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Oxygen Enriched Combustion of High Emission Fuels

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This Thesis was defended successfully on 1- 6 - 2008 and approved by

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Dedication

For my sweet, amazing, loving, funny, wonderful family who make it all possible, and worthwhile.

Mohammed

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الإقرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

Oxygen Enriched Combustion of High Emission Fuels

إحتراق الوقود كثير الانبعاثات باستخدام الهواء الغني بالأكسجين

أقر بأن ما اشتملت عليه هذه الرسالة إنما هي نتاج جهدي الخاص، باستثناء ما تمت الإشارة إليه حيثما ورد، وأن هذه الرسالة ككل، أو أي جزء منها لم يقدم من قبل لنيل أية درجة علمية أو بحث علمي أو بحثي لدى أية مؤسسة تعليمية أو بحثية أخرى.

Declaration

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

Student's name: **اسم الطالب:**

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Oxygen Enriched Combustion of High Emission Fuels

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Abstract

The main purpose of this study is to investigate the effects of using oxygen enriched combustion (OEC) technology with high emission fuels (biodiesel and petro-diesel in different ratios) on an experimental four stroke internal combustion engine (ICE) Volkswagen passat and a water heating boiler. To do so, an experimental setup was prepared for each case. In both cases, the intake air was enriched by injecting pure oxygen to the combustion chamber and ensure appropriate mixing before reaching the flame, the highest oxygen enrichments levels are 24% in ICE and 27% in the boiler. A Bacharach module 300 combustion analyzer was used in order to monitor the required oxygen enriched intake air level and to measure the combustion process emissions.

For internal combustion engine, it has been shown that using higher intake air oxygen concentrations with pure petro-diesel fuel or blended fuel (petro-diesel with biodiesel) increase the exhaust gas temperature obviously, the highest

exhaust temperature improvement was 14%, it has been achieved when using 24% O_2 concentration with pure petro-diesel. Also, it has been shown that biodiesel fuel intensify the combustion process and improve the exhaust gas temperature due to the additional oxygen quantities contained in it, results show that using B15 fuel with ambient intake air oxygen concentration (21% O_2) improves the exhaust temperature 7.4%, this temperature improvement can be assumed as an indicator of the thermal efficiency improvement. However, similar stack gas temperature improvement has been achieved when implementing the same experiments on water heating boiler, 21.1% temperature improvement has been achieved when using 26% O_2 intake air concentration with pure petro-diesel and optimum excess air conditions, this improvement is about 3.8% in terms of efficiency imrpovement.

In addition, using OEC with either the internal combustion engine or the water heating boiler affects the exhaust emissions by increasing or decreasing its quantities. In ICE, NOx emissions increased when using oxygen enriched intake air with blended fuel, but it has been decreased when using either higher intake oxygen concentration or higher biodiesel fuel concentrations. NOx emissions decreased in the water heating boiler case when operating under theoritical excess air level with respect to optimum excess air level due to the reduction in the ballast N_2 entering the process.

Experimental results show that CO emissions decrease by using higher intake air oxygen concentrations with pure petro-diesel in both of the internal combustion engine and water heating boiler, it has been clearly noticed that when operating under theoritical excess air conditions in the boiler case, 77.2% CO emissions reduction have been achieved when using 26% O_2 intake air concentration. In addition, CO exhaust emissions were reduced by using blended fuels (higher biodiesel concentrations) with ambient air oxygen concentration (21% O_2) as a result of the additional oxygen quantities enter the process and improve its completeness. But it has been shown that CO exhaust emissions increase in the internal combustion engine case when using higher intake air oxygen concentration with higher biodiesel fuel concentration at the same time, it happened as a result of CO prompt formation, results show that when using 23% O_2 intake air and B15 fuel, CO emissions increased 150.3% with respect to using 23% O_2 intake air and B0 fuel, but when analyzing the same results with respect to using 21% O_2 concentration with B15 fuel, CO emissions increased 104.5%.

Similarly, SO_2 emissions did not change when using OEC technology or biodiesel fuel in the ICE, but when operating under theoritical excess air conditions in the boiler section, SO_2 emissions were very high and it has been reduced by using oxygen enriched intake air and/or biodiesel fuel.

Chapter One
Combustion Technology

1.1 Combustion

Combustion processes have been and will be the prime generator of energy to our civilization in the near future. It can be defined as a chemical reaction during which a fuel is oxidized and a large quantity of energy is released, in common, the oxidizer in this process is atmospheric air, specifically the oxygen element in the air, which forms 21% of it. In other words, chemical energy is stored in the fuels, and it's released during combustion process in the form of thermal energy. [1]

In general, combustion products take two forms, flue gas and solid refuse, to understand the process sufficiently; it is important first to discuss some basic terms definitions concern combustion, these terms are:

- *Air supply:* air consists of 21% oxygen (O_2) and the rest which is 79% is Nitrogen (N_2), oxygen is the only active element in the air combined with the combustible elements of the fuel to produce heat, the large amount of nitrogen in the air performs no useful role in the burning process, but it cause air pollution problems, especially when the combustion is not controlled properly. [2]
- *Stoichiometric air (theoretical):* is the minimum amount of air needed for complete combustion, or it referred to the chemically correct amount of air or 100% percent theoretical air. If the air quantity is theoretical no O_2 will appear in the exhaust gases.

- *__Stoichiometric combustion (theoretical):__* is the ideal combustion process in which fuel is burned completely. [1]
- *__Conventional fuels:__* consists mainly of two elements hydrogen and carbon (it also consists of oxygen, nitrogen, water, and sulpher), the fuel value lies in the carbon and hydrogen contents and during combustion they combined with the oxygen and produce heat. [2]
- *__Pollutant:__* is the "introduction by man into the environment of substances or energy liable to cause hazards to human health, harm to living resources and ecological system, damage to structures or amenity, or interference with legitimate uses of the environment". [3]

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_2O), but an incomplete process creates undesirable and harmful products. In Figure 1.1, the combustion equation including inputs and outputs are demonstrated clearly.

$$Hydrocarbon\,(HC)\,Fuel + O_2 + 3.76N_2 \longrightarrow$$

$$\underbrace{\boxed{CO_2 + H_2O}}_{\textbf{unavoidable}} + \underbrace{\boxed{3.76N_2}}_{\textbf{unnecessary}} + \underbrace{\boxed{(CO, unburned\ HC, soot, NO_X)}}_{\textbf{undesirable}} + \underbrace{\boxed{Heat}}_{\textbf{needed}}$$

Figure 1.1: Combustion inputs/outputs basic equation.

According to the equation, it is notable that N_2 is unnecessary in the process, and it can form undesirable compounds (NOx). Also, O_2 is an input to the process and it combines with both of hydrogen and carbon in order to release stored energy, it can not be released without their formation, so that they called unavoidable [4]. To insure complete combustion even modern equipments with many features must operate in excess air. That is, more air carrying 21% O_2 by volume is passed through the burner than the chemically required (stoichiometric) for complete combustion. Excess air speeds up the mixing of fuel and air and ensure complete combustion as possible as can.

On one hand this process ensures that nearly all fuel molecules receive required oxygen for complete combustion before it is chilled below combustion temperature by contact with heat exchange surfaces, it also prevent fuel that is not burned completely from exploding within the burner.

Unfortunately, excess air wastes energy by carrying heat up the stack, a fine line exists between combustion efficiency and the safety in ensuring that as little excess air as possible is supplied to the burner.

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 illustrated in Table 1.1.

Table 1.1: Combustion process produced emissions and their environmental effects. [4, 5]

Emission	Source	Effect
CO_2 (carbon dioxide)	Complete combustion of carbon fuels	Global warming
CO (carbon monoxide)	Incomplete combustion of carbon fuels	Smog
SO_2 (sulphur dioxide)	Combustion of sulphur fuels	Smog, acid rain
NO_x (nitrogen oxides)	By-product of most combustion processes	Acid rain
N_2O (nitrous oxide)	By-product of most combustion processes	Global warming
VOCs (volatile organic compounds)	Leakage and evaporation of liquid fuels (eg. from vehicles, fuel tanks, fuel pumps)	Smog
CH_4 (methane)	Principal component of natural gas; leakage from gas wells, pipelines and distribution systems	Global warming
H_2O (water vapor)	Combustion of hydrogen in fuel	Localized fog
Particulates (dust, soot, fumes)	Unburned of partially burned carbon and hydrocarbons; also ash and dirt in fuels)	Smog
Trace elements	Impurities in fuel	Potential carcinogens
Halogenated compounds	Compound of fuel or combustion air containing halogens (chlorine, fluorine, bromine and iodine)	Potential carcinogens, global warming
Hydrocarbons (HC)	Incomplete combustion of fuels and other carbon containing substances	Acute exposure causes eye, nose, and throat irritation; chronic exposure suspected to cause cancer

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 release of heat, and if the supplied air is exactly the theoretical air needed then the exhaust gaseous products consists of 21% carbon dioxide (CO_2), about 78% Nitrogen, and 1% of various gases, plus release of heat. [6-9]
- When the air supply is not sufficient the carbon partially is burnt to carbon monoxide (CO) and the full calorific value of the fuel will not released, this is known as incomplete combustion which is one of the combustion process main sources of heat losses. [6]

1.1.1 Reasons Behind Incomplete Combustion

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

Because the electronegative atom pulls the electron from the 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 other molecules, and vice versa”. [6]

1.2 Oxygen Enhanced Combustion

Oxygen enhanced combustion (OEC) has become one of the most attracting combustion technologies in the last decade, two developments have increased the significance of it, the first one is the new technology of producing oxygen less expensively and the second one is the increased importance of environmental regulations.
The principle of this technology is to use air with higher oxygen concentration 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 energy efficiency and productivity.

1.2.1 Oxygen Element

About 21% of the earth atmosphere consists of oxygen. “The name oxygen means “acid-former” because of its ability to combine with 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 O_2, with a molecular weight of 32".

In contrast with air, gaseous oxygen is slightly heavier. At atmospheric pressure, oxygen is a liquid below –297.3°F (90 K). 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".

Oxygen enriched combustion is used in a wide variety of industrial applications such as metal industry, glass manufacturing, wastewater treatment, and waste incineration. [7]

1.2.2 Oxygen Enriching Methods in Combustion Processes.

There are four commonly used methods to enhance combustion process with oxygen:

1. **Air Enrichment:** In this method the "oxygen is injected into the incoming combustion air supply through a diffuser to ensure adequate mixing", Figure 1.2 describes the process schematically. This method may be referred to as low-level O_2 enrichment or premix enrichment. Many conventional air/fuel burners can be adapted for this technology by making small modifications. "The advantage of this method that it is usually an inexpensive retrofit that can provide substantial benefits. On the other hand, it has a disadvantage; the added O_2 will shorten and

intensify the flame. However, there may be some concerns if too much O_2 is added. The flame shape may become unacceptably short, and the high flame temperature may damage the burner or burner block".

