed diesel fuels of the past were good boundary lubricants. This was not caused by the hydrocarbons that constitute the bulk of the fuel, but was attributed to trace amounts of oxygen- and nitrogen-containing compounds and certain classes of aromatic compounds. Evidence for the role of trace quantities is the fact that the lubricity of a fuel can be restored with the addition of as little as 10 parts per million (ppm) of an additive.
Lubricity enhancing compounds are naturally present in diesel fuel derived from petroleum crude by distillation. They can be altered or changed by hydro treating, the process used to reduce sulfur and aromatic contents. However, lowering sulfur or aromatics, per se, does not necessarily lower fuel lubricity. The use of fuels with poor lubricity can increase fuel pump and injector wear and, at the extreme, cause catastrophic failure.

The problem was solved by treating the fuel with a lubricity additive. As regions regulate lower sulfur levels, mostly accomplished with more severe hydro treating, the general trend is lower levels of lubricity in unfinished, unadditized fuels. The additized finished fuel in the market, however, should have adequate lubricity because of the fuel specifications in place. Oxygen enriched combustion does not affect lubricity.

3.1.6 Cleanliness

Inadequate lubricity is not the only cause of wear in diesel engine fuel systems. Diesel fuel can cause abrasive wear of the fuel system and the piston rings if it is contaminated with abrasive inorganic particles. Fuel injectors and fuel injection pumps are particularly susceptible to wear because the high liquid pressures they generate require extremely close tolerances between parts moving relative to one another.

3.1.7 Low temperature operability

The low temperature operability is an issue with middle distillate fuels because they contain straight and branched chain hydrocarbons (paraffin waxes) that become solid at ambient winter temperatures in colder geographic areas. Wax formation can also be exacerbated by blends of biodiesel with conventional diesel fuel. Wax may plug the fuel filter or completely gel the fuel, making it impossible for the fuel system to deliver fuel to the engine.
Engine design changes to address this problem include locating the fuel pump and filter where they will receive the most heat from the engine. The practice of pumping more fuel to the injectors than the engine requires is also beneficial because the warmed excess fuel is circulated back to the tank. While the primary purpose of this recycle is to cool the injectors, it also heats the fuel in the fuel tank.

Sometimes operators may allow diesel equipment to idle in cold weather rather than turn the engine off when it is not in use. This practice is no longer allowed in certain regions. In some cases the cost of the fuel may be less than the cost of winterizing the engine; vehicles designed for low-temperature operation are usually equipped with heated fuel tanks, insulated fuel lines, and heated fuel filters.

In a refinery, there are a number of approaches to improve a fuel’s low-temperature operability, such as:

- Manufacture it from less waxy crude.
- Manufacture it to a lower distillation end point. (This excludes higher boiling waxy components with higher melting points.)
- Dilute it with a fuel with lower wax content
- Treat it with a low-temperature operability additive

Additives are used to improve low temperature filterability and lower the pour point. When they work, additives have several advantages over dilution: they are readily available in most areas of the world, treatment cost is less, and the treatment does not lower fuel density (thus the heating value and fuel economy are not affected).
3.1.8 Fuel stability & Filter life

Unstable diesel fuels can form soluble gums or insoluble organic particulates. Both gums and particulates may contribute to injector deposits, and particulates can clog fuel filters.

The formation of gums and particulates may occur gradually during long-term storage or quickly during fuel system recirculation caused by fuel heating.

Storage stability of diesel fuel has been studied extensively because of governmental and military interest in fuel reserves. However, long-term (at ambient temperatures) storage stability is of little concern to the average user, because most diesel fuel is consumed within a few weeks of manufacture. Thermal (high-temperature) stability, on the other hand, is a necessary requirement for diesel fuel to function effectively as a heat transfer fluid. Thermal stability may become more important because diesel engine manufacturers expect future injector designs to employ higher pressures to achieve better combustion and lower emissions. The change will subject the fuel to higher temperatures and/or longer injector residence times.

Low sulfur diesel fuels tend to be more stable than their high sulfur predecessors because hydrotreating to remove sulfur also tends to destroy the precursors of insoluble organic particulates. However, hydrotreating also tends to destroy naturally occurring antioxidants. It may be necessary for the refiner to treat some low sulfur diesel fuels with a stabilizer to prevent the formation of peroxides that are the precursors of soluble gums.
3.1.9 Smoke

The fuel system of a diesel engine is designed and calibrated so that it does not inject more fuel than the engine can consume completely through combustion. If an excess of fuel exists, the engine will be unable to consume it completely, and incomplete combustion will produce black smoke. The point at which smoke production begins is known as the smoke limit. Most countries set standards for exhaust smoke from high-speed, heavy-duty engines. Smoke that appears after engine warm-up is an indication of maintenance or adjustment problems. A restricted air filter may limit the amount of air, or a worn injector may introduce too much fuel. Other causes may be miscalibrated fuel pumps or maladjusted injection timing. Changes made to fuel pump calibration and injection timing to increase the power of an engine can lead to increased emissions. Because smoke is an indication of mechanical problems, California and other states have programs to test the exhaust opacity of on-road heavy-duty trucks under maximum engine speed conditions (i.e., snap idle test). Owners of trucks that fail the test are required to demonstrate that they have made repairs to correct the problem. There are also smoke regulations for ships in port.

Variation of most fuel properties within the normal ranges will not lead to the high level of particulate matter (PM) represented by smoking. The exception is cetane number; fuel with a very high cetane number can cause smoking in some engines. The short ignition delay causes most of the fuel to be burned in the diffusion-controlled phase of combustion which can lead to higher PM emissions. Noboru et al (1996) experimented effect of oxygenated agents on combustion and emissions characteristics of a diesel engine, more reduction on smoke and particulate emissions was found.

Fuel can indirectly lead to smoking by degrading injector performance over time, when:
• Gums in the fuel are deposited on the injectors, causing sticking, which interferes with fuel metering.

• Petroleum resid or inorganic salts in the fuel result in injector tip deposits that prevent the injector from creating the desired fuel spray pattern. (Some low-speed, large diesel engines are designed to burn fuel containing large amounts of petroleum resid. These are typically used in marine and power generation applications.)

• Abrasive contaminants or organic acids in the fuel, or inadequate fuel lubricity cause excessive abrasive or corrosive injector wear.

3.2 COMBUSTION Vs OXYGEN ENRICHED COMBUSTION

3.2.1 General

The combustion process will be the prime generator of energy to our civilization in the near future. It can be defined as a chemical reaction during which fuel is burned and a large amount of heat is released. The oxidizer in this process is atmospheric air. Chemical energy stored in the fuel is released during this process and released in the form of Thermal energy. The physic and chemistry of combustion are covered in some detail by both Gaydon and Wolfhard (1979) and Lewis and von Elbe (1961), but neither book much attention to combustion in internal combustion engines.

To understand the process of combustion it is important to discuss some basic terms and definitions related to combustion, these terms are

• Air supply: air consists of 21% oxygen(O₂) and 79% Nitrogen(N₂), oxygen is the only active element in the air combined with combustion elements of the fuel to produce
heat, the large amount of nitrogen in the air performs no useful role in the burning process.

- **Stoichiometric air (theoretical)**: is the minimum amount of air needed for complete combustion, or it is known as chemically correct amount of air. If the air quantity is theoretical no oxygen will appear in the exhaust gas.

- **Stoichiometric combustion (theoretical)**: is the ideal combustion process in which fuel burned completely.

- **Conventional fuels**: consists mainly of two elements hydrogen and carbon, the fuel value lies in the carbon and hydrogen contents and during combustion they combined with oxygen and produce heat.

- **Pollutant**: is the introduction by man to the environment of substances or energy liable to cause hazards to human health, harm to living resources and ecological system damage to structure or amenity.

The two active elements in fuels are carbon and hydrogen. Ideally, combustion breaks down the molecular structure of the fuel; the carbon oxidizes to carbon dioxide (CO$_2$) and the hydrogen to water vapor (H$_2$O), but an incomplete process creates undesirable and harmful products. In the following chemical equation combustion inputs and outputs are explained clearly.

\[
\text{Hydrocarbon + Fuel + O}_2 + 3.76\text{N}_2 \rightarrow \\
\text{CO}_2 + \text{H}_2\text{O} + 3.76\text{N}_2 + \text{CO, unburned HC, soot, NO}_x + \text{Heat}
\]

According to the above equation, it is notable that N$_2$ is unnecessary in the process, and it can form undesirable compounds (NO$_x$). Also O$_2$ is an input to the process and it combines with both hydrogen and oxygen in order to release heat energy, It cannot be released without their
formation, so that they are called unavoidable. To insure complete combustion even modern equipments with many futures operates in excess air. That is more air carrying 21% O₂ by volume passed through the inlet manifold than the minimum air for complete combustion. Excess air speed up the mixing of fuel and air and ensure complete combustion as possible as can. This process ensure that nearly all fuel molecules receive required oxygen for complete combustion. In addition to the required energy, combustion produce various chemical products in the form of gaseous emissions and release it to the atmosphere, these emissions adversely affect both of humans and environment, their chemical structure and effects are explained in the following table 3.1