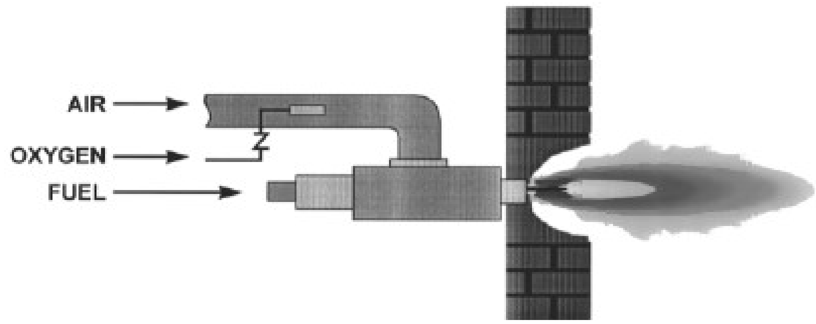


Figure 1.2: Schematic description of air enrichment method.

2. **O_2 Lancing:** in this method the O_2 is injected directly to the flame, Figure 1.3 describes the process schematically; this O_2 injection method is also generally used for lower levels of O_2 enrichment.

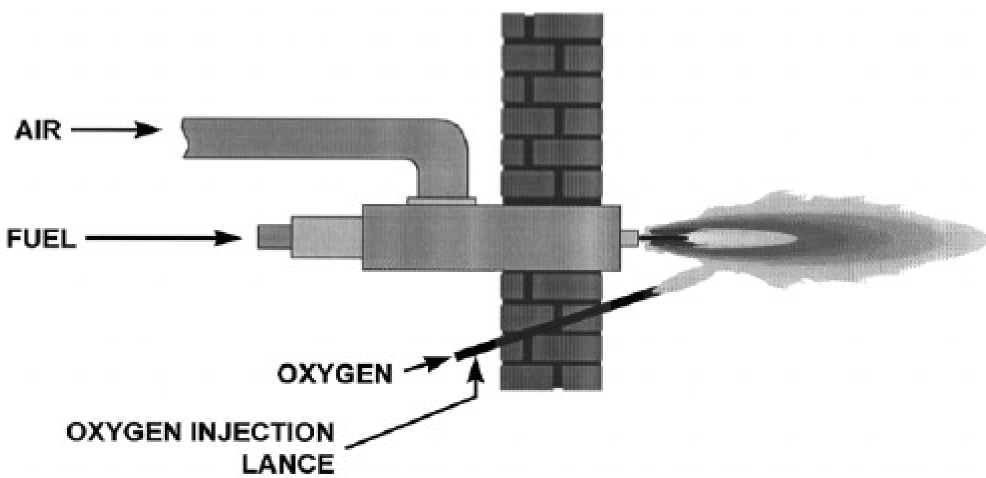


Figure 1.3: Schematic description of O_2 lancing.

However, oxygen lancing may have several advantages over air enrichment. "First, no modifications to the existing air/fuel burner need to be made. Second, the NOx emissions are lower using O_2 lancing compared with premixing since this is a form of staging, which is a well-accepted technique for reducing NOx. Third, Depending on the injection location, the flame shape may be lengthened by staging the combustion reactions which improves the heat transfer efficiency".

3. **Oxy/Fuel:** The third oxygen enrichment method which is mixing O_2 with the fuel supply as described in Figure 1.4, it is commonly referred to as oxy/fuel combustion. In this method, high-purity oxygen (>90% O_2 by volume) is used to combust the fuel and it has the greatest potential for improving a process, but it also may have the highest operating cost.

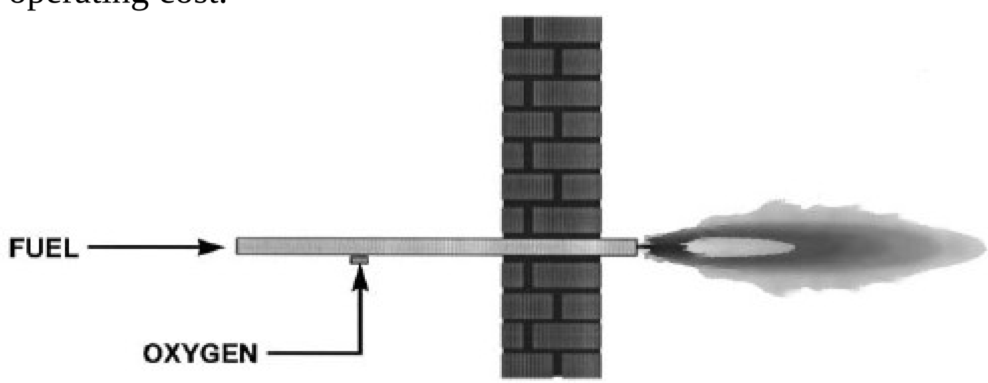


Figure 1.4: Schematic description of Oxy/Fuel.

"One specific variation of oxy/fuel combustion, known as dilute oxygen combustion, is where fuel and oxygen are separately injected into the combustion chamber. In order to ensure ignition, the chamber temperature must be above the auto-ignition temperature of the fuel".

4. **Air–Oxy/Fuel:** The fourth common method of using OEC involves separately injecting air and O_2 through a burner, as shown in Figure 1.5. It is sometimes referred to as an air–oxy/fuel burner.

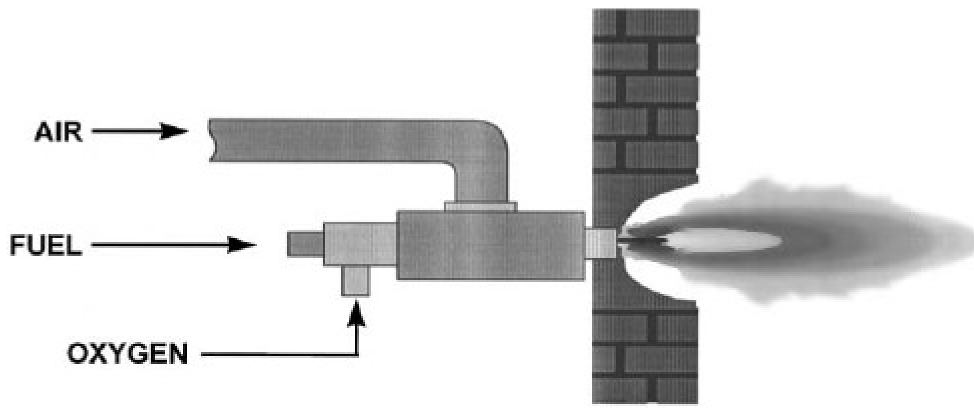


Figure 1.5: Schematic description of air–oxy/fuel.

This is a variation of the first three methods discussed above. "In some cases, an existing air/fuel burner may be easily retrofitted by inserting an oxy/fuel burner through it. In other cases, a specially designed burner may be used. This method of OEC can have several advantages. It can typically use higher levels of O_2 than air enrichment or O_2 lancing, which yields higher benefits. Furthermore, the operating costs are less than for oxy/fuel, which uses very high levels of O_2. The flame shape and heat release pattern may be adjusted by controlling the amount of O_2 used in the process. It is also generally an inexpensive retrofit".

With this method, "the oxidizer composition may be specified in an alternative way. Instead of giving the overall O_2 concentration in the oxidizer, the oxidizer may be given as the fraction of the total oxidizer that is air and the fraction of the total oxidizer that is pure O_2". The equivalent overall O_2 in the oxidizer can be calculated as shown in Equation 1.1:

$$\Omega = \frac{20.9}{0.209\left(\text{vol\% } O_2\right)+\left(\text{vol\% air}\right)} \quad \text{.............................} \quad (1.1)$$

Ω: The amount of O_2 enrichment or the oxygen concentration in the intake air.

This conversion in the previous equation is graphically shown in Figure 1.6. For example, the oxidizer may be specified as a blend of 60% O_2 and 40% air. That ratio of O_2 to air produces an equivalent of 39.8% overall O_2 in the oxidizer.

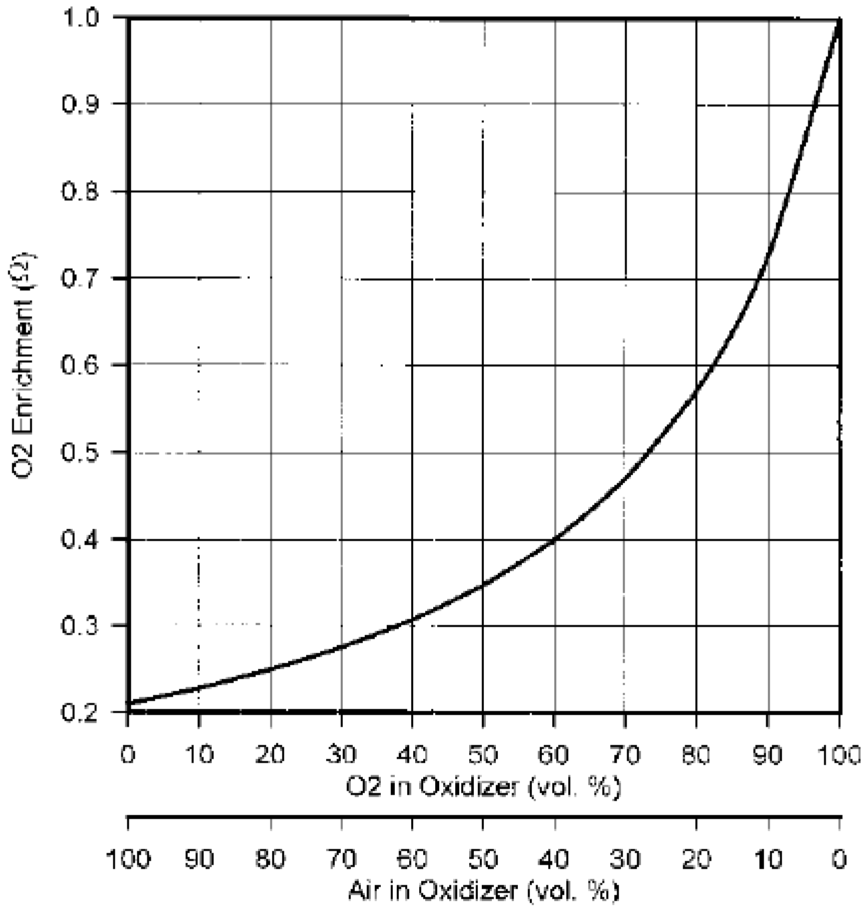


Figure (1.6): Oxidizer compositions for blending air with pure oxygen. [7]

1.2.3 Operating Regimes

Depending on the oxygen enrichment levels, there are three common operating regimes for OEC:

1. The low level Enrichment ($\Omega < 0.30$): it is usually used when only incremental benefits are required and it needs a few of modifications to the existing combustion equipment. For example, in many cases the production rate in a heating process can be significantly increased even with only relatively small amounts of oxygen enrichment.

In most cases, air/fuel burners can successfully operate up to about Ω = 0.28 with no modifications. For $\Omega > 0.28$, the flame may become unstable or the flame temperature may become too high for a burner designed to operate under air/fuel conditions.

2. The medium level enrichment ($0.30 < \Omega < 0.90$): Again, these usually require specially designed burners or retrofits of existing burners.
3. The high level enrichment ($\Omega > 0.90$): this regime is used in higher-temperature applications where the benefits of higher-purity oxygen justify the added costs. [7]

1.2.4 General Benefits of Using OEC

As mentioned before, air consists of approximately 78% N_2, 21% O_2, and 1% various other gases by volume. Taking into consideration that only the oxygen is needed in the combustion reaction, and by eliminating N_2, many benefits can be realized. These benefits include increase available heat, improve ignition characteristics, flue gas reduction, increase productivity, energy efficiency, turndown ratio, and flame stability, with reduction in exhaust gas volume and pollutant emissions. [7-9]

Here is the explanation for each main benefit:

1. **Available Heat:** the term available heat can be defined as the gross heating value of the fuel less the energy carried out of the combustion

process by the hot exhaust gases (N_2 in air acts as a ballast that carries energy out with the exhaust), OEC technology proved to be a useful method to increase the available heat value, or in other words to reduce fuel consumption. [7]

2. **Ignition Characteristics:** using OEC technology also has its effect on the ignition characteristics; it increases the flammability limits and flame speeds, and it decreases ignition energy and ignition temperature.
3. **Flue Gas:** the size of the exhaust gas ductwork can be reduced. And as a result it can increase the efficiency of the existing flue gas treatment equipment, the size of the post treatment equipment can be proportionally reduced, it also saves space, energy, materials, and money. In addition, lower gas velocities entrain fewer fine particles from the waste. This reduces particulate emissions.
4. **Increase Productivity:** The higher temperatures associated with OEC increase the radiation from the flame, which improves the heat transfer rate, and leads to increase material processing rates through the combustion chamber. Experience shows that OEC can increase the production rate in industrial furnaces from 10% to 30%. [7, 9]
5. **Higher Thermal Efficiencies:** by using higher oxygen concentrations in combustion, “more energy goes into the load, instead of being wasted in heating up N_2. The energy needed to separate O_2 from air is only a small fraction of the energy used in the combustion process”.

Therefore, the overall process uses less energy for a given amount of production due to the higher available heat. OEC can cut energy consumption 30% to 50%. [9]

6. **Improve Flame Characteristics:** by using OEC technology, the flame characteristics and stability is improved.
7. **Flame-Shape Control:** OEC can be used to control the shape of a flame for an existing air/fuel system. For example, premix enrichment of oxygen into a combustion air stream has been used to shorten the flame length. Undershot enrichment can be used to lengthen a flame. Controlling the flame shape may be done to avoid overheating the refractory in a given location or to change the heat flux and temperature profile within the combustion chamber.
8. **Increased Flexibility:** oxygen enriched combustion may be required if very high melting temperatures are required. For example, "some ceramic and refractory products require firing temperatures of 2900°F (1900 K) and higher. Those temperatures are difficult if not impossible to achieve with standard air/fuel combustion with no air preheating. A heating system may also be brought up to operating conditions more quickly with OEC compared with air/fuel systems because of the higher heating intensity". [7]

1.2.5 Potential Problems of Using OEC

If the system is not properly designed, it will cause potential problems. Many of them can be generally attributed to the increased combustion intensity, these problems are:

1. **Refractory Damage:** OEC can cause refractory damage due to improper system design, this damage comes as a result of:
   - ***Overheating:*** Oxygen-enhanced flames generally have significantly higher flame temperatures compared with conventional air/fuel flames. If the heat is not properly distributed, the intensified radiant output from the flame can cause refractory damage.
   - ***Corrosion:*** It is another potential refractory problem can result from the increased volatile concentration in the combustion chamber by using OEC, especially in glass industry. By removing the large quantity of diluent N_2, the volatile species are concentrated in the gas space. This can cause damage to the refractory by corrosion.
2. **Non-uniform Heating:** It is an important concern when retrofitting existing systems that were originally designed for air/fuel combustion. By intensifying the combustion process with OEC, there is the possibility of adversely affecting the heat and mass transfer characteristics within the combustion chamber, the common two related problems are:

- ***Hot Spots:*** OEC normally increases the radiant heat flux from the flame to the load. If the increased radiant output is strongly localized, then there is the possibility of producing hot spots on the load.
- ***Reduction in Convection:*** the total volume flow rate of exhaust products is significantly reduced using OEC. However, the average gas temperature is usually higher, but not by enough to offset the reduced gas flow rate.

  The convective heat transfer from the exhaust gases to the load may be reduced as a result.

3. **Flame Disturbance:** OEC causes flame disturbance. It can be eliminated by the proper choice of burners and their operating conditions.
4. **Increase Pollutant Emissions:** using OEC technology may increase the pollutant emissions such as NOx which increased due to high flame temperature that increases NOx thermal formation.
5. **Noise:** the flame velocity increases with OEC compared with air/fuel combustion. This means that the gas velocities exiting the burner must be increased to compensate for the higher flame speed. These higher gas velocities can increase the jet noise of the burner. Also, although the gas velocities were high, the total volume flow rate was much lower by removing N_2 from the oxidizer, which also was a mitigating factor for the noise.

6. **Flashback:** The use of OEC intensifies the combustion reactions. One consequence of this higher reactivity is the increased risk of flashback. Flashback occurs when the gas velocity exiting the burner is less than the flame velocity.

1.2.6 Industrial Heating Applications

OEC is used in a wide range of industrial heating applications. In general, OEC has been used in high-temperature heating and melting processes that are either very inefficient or not possible with air/fuel combustion. These applications are categorized as metals, minerals, incineration, and other.

1. **Metals:** OEC has been widely used in steel mills, and in the production of nonferrous metals such as aluminum, brass, copper, and lead.
2. **Minerals:** such as glass, cement, lime, bricks, ceramics, and other related materials that require high-temperature heating and melting during their manufacture.
3. **Incineration:** Incinerators are designed to burn and destroy solid, liquid, and gas waste materials which may sometimes be contaminated with hazardous substances. “The most common examples of incinerators are municipal waste incinerators, sludge incinerators, mobile incinerators which are used to clean up contaminated soil and water at superfund sites, and transportable incinerators which are also used at superfund clean up sites”.

4. **Other:** OEC has been used in a wide variety of specialty applications. Some of these include gasifying organic materials and vitrifying residual ash, removing unburned carbon from fly ash, and oxygen enrichment of fluid catalytic crackers. [7]

1.3 Pollutant Emissions

OEC technology affects the pollutant emissions significantly. As will be shown, pollutant emissions may either increase or decrease depending on the level of OEC used in a given combustion process, each of these pollutants and how it affected by OEC is discussed below.

1.3.1 NOx Emissions

NOx refers to oxides of nitrogen. These generally include nitrogen monoxide, also known as nitric oxide (NO), and nitrogen dioxide (NO_2). “They may also include nitrous oxide, also known as laughing gas (N_2O), as well as other, less common combinations of nitrogen and oxygen, such as nitrogen tetroxide (N_2O_4). In most high-temperature heating applications, the majority of the NOx exiting the exhaust stack is in the form of NO”.

NO is a human poisonous colorless gas that rapidly combines with O_2 in the atmosphere to form NO_2. “NO can cause irritation of the eyes and throat, tightness of the chest, nausea, headache, and gradual loss of strength.

Prolonged exposure to NO can cause violent coughing, difficulty in breathing, and cyanosis, and could be fatal.

NO_2 is a reddish brown gas which has a suffocating odor. It is highly toxic and hazardous because of its ability to cause delayed chemical pneumonitis and pulmonary edema. NO_2 vapors are a strong irritant to the pulmonary tract. Inhalation may also cause irritation of the eyes and throat, tightness of the chest, headache, nausea, and gradual loss of strength. Severe symptoms may be delayed and include cyanosis, increased difficulty in breathing, irregular respiration, lassitude, and possible death due to pulmonary edema. Chronic or repeated exposure to NO_2 could cause a permanent decrease in pulmonary function".

In addition to the poisoning effect that NOx has on humans, there are also environmental problems associated with these chemicals. "In the lower atmosphere, NO reacts with oxygen to form ozone (O_3) which is also a health hazard that can cause respiratory problems in humans. NO_2 decomposes on contact with water to produce nitrous acid (HNO_2) and nitric acid (HNO_3), which are highly corrosive". When NO_2 forms in the atmosphere and comes in contact with rain, acid rain is produced, which is destructive to whatever it comes in contact with. Besides acid rain, another problem with NO_2 is its contribution to smog. To sum up, NOx emissions are among the primary air pollutants because of their contribution to smog formation, acid rain, and ozone depletion in the upper atmosphere. [7]

Oxy/fuel combustion is a recognized method for reducing NOx emissions under carefully controlled conditions. As an example, OEC has been successfully used in the glass industry to reduce NOx emissions from 70 to 95%.

1.3.1.1 Theories behind NOx Generation

There are three generally accepted mechanisms for NOx production: thermal, prompt, and fuel.

- Thermal NOx is formed by the high-temperature reaction of nitrogen with oxygen. It is given by the simplified reaction:

  $$N_2 + O_2 \rightarrow NO, NO_2$$

- Prompt NOx is formed by the relatively fast reaction between nitrogen, oxygen, and hydrocarbon radicals. In methane as an example, it is given by the overall reaction:

  $$CH_4 + O_2 + N_2 \rightarrow NO, NO_2, CO_2, H_2O, \text{trace species}$$

  Prompt NOx is generally an important mechanism at lower-temperature combustion processes.

- Fuel NOx is formed by the direct oxidation of organo-nitrogen compounds contained in the fuel. It is given by the overall reaction:

  $$R_xN + O_2 \rightarrow NO, NO_2, CO_2, H_2O, \text{trace species}$$

  Fuel NOx is not a concern for high-quality gaseous fuels like natural gas or propane, which normally have no organically bound nitrogen.

However, fuel NOx may be important when oil, coal, or waste fuels that may contain significant amounts of organically bound nitrogen are used. [7]

1.3.2 Combustibles

Combustibles can be divided into two main categories. The first is the incomplete combustion of the fuel, which usually produces carbon monoxide and the second type of combustible is volatile organic compounds (VOCs), which are generally only important in a limited number of processes, typically involving contaminated or otherwise hazardous waste streams.

1. **CO and unburned fuel:** CO is generally produced due to incomplete combustion. "It is flammable, nonirritating, colorless, odorless, tasteless, and normally noncorrosive gas. CO is highly toxic to humans and acts as a chemical asphyxiant by combining with hemoglobin in the blood, which transports oxygen inside the body. The affinity of carbon monoxide for hemoglobin is approximately 300 times more than the affinity of oxygen for hemoglobin. CO preferentially combines with hemoglobin to the exclusion of oxygen so that the body becomes starved for oxygen which can eventually lead to asphyxiation". Therefore, CO is regulated pollutant. It is generally produced by the incomplete combustion of a carbon-containing fuel. Normally, a combustion system is operated under excess air conditions to ensure

complete combustion and to minimize CO emissions. OEC generally reduces CO emissions compared with air/fuel systems, due to more-complete combustion.