**Table 3.1 Emissions from Combustion process and their environmental effects.**

<table>
<thead>
<tr>
<th>Emission</th>
<th>Source</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ (Carbon dioxide)</td>
<td>Complete combustion of carbon fuels</td>
<td>Global warming</td>
</tr>
<tr>
<td>CO (carbon monoxide)</td>
<td>Incomplete combustion of carbon fuels</td>
<td>Smog</td>
</tr>
<tr>
<td>SO₂ ( Sulphur dioxide)</td>
<td>Combustion of sulphur fuels</td>
<td>Smog, acid rain</td>
</tr>
<tr>
<td>NOₓ (nitrogen oxides)</td>
<td>By-Product of most combustion processes</td>
<td>Acid rain</td>
</tr>
<tr>
<td>N₂O(nitrous oxide)</td>
<td>By-Product of most combustion processes</td>
<td>Global warming</td>
</tr>
<tr>
<td>VOCs (Volatile organic compounds)</td>
<td>Leakage and evaporation of liquid fuels</td>
<td>Smog</td>
</tr>
<tr>
<td>CH₄ (methane)</td>
<td>Principle compound of natural gas; leakage from gas wells, pipelines and distribution system.</td>
<td>Global warming</td>
</tr>
<tr>
<td>H₂O (water vapor)</td>
<td>Combustion of hydrogen fuel</td>
<td>Localized fog</td>
</tr>
<tr>
<td>Particulates (dust, soot, fumes)</td>
<td>Unburned of partially burned carbon and hydrocarbons; also ash and dirt in fuels</td>
<td>Smog</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>--------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Trace elements</td>
<td>Impurities in fuel</td>
<td>Potential carcinogens</td>
</tr>
<tr>
<td>Hydrocarbons (HC)</td>
<td>Incomplete combustion of fuels and other carbon containing substances</td>
<td>Acute exposure causes eye, nose and throat irritations; chronic exposure suspected to cancer.</td>
</tr>
</tbody>
</table>

From the table it is notable that carbon can produce two compounds depending on the availability of the air supply and these two compounds are very helpful in analyzing combustion process as the following:

- If enough air is supplied to the fuel during combustion, carbon dioxide (CO$_2$) will appear in the products plus the release of heat, and if the supplied air is exactly theoretical air needed then the exhaust gaseous products consists of 21% carbon dioxide about 78% nitrogen and 1% various gases, plus release of heat.

- When the air supply is not sufficient the carbon partially burnt to carbon monoxide (CO) and the full calorific value of the fuel will not release, this is known as incomplete combustion which is one of the combustion process main sources of heat losses.
3.2.2 Reasons behind incomplete combustion

There are many contributing reasons to why a combustion process becomes incomplete in an actual case. One of the easier reasons to see is that a lack of oxygen leaves some of the fuel unburned. But also incompletion can be associated to insufficient mixing between a fuel and oxygen in the combustion chamber due to short time intervals in which these combustions are occurring. Another cause for incomplete combustion is because of a process called hydrogen bonding. Hydrogen bonding is a process in which chemical bonds form between molecules containing hydrogen atom boned to strongly electronegative atom (an atom that attracts electrons).

Because the electronegative atom pulls the electron from a hydrogen atom, the atoms form a very polar molecule, meaning one end is negatively charged and the other end is positively charged. Hydrogen bonds form between these molecules because the negative ends of the molecules are attracted to the positive ends of the other molecules, vice versa.

3.2.3 Oxygen Enhanced combustion

Oxygen enhanced combustion has become one of the most attracting combustion technologies in the last decades, two developments have increased the significance of it, the first one is a new technology of producing oxygen less expensive and the second one is the increased importance of environmental regulations.

The principle of this technology is to use the air with higher oxygen concentrations in the combustion process as an intake air, this will reduce the volume of unnecessary nitrogen enters the process. Advantages of Oxygen enhanced combustion include numerous environmental benefits as well as improving engine efficiency and power output.
3.2.4 Oxygen element

About 21% of the earth's atmosphere consists of oxygen. The name oxygen means “acid-former” because of its ability to combine with the other elements to form acids. It is a colorless, odorless, tasteless gas at standard temperature and pressure. In its normal uncombined form, it is a diatomic molecule, designated as \( \text{O}_2 \) with a molecular weight of 32.

In contrast with air, gaseous oxygen is slightly heavier. At the atmospheric pressure, oxygen is a liquid below -297.3°F. Liquid oxygen is light blue in color, transparent, odorless, and slightly heavier than water. Oxygen is a strong oxidant, which means that it is nonflammable but that it can greatly accelerate the rate of combustion.

3.2.5 General benefits of using OECT

- Improved Brake power
- Increases SFC
- Increases MEP
- Increases Exhaust gas temperature
- Increases Brake thermal Efficiency
- Increases Combustion Efficiency
- Decreases CO emissions
- Decreases Ignition delay period
- Increases Heat release rate
- Decrease combustion duration
- Reduced combustion noise
- Higher adiabatic flame temperature
- Destruction of availability decreased