Although operating under sufficient excess air conditions ensure solving the problem, but using high levels of oxygen enrichment causes thermal dissociation, where CO is thermodynamically preferred to CO_2 at high temperatures, this is not usually a problem in most industrial heating processes because the temperatures of actual oxy/fuel flames are generally much less than the adiabatic flame temperature. If sufficient O_2 is available, CO_2 is thermodynamically preferred at those lower temperatures, instead of CO.

2. **Volatile Organic Compounds:** Typical VOCs include benzene, acetone, acetaldehyde, chloroform, toluene, methanol, and formaldehyde. These compounds are typically considered to be regulated pollutants, if they released into the atmosphere they cause photochemical smog and ozone depletion. They are not normally produced in the combustion process, but they may be contained in the material that is being heated, such as in waste incinerators.

   “VOC emissions expected to decrease by using OEC because of the higher flame temperatures, lower dilution, and increased residence time within the combustor”.

1.3.3 Particulates

There are two primary sources of particulates which may be carried out through a combustion process with the exhaust gases. One is entrainment and carryover of incoming raw materials and the other is the production of particles as a result of the combustion process.

1. **Particle Entrainment:** The gas flow through the combustor may contain particles from the raw materials used in the process. This is often referred to as carryover. The gas flow within the furnace is generally high enough that some of the batch may be entrained into the gas flow and carried out the exhaust stack (this process is defined as carryover process) where it must then be removed before the gases exit to the atmosphere.

   OEC can dramatically reduce the carryover in a process originally designed for air/fuel combustion because of the reduction in the average gas velocity through the combustor that results from removing some or all of the diluent nitrogen from the system, this process is illustrated in Figure 1.7.

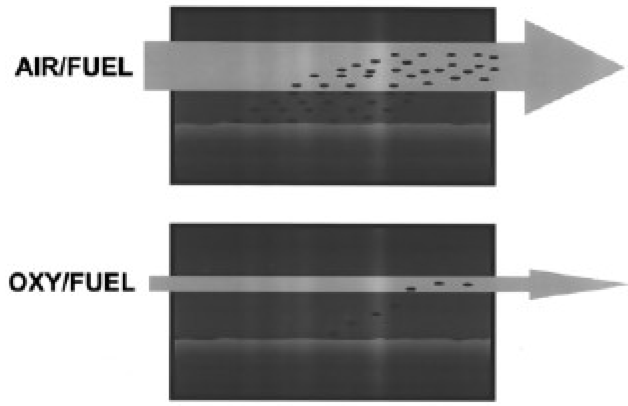


Figure (1.7): Particle entrainment comparison between a furnace using air/fuel and a furnace using oxy/fuel.

2. **Combustion-Generated Particles:** The second method that particles may be emitted from the combustion system is through the production of particles in the combustion process. For example, in the combustion of solid fuels, like coal, for example, ash is normally produced. The airborne portion of the ash, usually referred to as fly ash, may be carried out of the combustor by the exhaust gases. The use of OEC should reduce fly ash emissions because of more-complete combustion of the fuel compared with an air/fuel system.

   Another source of combustion-generated particles is soot, which may be produced in a flame, even for gaseous fuels, under certain conditions. Fuels that have a higher ratio of carbon to hydrogen mass tend to produce more soot than fuels with a lower ratio.

Flames containing more soot are more luminous and tend to release their heat more efficiently than flames containing less soot, which tend to be nonluminous.

The use of OEC generally reduces the likelihood of emitting soot into the exhaust products because of the intensified combustion and higher flame temperatures compared with air/fuel systems. Soot carryover into the exhaust has not been identified as a problem for OEC. [7]

1.3.4 Carbon Dioxide (CO_2) Emissions

“CO_2 is a colorless, odorless, inert gas which does not support life since it can displace oxygen and act as an asphyxiant. CO_2 is found naturally in the atmosphere at concentrations averaging 0.03% or 300 ppmv. Concentrations of 3 to 6% can cause headaches, dyspnea, and perspiration. Concentrations of 6 to 10% can cause headaches, tremors, visual disturbance, and unconsciousness. Concentrations above 10% can cause unconsciousness eventually leading to death”.

CO_2 emissions are produced when a fuel containing carbon is combusted near or above stoichiometric conditions. Studies indicate that CO_2 is a greenhouse gas that contributes to global warming.

1.3.5 SOx Emissions

Sulfur oxides, usually referred to as SOx, include SO, S_2O, S_nO, SO_2, SO_3, and SO_4 of which SO_2 and SO_3 are of particular importance in combustion processes. SO_2 tends to be preferred at higher temperatures, while SO_3 is preferred at lower temperatures.

“Since most combustion processes are at high temperatures, SO_2 is the predominant form of SOx emitted from systems containing sulfur. Sulfur dioxide (SO_2) is a colorless gas with a pungent odor which is used in a variety of chemical processes”. [7]

Sulfur dioxide can be very corrosive in the presence of water. SO_2 is considered to be a pollutant because of the choking effect it can cause on the human respiratory system, as well as the damage that it can do to green plants which are more sensitive to SO_2 than people and animals. It can produce acid rain when it is released into the atmosphere by combining with water to produce sulfuric acid (H_2SO_4) which is very corrosive and can cause considerable damage to the environment [7]. “Recently, the reduction in sulfur content has become strongly restricted. In Europe, it is not allowed to exceed 50 ppm, and by the year 2009 it will not be allowed to exceed 10 ppm”. [10]

It is often assumed that any sulfur in a combustor will be converted to SO_2 which is then carried out with the exhaust gases. The sulfur may come from the fuel or from the raw materials used in the production process. [7]

1.4 Oxygen Generation Technology

Oxygen generation technology is a vital process in implementing OEC, the generator should be appropriate by its capacity and cost in order to ensure feasible results. As mentioned before, atmospheric air contains 21% of oxygen, and in order to increase its concentration we have either to separate Nitrogen and get rid of it, or to separate oxygen and use it in enriching combustion air. Membranes technology is the used one for this purpose.

A precise and complete definition of a membrane which covers all its aspects is rather difficult, even when the discussion is limited to synthetic structures. In the most general sense, “a synthetic membrane is a barrier which separates two phases and restricts the transport of various chemical species in a rather specific manner. A membrane can be homogeneous or heterogeneous, symmetric or asymmetric in structure; it may be solid or liquid; it may be neutral, may carry positive or negative charges, or may be bipolar. Its thickness may vary between less than 100 nm to more than a centimeter. The electrical resistance may vary from several mega ohms to a fraction of an ohm, Mass transport through a membrane may be caused by convection or by diffusion of individual molecules, induced by an electric field, or a concentration, pressure or temperature gradient”.

The term “membrane”, therefore, includes a great variety of materials and structures, and a membrane can often be better described in terms of what it does rather than what it is. Some materials, though not meant to be membranes, show typical membrane properties, and in fact are membranes, e.g., protective coatings, or packaging materials. All materials functioning as membranes have one characteristic property in common: they restrict the passage of various chemical species in a very specific manner. [11]

1.4.1 Gas Separation Membranes

Organic polymers are the dominating materials for gas separation membranes. Many polymers exhibit as a sufficient gas selectivity and they can be easily processed into membranes. Palladium alloys are the only inorganic materials which are currently used for gas separation (ultra-pure hydrogen generation) on a commercial scale. However, during the last decade inorganic materials have been developed with exciting unmatched selectivity for certain gas mixtures and some of the inorganic membranes described in the scientific literature seem to be on the brink of commercialization.

Gas separation membranes has enormous applications, these applications and membranes suppliers are illustrated in Table 1.2

Table (1.2): Membranes applications and suppliers. [12]

Gas separation	Application	Suppliers
O_2/N_2	Nitrogen generation, oxygen enrichment	A/G Technology Permea (Air Products) Generon (Messer) IMS (Praxair) Medal (DuPont, Air Liquide) Aquilo (Parker Hannifin) Ube
H_2/Hydrocarbons	Refinery hydrogen, recovery	Air Products Air Liquide Praxair
H_2/CO	Syngas ratio adjustment	as above
H_2/N_2	Ammonia purge gas	as above
CO_2/Hydrocarbon	Acid gas treating, enhanced oil recovery, landfill gas upgrading	Kvaerner (Grace Membrane System) Air Products Ube
H_2S/Hydrocarbon	Sour gas treating	as above
H_2O/Hydrocarbon	Natural gas dehydration	Kvaerner Air Products
H_2O/Air	Air dehydration	Air Products Ube
Hydrocarbons/Air	Pollution control, hydrocarbon recovery	MTR, GMT, NKK
Hydrocarbons from process streams	Organic solvent recovery, monomer recovery	MTR, GMT, SIHI

There are various materials which is used in producing organic and inorganic membranes, a number of these materials are illustrated in the Table 1.3.

Table (1.3): Used materials for producing gas separation membranes [12]

Organic polymers	Inorganic materials
Polysulfone, polyethersulfone	Carbon molecular sieves
Celluloseacetate	Nanoporous carbon
Polyimide, polyetherimide	Zeolites
Polycarbonate (brominated)	Ultramicroporous amorphous silicia
Polyphenyleneoxide	Palladium alloys
Polymethylpentene	Mixed conducting perovskites
Polydimethylsiloxane	
Polyvinyltrimethylsilane	

1.4.2 Oxygen Enriched Air

As explained before, "increasing the oxygen content of air brings advantages in any combustion process where inert nitrogen has a ballast effect. The benefit is achievable even at only low level enrichment. For example, air with oxygen enriched from 21% to only 30% – an enrichment of only 9% – will contain nearly 40% less nitrogen per unit oxygen" as shown in Figure 1.8 which illustrates the effect of oxygen enrichment on the nitrogen concentration. [13]

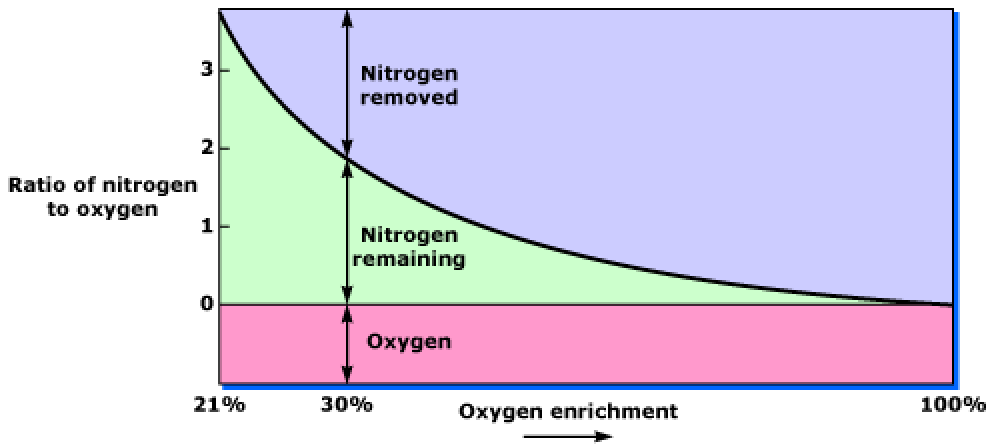


Figure (1.8): Oxygen enriched air – nitrogen to oxygen ratio. [13]

Various approaches for using membranes to separate oxygen from air have been investigated. All rely on selectively permeating oxygen and rejecting nitrogen. Because of the fact that air already contains 80% nitrogen and because nitrogen remains on the residue side of the membrane, producing essentially pure nitrogen is comparatively easy in comparison with producing pure oxygen. It is more difficult because some nitrogen always permeates with the oxygen, resulting in oxygen enriched air rather than pure oxygen. The process was developed to the early commercial stage in the 1980s using silicone rubber and ethyl cellulose membranes, but the performance of these membranes was not good enough to make the process competitive with other technologies. A simplified flow schematic of a membrane separation process for producing oxygen-enriched air is shown in Figure 1.9. Feed air containing 21% oxygen is passed across the surface of a membrane that preferentially permeates oxygen. In the schematic shown, the pressure difference across the membrane required to drive the process is maintained by drawing a vacuum on the permeate gas. The alternative is to compress the feed gas, but a few trial calculations show that this is never likely to be economical because of the quantity of electric power consumed.

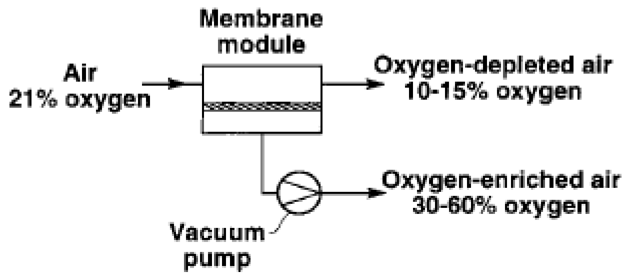


Figure (1.9): One stage membrane separation process. [14]

All of the feed air must be compressed, but only a small portion permeates the membrane as oxygen-enriched product. The power consumption of a vacuum pump on the permeate side of the membrane is one-half that of a feed compressor, because the only gas that needs to pass through the pump is the oxygen-enriched product. However, because the pressure difference across the membrane is less than 1 atm, vacuum operation requires a larger membrane area to produce the same flow of product gas. To make this operating mode economical, high-flux membranes and low-cost membrane modules are required.

"Depending on the properties of the membrane and the pressure difference, a permeate gas containing (30-60) % oxygen is produced. Oxygen-enriched air can be used in a number of processes". "Pure oxygen can be produced by adding a second separation stage, as shown in Figure 1.10. Because the volume of gas sent to the second-stage separator is one third to one-quarter of the volume entering the first stage unit and because the gas is more concentrated, the second stage will be much smaller and lower-cost on air. This second separation stage could be a vacuum swing adsorption system for small plants producing less than 200 tons / day of oxygen or a cryogenic fractionation system for plants producing more than 200 tons / day of oxygen". [14]

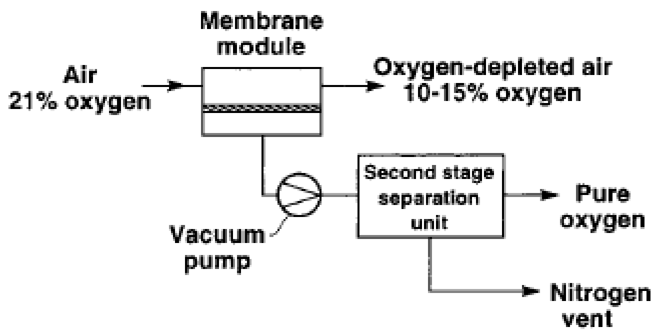


Figure (1.10): Two stage separation process. [14]

Recently, many membrane manufacturing parties developed and commercialized low cost micro-membranes. For example, Panasonic produces micro oxygen enrichment membranes with different capacities and sizes; these membranes are used in oxygen concentrators, air conditioner with oxygen supply function, establishing home comfort and healthy spaces, and the most important issue that it is currently used in automotive appliances as air conditioner oxygen concentrators. A number of these oxygen membranes specifications are illustrated in Table 1.4. [15]

Table 1.4: Commercial micro oxygen separation membranes specifications. [15]

Specifications	Module 1	Module 2	Module 3	Module 4	Module 5	Module 6
Dimension (mm)	130*180*9	130*183*14	130*183*19	130*182*24	130*183*29	130*183*34
Weight (g)	125	180	230	280	330	380
Oxygen enrichment	30%	30%	30%	30%	30%	30%
Flow (liter/min.)	1	2	3	4	4.2	5
Working temp. (^{o}C)	-20 to 60	-20 to 60	-20 to 60	-20 to 60	-20 to 60	-20 to 60

Another example, Ube Company has successfully developed and produced micro membrane which can be used to enrich oxygen up to 28% in the air. "Many benefits achieved by these micro-membranes such as, these units are totally self-contained, operate continuously, require no tanks, and avoided dangerously high oxygen concentrations". An example of these Ube micro membranes is shown in Figure 1.11. [13]

Figure (1.11): Ube Industries and MTR commercialized low-cost micro-membrane module. [13]

For their feasibility usage, there are a number of micro oxygen membranes that can enrich between 5 to 15 liter per minute of oxygen up to 90% purity with low prices, most of these membranes are available at prices under US$ 900. [16]

Chapter Two
High Emission Fuels

High emission fuels can be defined as fuels which have the potential to adversely affect both of human's health and environment because of its high levels of exhaust emissions. Exhaust emissions has been regulated in most of world countries, each country or group of countries has its own standards. In this research, two types of these high emission fuels will be discussed, these two types are diesel fuel and biodiesel fuel:

2.1 Diesel Fuel

Diesel fuel is a specific fractional distillate of fuel oil (mostly petroleum) that is used as fuel in different applications such as diesel engines and boilers. It is produced from petroleum, and is sometimes called petro-diesel when there is a need to distinguish it from diesel obtained from other sources such as biodiesel. It is a hydrocarbon mixture, obtained in the fractional distillation of crude oil between 200 °C and 350 °C at atmospheric pressure.

"The density of diesel fuel is about 850 g/L whereas gasoline fuel has a density of about 720 g/L, about 15% less. When burnt, diesel typically releases about 40.9 MJ/L, whereas gasoline releases 34.8 MJ/L, about 15% less. Diesel is generally simpler to refine than gasoline and often costs less. Also, due to its high level of pollutants, such as its higher quantities of sulfur, diesel fuel must undergo additional filtration which contributes to a sometimes higher cost". [17]

“Diesel engine exhaust emissions which are commonly known as 'diesel fumes' have the potential to cause a range of health problems. They are a mixture of gases, vapors, liquid aerosols and substances made up of particles. They contain the products of combustion including:

1. carbon (soot);
2. nitrogen;
3. water;
4. carbon monoxide;
5. aldehydes;
6. nitrogen dioxide;
7. sulphur dioxide;
8. polycyclic aromatic hydrocarbons.

The carbon particle or soot content varies from 60% to 80% depending on the fuel used and the type of engine. There are some factors affecting the quantity and composition of diesel fumes such as:

1. The quality of diesel fuel used;
2. The type of engine;
3. The fuel pump setting;
4. The workload demand on the engine;
5. The engine temperature;
6. The state of the engine tuning: whether the engine has been regularly maintained”. [18]

2.1.1 Effects of Diesel Fumes on Human Health and Environment

“Breathing in diesel fumes can adversely affect human health; short term exposure can cause irritation of the eyes or respiratory tract. These effects are generally short term and should disappear when the affected person are away from the source of fumes.

However, prolonged exposure to diesel fumes, in particular to any blue or black smoke, could lead to coughing, chestiness and breathlessness”. [18]

In the long term, there is some evidence that repeated exposure to diesel fumes over a period of about 20 years may increase the risk of lung cancer [18, 19]. Also, diesel fumes can adversely affect the environment with serious and harmful problems such as ozone formation, acid rain, and global climate changes. [19]

2.2 Biodiesel Fuel

Biodiesel is a renewable clean burning alternative fuel which made from vegetable oils, waste frying oils, and animal fats. In general, biodiesel flash point is above 149 ^{o}C. It is free from sulfur and aromatic compounds and does not overburden the environment with CO_2 emission as CO_2 from the atmosphere is absorbed by the vegetable oil crop during the photosynthesis process, while the plant is growing. Hence biodiesel offers net CO_2 advantage over conventional fuels [20-22]. It is used in compression ignition (diesel) engines with little or no modifications, such as, cars, buses, trucks, construction equipment, boats, generators, and oil home heating units. Biodiesel is usually made from soy or canola oil, animal fat, and can also be made from recycled fryer oil. It is simple to use, nontoxic, and essentially free of sulfur and aromatics. In application, systems can run using biodiesel or blended fuel contains both of biodiesel and petro-diesel. [23-25, 27]

“Automotive fuels are delivered in petrol stations by volume, and their price is correspondingly established per unit volume. However, it is not the volume but the energy which moves vehicles. Both volume and energy are related through fuel density and its heating value, or in summary, through the heating value in energy basis (MJ/L). It should be kept in mind that biodiesel has around 9% less heating value in volume than conventional diesel fuel. Thus, if engine efficiency is the same, engine fuel consumption should be proportionally higher, and consequently vehicle autonomy proportionally lowers, when using biodiesel”. [10]

Operating systems with biodiesel have many advantages, such as:

1. National security. Since biodiesel is made domestically, biodiesel reduces dependence on foreign oil.
2. Economical Benefits: using biodiesel keeps reducing fuels importing budgets. The saved money can be invested in other national development fields.
3. It's sustainable & non-toxic.

4. Environmental benefits: using biodiesel in a conventional diesel engine results substantial reduction of unburned hydrocarbons, carbon monoxide, carbon dioxide, it means that biodiesel can contribute in decreasing greenhouse effects [22-26], and particulate matter.
5. Biodiesel has high cetane rating which contributes in improving engine performance.
6. Biodiesel improves engine lubricating due to its higher viscosity that extends engine life.
7. Biodiesel is biodegradable and nontoxic so it has less bad effects on soil. [27]
8. Engine life. Studies have shown biodiesel reduces engine wear by as much as one half, primarily because biodiesel provides excellent lubricity. Even a 2% biodiesel and 98% diesel blend will help.
9. Biodiesel just runs quieter, and produces less smoke.
10. Biodiesel industry will generate a huge number of employment opportunities in the fields of agriculture, production, and distribution, so that it can contribute in solving unemployment problems.

Unfortunately, there is no perfect fuel. Biodiesel has many disadvantages such as:

1. Biodiesel is not available for all nations; it needs a large area of lands to produce its raw material.

2. Old vehicles (older than mid-90s) might require upgrades of fuel lines (a cheap, easy upgrade), as biodiesel can eat through certain types of rubber. Almost all new vehicles should have no problem with biodiesel.
3. NOx emissions increase when using biodiesel, it happened as a result that biodiesel contains higher oxygen level about 10 wt.% of oxygen and thus can be considered a kind of oxygenated fuel. The high oxygen content in biodiesel results in the improvement of its burning efficiency, reduction of CO and other gaseous pollutants, but at the same time produces larger NOx formation, particularly under a high temperature burning environment. It is estimated that the burning of neat biodiesel would produce about 10%-13% more NOx than that of petroleum-based diesel, primarily due to the high oxygen content of the neat biodiesel. NOx contributes to smog. It found that a slight increase (up to 15%) in NOx is greatly offset by the reduction in all other emissions and the major reduction in greenhouse gasses. [10, 20-25]
4. Biodiesel cost is higher than petro-diesel due to the high cost of its feed stock
5. It has higher viscosity and higher cloud point than petro-diesel; as a result it becomes less useful in low temperature applications. [27]

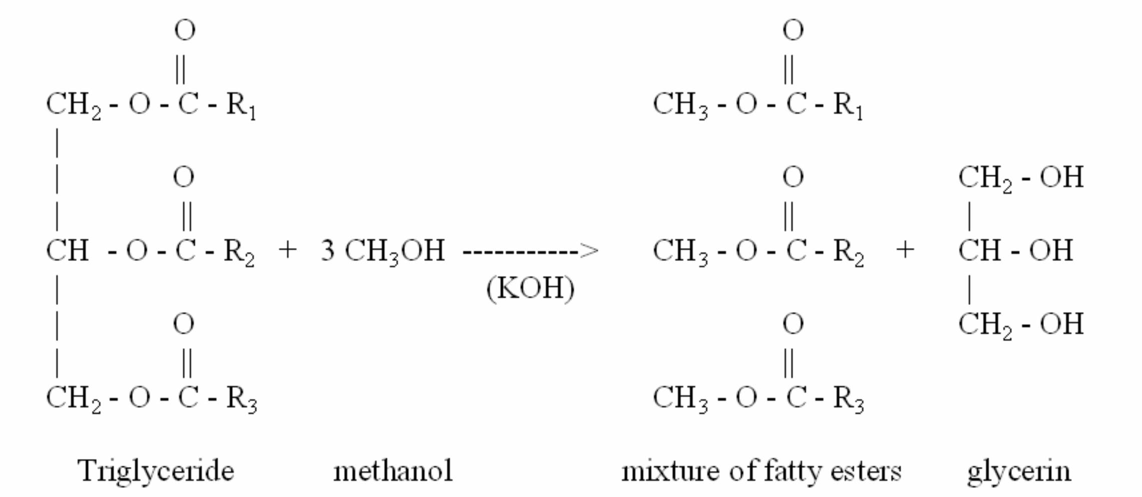
2.2.1 Biodiesel Production Method

Biodiesel production process goes through a number of main station, these stations are:

A. Biodiesel feedstock: it means choosing the source of triglycerides to be used in biodiesel production such as vegetable oils, animal triglycerides, waste yellow grease or technical fat.
B. Adding chemical agents: methanol or ethanol is added.
C. Catalysts: pretreating the high free fatty acid feedstock by adding sodium methoxide. [27]
D. Transesterification: this step is the main step of the biodiesel production process, whereby the glycerin is separated from the fat or vegetable oil. The process leaves behind two products -- methyl esters (the chemical name for biodiesel) and glycerin (a valuable byproduct usually sold to be used in soaps and other products) [25]. There are three kinds of catalysts that can be used in transesterification reaction, a strong alkaline catalyst, a strong acid, and an enzyme. The main advantages of using a strong alkali as a catalyst are shorter reaction time and less amount of catalyst required in the manufacturing process of the transesterification reaction. Therefore, a strong alkaline catalyst is widely used in the industry for mass biodiesel production. [23]
E. Product separation.

F. Product purification: by removing the excess methanol, unreacted triglycerides, glycerine, and caustic catalyst. [27]

Biodiesel production process can simply be described by the following equation



According to the equation the glycerin is separated from triglyceride product such as vegetable oils and animal fats by using methanol, this process produce mixture of fatty acids which is the biodiesel and glycerin.

2.2.2 Biodiesel Challenges

Although biodiesel fuel is one of the most promising future alternative, until now it has some challenges that should be overcome, these challenges are:

- Cold Weather Operation (Chemistry)
- The ability to produce enough quantities of biodiesel to substitute large portions of petro-diesel consumption. In order to do so, it needs team

work effort from both the scientists and economists, scientists should work on improving the production process, by which it can produce more biodiesel quantities in lower costs and efforts, and economists should work on making proper analysis to encourage investors to invest more money in this field.

- Biodiesel engine emissions, and to overcome this challenge engine manufacturing facilities should work to improve their engines in order to produce environmentally products. [20]

Chapter Three
Combustion Systems

3.1 Boilers Technology

A boiler is a closed vessel in which water or other fluid is heated under pressure. The steam or hot fluid is then circulated out of the boiler for use in various process or heating applications. A safety valve is required to prevent over pressurization and possible explosion of a boiler.

Construction of boilers is mainly limited to copper, steel, cast iron, and brass. Sources of heat for the boiler can be the combustion of fuels such as wood, coal, oil or natural gas. [28]

3.1.1 Conservation of Energy and Boiler Efficiency

One of the laws of physics is that energy is always conserved, and so that in combustion, it's conserved too, chemical energy is converted to thermal energy and nothing is lost, for instance, if we added up the energy in the hot water or steam, the energy in the flue gas, the energy radiated from the boiler, and all other form of energy leaving the boiler they will exactly equal the energy in the coal, oil, or gas burned on.

In a simple formula it would look like

(coal, oil, or gas) energy = steam energy or hot water + heat losses energy

Boiler efficiency can be simply defined as the percentage (or ratio) of the coal, oil, or gas energy which is converted to hot water or steam energy.

In a simple formulas it looks like

$$\text{Boiler efficiency} = 100\% - \text{heat losses } \%$$

$$\text{Boiler efficiency} = (\text{output useful energy} / \text{fuel actual input energy}) * 100\%$$

Since most boilers are between (65-85) % efficient, there should be ways to reduce the resulting (15-35) % waste energy. To better understand these ways, it is necessary first to understand how the losses generated, and to take into consideration that some of this waste energy is unavoidable, but some of it can be recovered. [5, 29]

3.1.2 Sources of Heat Losses

The main sources of heat losses in boilers are:

1. **Flue Gas Losses:** it is the heat losses which goes up the chimney with exhaust air, it can be considered as the biggest energy loss in a conventional fossil fuel fired boilers, the losses could amount to as much as (30-35) % of the fuel input in the worst cases. These flue gas heat losses consist of heat loss due to dry gasses, heat loss due to the moisture in the fuel, and heat loss due to water from the combustion of hydrogen [29], and

it depend mainly on the amount of excess air and flue gas temperature. as the following:

- **Excess Air:** boiler should always be supplied with more combustion air than theoretically required in order to ensure complete combustion. However, to achieve as high thermal efficiency as possible the excess air ratio shall be kept at a minimum or the lowest practical level, in practice, around (15-25) % excess air will be necessary. The amount of excess air depends on type of fuel used, type of boiler used, method of operation and effectiveness of combustion equipment. The amount of excess air is also depend on load of the boiler, at low loads excess air increases and efficiency goes down.
- **Flue Gas Temperature:** the flue gas temperature should be held at minimum to get the highest boiler efficiency. The main reasons behind high flue gas temperature are cleanliness of heat transfer surfaces on flue gas side**,** cleanliness of heat transfer surfaces on water side, and insufficient heat transfer surface.

2. **Incomplete Combustion:** If the burning process is complete, the combustion products will consist of flue gases, solid refuse, and higher quantities of carbon monoxide (CO). And carbon dioxide (CO_2) will appear in lower quantities in the flue gases because it is a result of complete combustion. So that, it is important to find optimum operating point for the boiler. The principle of the relation between O_2 and CO is shown in Figure 3.1:

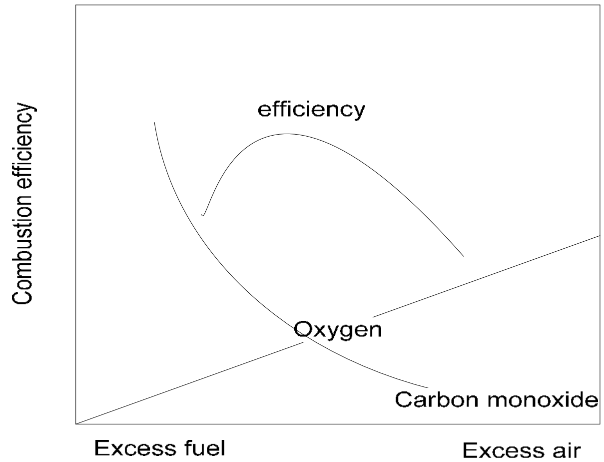


Figure (3.1): Excess air effect on combustion efficiency

If the mix is bad for combustion some hydrocarbons may appear in the flue gases, this fuel element are in a gaseous state and represent a loss in efficiency.

3. **Losses in the Bottom and Fly Ash:** Solid refuse may be in the form of fly ash to the stock or ash collected in the boiler ash hopper and on the heat transfer surfaces. The refuse consists of the ash in the fuel, but some times there is also a small amount of carbon.

   It is important to take these losses into consideration when using solid fuels as they might account several percentage points. It is also important to estimate the unburned amount of materials in the ash.

   The losses in the ashes also depend upon the temperature of the ashes. If the amount of ashes is big it is important to take these losses into consideration. In really bad cases these losses might be as high as several percents.

4. **Radiation and Convection Losses:** it refers to heat losses from the external surface of the operating boiler due to convection and conduction, theses losses are usually very small (1-2)% of the maximum heat capacity for modern boilers, however, it can be much higher, up to 10% for old boilers with poor insulation.

   Calculating these losses is difficult, and therefore they are commonly included as a percentage in the unaccountable losses.

   Since boiler body surface area is constant, then he radiation and convection losses are constant during firing and do not depend on the boiler load, this mean that when the boiler is run at low load the radiation and convection losses represent a higher proportion of the total fuel used than at high load.

   To reduce these losses the insulation of the boiler should reduce the surface temperature to around 30 ^{o}C above the ambient temperature. [2]

5. **Feed Water Losses:** the feed water characteristics can adversely affect boiler efficiency especially in steam generating boilers. Boiler water problems generally fall into two classes which are deposits related and corrosion related. The most common deposit problems is boiler scale, this happens when calcium, magnesium, and silica which is common found in most water supplies, react with metal tube found in the boilers to form a hard scale on the interior surface of the boiler tubes, it reduces heat transfer and lowers boilers efficiency, If it is treated; it properly can increase the efficiency of the boiler as well as extended the boiler life. [29]

3.1.3 Measures to Improve Boiler Efficiency

There are different methods to reduce losses and increase boilers efficiency, most of them are effective and easy to apply, these methods are:

1. **Control Systems:** As mentioned even modern boiler operates under excess air conditions, if excess air level is not properly controlled, efficiency will be decreased, but efficiency can be increased and boiler life can be extended if oxygen regulated in a proper way.

   It is necessary to know that controlling excess air is the most important tool for managing the efficiency improvement and atmospheric emissions of boiler system. As a general rule of thumb 1% reduction in excess O_2 level will reduce fuel consumption by 1%.

2. **Cleaning Equipment in the Flue Gas Side:** Except for natural gas, practically every fuel leaves a certain amount of deposit on the fireside of the tubes. This is called fouling, and it reduces heat transfer dramatically. Tests show that a soot layer just 0.8 mm (0.03 in.) thick reduces heat transfer by 9.5 percent and a 4.5 mm (0.18 in.) layer by 69%. As a result, the flue gas temperature rises – as does the energy cost.

   Boilers that burn solid fuels (such as coal and biomass) have a high fouling tendency, and which burn liquid fuels (particularly refined oils) have a low fouling tendency. Maintaining the boiler at peak efficiency requires keeping the boiler surfaces as clean as possible. Figure 3.2 shows the fuel losses due to scales deposits

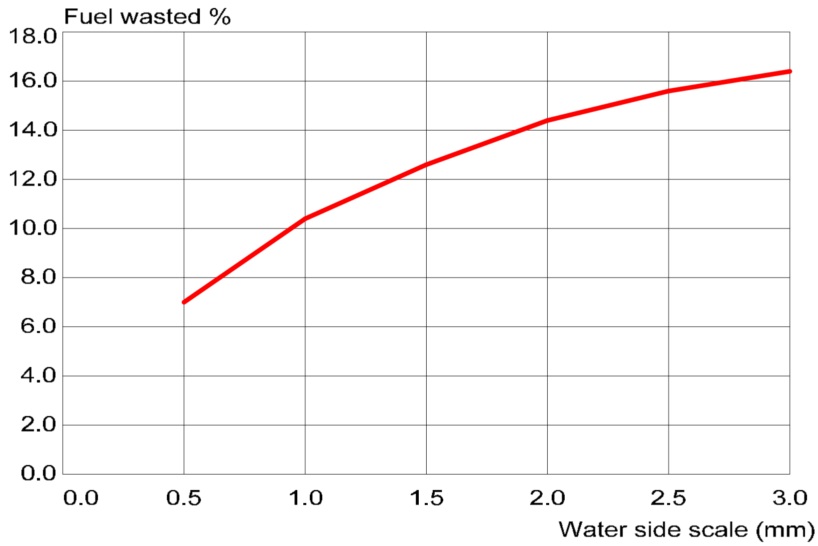


Figure (3.2): Fuel losses due to scales deposits [2]

3. **Combustion Air-Preheat:** one of the most common increasing boilers efficiency methods is by preheating combustion air. There are few heat sources for the air combustion preheating and it is as follows:
   - Heat from the flue gas.
   - Taking the combustion air from the top of the boiler house.
   - Taking the combustion air over or though the boiler casing to reduce shell (surface) losses.

The boiler efficiency will be improved only if the boiler exhaust heat is used to preheat the combustion air, if any other sources of heat be used this will save the fuel consumption in the boiler but will not improve boiler efficiency.

In general the efficiency will increase by approximately 1% if the combustion air temperature is increased by 25^{o}C using exhausted heat from the boiler; energy saving for intake air pre-heating can be seen in figure 3.3:

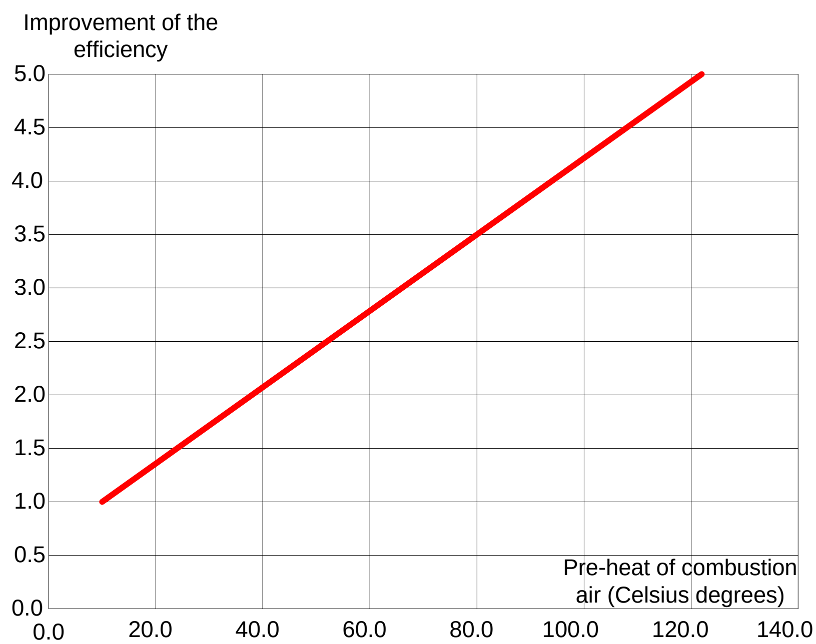


Figure (3.3): Combustion air pre-heating efficiency improvement

4. **Feed Water Pre-Heating:** boiler efficiency can be improved by pre-heating the feed water in an economizer using the flue gas temperature losses; in general, an increase in feed water temperature of 6 ^{o}C will reduce fuel consumption by 1% and improve efficiency. Figure 3.4 shows the relation between the pre-heating water temperature and the boiler efficiency:

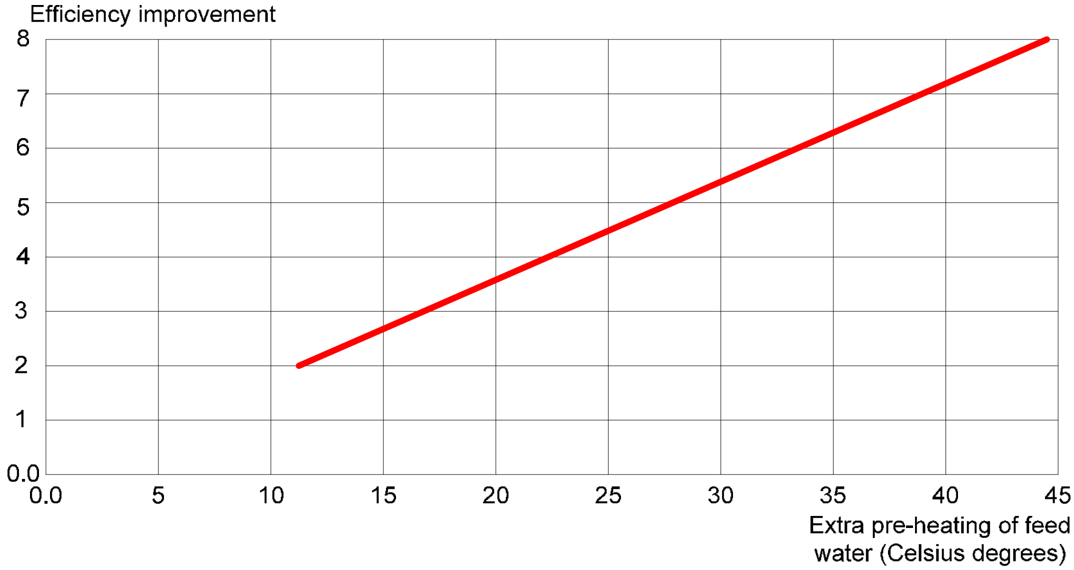


Figure (3.4): Feed water pre-heating efficiency improvement

5. **Blow-Down:** it is necessary to blow down steam boilers regularly. The reason for this regularly action that the concentration of solids in the boiler water increases due to the fact that the solids mainly remain in the water instead of leaving the boiler with the steam. To control the level of concentration of solids in the boiler a certain volume of water is drawn of and replaced by (pure) feed water. As the drawn of water is hot this means an energy lost. The energy in the blow-down should preferably be recovered by using heat exchangers.

   To have the most efficient operation of the boiler it is important that the amount of blow down is kept to a minimum level while maintaining the recommended level of solids. Any thing in excess is a waste of energy.

6. **Feed Water Treatment:** feed water treatment program is needed especially for the steam boiler, the reasons for this treatment are:

- To prevent the formation of hard scale in the boiler.
- To prevent the formation of other deposits in the surrounding equipments such as economizers.
- To control the amount of sludge in the boiler.
- To reduce or eliminate the corrosion in the boiler due to dissolved oxygen in the feed water. [2]

3.2 Internal Combustion Engines Technology

The purpose of internal combustion engines (ICE) is to produce mechanical power from the chemical energy contained in the fuel, it happens as a result of exothermic reaction which creates gases at high temperature and pressure, these gases are permitted to expand and perform work by moving mechanical components in the engine (piston, rotor,…etc). The fuel-air mixture before combustion and the burned products after combustion are the actual working fluids. As distinct from external combustion engines, the energy is released as a result of burning or oxidizing the fuel inside the engine. [30, 31]

The most common modern fuels for ICE are made up of hydrocarbons and are derived from mostly petroleum. These include the fuels known as diesel, gasoline, petroleum gas, propane gas. Liquid and gaseous bio-fuels such as Ethanol and biodiesel, and some can also run on Hydrogen gas. [30]

ICE has various applications; such as automobile, trucks, locomotive, marine, power generation, and other portable machinery. [30, 31]

3.2.1 Internal Combustion Engines Classifications

ICEs have many different types, these types can be classified according to the differences between them, and they can be classified according to:

1. Application: like if we are talking about transportation equipment like automobiles, or we are talking about power generation equipment.

2. Basic engine design: for example if the system is reciprocating or rotary.

3. Operating cycle: for example if the engine four or two stroke cycles, and in this field of experiment we need to concentrate on four stroke engines.

4. Fuel type: like if the engine works by using diesel, gasoline, natural gas ...etc.

5. Method of ignition: if its spark ignition system or compression ignition system.

6. Combustion chamber design: there are many chamber designs IEC can be classified by, such as open chamber and divided chamber.

7. Method of cooling: such as water cooled, air cooled, or natural convection and radiation. [31]

This research was performed using compression ignition four stroke engine. Thus, this type of engines will be described in details in the next section.

3.2.2 Main Parts of Four Stroke ICEs

For a four-stroke engine, key parts of the engine include the crankshaft, one or more camshafts and valves. There are one or more cylinders and for each cylinder there is a spark plug, a piston and a crank. “A single sweep of the cylinder by the piston in an upward or downward motion is known as a stroke. The downward stroke that occurs directly after the air/fuel mix passes from the carburetor to the cylinder where it is ignited is known as a power stroke. Figure 3.5 shows an illustration of several key components in a typical four-stroke engine”. [30, 31]

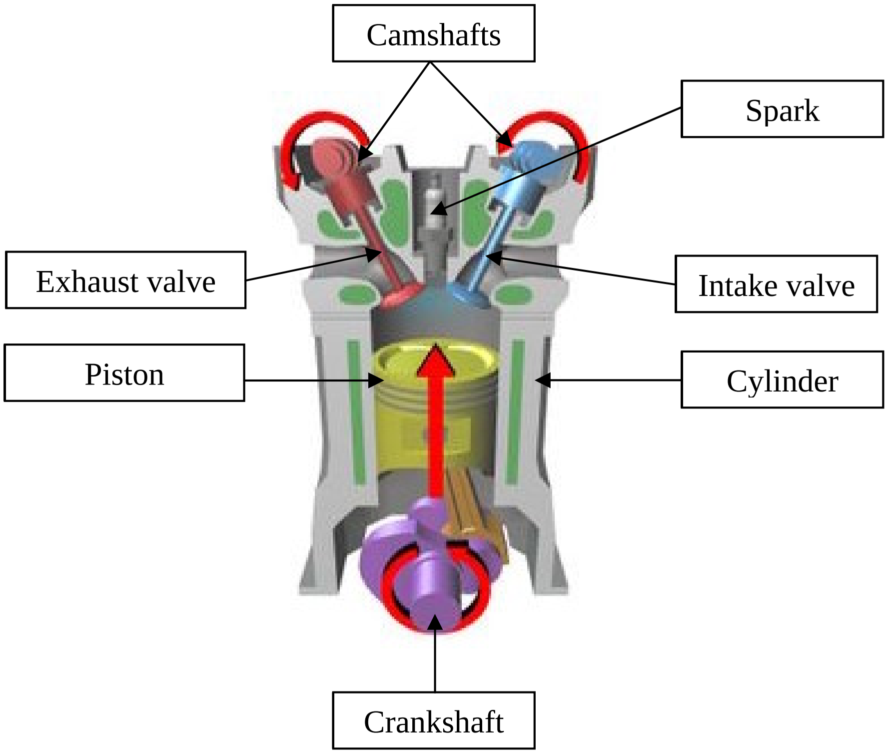


Figure (3.5): Key components in a typical four stroke engine. [30]

3.2.3 Ignition Systems

All internal combustion engines must achieve ignition in their cylinders to create combustion. Typically engines use either a spark ignition (SI) system or a compression ignition (CI) system. In the past other methods using hot tubes or flames have been used.

- Spark ignition system (SI): the most common example of this system is gasoline engines. The SI engine is a piston engine with homogeneous external or internal formation and externally generated ignition. In the compression stroke the homogeneous air fuel mixture is compressed to 20-30 bar to generate a final compression temperature of 400-500 ^{o}C.

This is still below the mixture auto-ignition temperature, which is then ignited using electrical spark.

- Compression ignition system (CI): the most common example of this system is diesel engine; “it varies from SI system that in during compression stroke, intake air is compressed to 30-55 bar, so its temperature increases to 700-900 ^{o}C. This temperature is sufficient to induce auto-ignition in the fuel injected into the cylinders shortly before the end of the compression stroke. It means that this system does not need electrical spark to ignite fuel air mixture, but most diesel engines also have battery and charging systems, however this system is secondary and is added by manufacturers as luxury for ease of starting, turning fuel on and off (which can also be done via a switch or mechanical apparatus), and for running auxiliary electrical components and accessories. Most old engines, however, rely on electrical systems that also control the combustion process to increase efficiency and reduce emissions”. [30, 32]

3.2.4 Operating System

Engines based on the four-stroke cycle have one power stroke for every four strokes (up-down-up-down) and are used in cars, larger boats and many light aircraft. Most truck and automotive diesel engines use a four-stroke cycle with a compression heating ignition system. It is called the diesel cycle.

The Four steps involved in this cycle are:

1. Intake stroke - Air and vaporised fuel are drawn in.
2. Compression stroke - Fuel vapor and air are compressed and ignited.
3. Combustion (power) stroke - Fuel combusts and piston is pushed downwards.
4. Exhaust stroke - Exhaust is driven out. [30, 33]

3.2.5 Engine Efficiency

The efficiency of various types of internal combustion engines varies obviously; it depends on the application for which the engine was designed. One of the major reasons for the losses is mechanical friction between moving parts. “ICEs have a typical mechanical efficiency of about 20-25%. The efficiency may be as high as 37% at the optimum operating point in engines. Most internal combustion engines waste about 36% of the energy as heat lost to the cooling system, and another 38% through the exhaust. The rest, about 6%, is lost to friction and the typical internal combustion engine remains only about 20-25% efficient”. [30, 34]

3.2.6 Engine pollution

Generally internal combustion engines produce moderately high pollution levels, due to incomplete combustion of carbonaceous fuel, leading to carbon monoxide and some soot along with oxides of nitrogen & sulfur and some un-burnt hydrocarbons depending on the operating conditions and the fuel/air ratio. The primary causes of this are the need to operate near the stoichiometric ratio for petrol engines in order to achieve combustion (the fuel would burn more completely in excess air) and the "quench" of the flame by the relatively cool cylinder walls.

Diesel engines produce a wide range of pollutants including many small particles that are believed to penetrate deeply into human lungs such as:

- Many fuels contain sulfur leading to sulfur oxides (SOx) in the exhaust, promoting acid rain.
- Diesel engines operate with an excess air ratio 1.5–1.8 on full load and higher values at lower loads. The high flame temperature of combustion with the existence of abundant oxygen and nitrogen creates greater proportions of nitrogen oxides (NOx), demonstrated to be hazardous to both plant and animal health. [22, 30]
- Net carbon dioxide production is not a necessary feature of engines, but since most engines are run from fossil fuels this usually occurs. If engines are run from biomass, then no net carbon dioxide is produced as the growing plants absorb as much or more carbon dioxide while growing.
- When air is used as the oxidizer nitrogen oxides (NOx) are produced. [30]

3.2.7 Diesel Engine Emissions

The composition of diesel internal combustion engines varies depending on the engine load. In general, it can be defined with two main limits; these limits are the idle state and the maximum output limits, Table 3.1 shows the main automotive diesel internal combustion engine emissions and their values on both of the idle and maximum output case.

Table (3.1): Automotive internal combustion engines emissions. [32]

Exhaust gas components	At idle	At maximum output
Nitrous Oxides (NOx) ppm	50-250	600-2500
Hydrocarbons (HC) ppm	50-500	150
Carbon Monoxide (CO) ppm	100-450	350-2000
Carbon Dioxide (CO_2) Vol.%	3, 5	12-16
Water vapor (Vol.%)	2-4	11
Oxygen (Vol.%)	18	2-20
Nitrogen (Vol.%)	Residual	Residual
Soot (mg/m^3)	20	200
Exhaust gas temperature (^oC)	100-200	550-750

Chapter Four
Experimental Work

The experimental work was divided into two parts; the first one was conducted on a four stroke compression internal combustion engine, while the second one was conducted on a water heating boiler. In both parts, oxygen concentration was increased by using pure oxygen cylinder, and both of petro diesel and biodiesel were used in different portions as a combustion fuel.

4.1 Internal Combustion Engine

In the first part of experimental work, oxygen enriched combustion (OEC) technology was implemented on four stroke diesel internal combustion engine; the engine is Volkswagen Passat type. The engine photo is shown in Figures 4.1.a and 4.1.b.

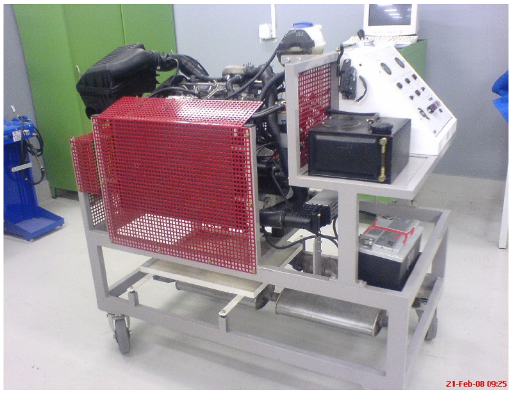


Figure (4.1.a): Volkswagen Passat 4 stroke compression ignition engine.

Figure (4.1.b): Volkswagen passat 4 stroke compression ignition engine.

For experimental purposes, this engine is provided with special simulation software which is designed to measure a group of operating variables such as motor speed (RPM), fuel consumption, motor temperature…etc; engine specifications are illustrated in Table 4.1.

Table (4.1): Experimental engine and software specifications

Number of cylinders	4/OHC
Capacity	1896 CC
Compression ratio	19.5:1
Injection pump assembly	Bosch
Pump type	Rotary
Injection sequence	1-3-4-2
Injection nozzle	Bosch
Nozzle opening pressure-new/used	190-200/170
Leak rate (dribble)	150/10 bar/sec.
Simulation software	Herman DiGIS-applications © AVL DiTEST V2.2

The objective of this experiment is to analyze the effects of using higher intake air oxygen concentrations on internal combustion engines using high emission fuels such as diesel and biodiesel. A “Bacharach” module 300 combustion analyzer was used to analyze the exhaust gases, the analyzer can measure the concentration of CO, CO_2, O_2, NOx, SO_2, Temperature,…etc. The combustion analyzer and its specifications are shown in Figure 4.2 and Table 4.2.

Figure (4.2): Bacharach module 300 combustion analyzer

Table (4.2): Bacharach module 300 combustion analyzer specifications

Manufacturer	Bacharach
Model	300
Size	45.7 x 35.6 x 20.3 cm Standard Probe: 29.2 cm Hose: 6.7 m
Weight	6.8 kg
Materials	HDPE Case, medium gray; polycarbonate membrane switch; stainless steel probe
Calibration Interval	60 seconds
Storage Environment	–20 to 50°C, 0 to 100% relative humidity
Operating Environment	0 to 40°C, 0 to 99% relative humidity, non-condensing
Sample Gas Flow	0.7 to 1.5 liters/min
Power source	Either 120 VAC, 240 VAC, or internal battery pack per sales order
Directly measures and displays	• Stack Temperature (up to [1093°C]) • Carbon Monoxide level: (0–3700 ppm over [0– 40°C]) • Oxygen level (0.1 to at least 23.5%) • Oxygen Sensor output in millivolts • NOX level (0-1999 ppm) (NSX units) • SO_2 level (0-1999 ppm) (NSX units)

As mentioned before, the fuel which used in this experiment was a mixture of biodiesel and petro-diesel with different ratios. The biodiesel was produced using waste cooking oil in An-Najah National University Chemical Engineering laboratories by another group. In all experiments, the biodiesel portions did not exceed 15% from total fuel volume in order to protect the engine, because 20% and above biodiesel concentrations needs special engine modifications [34], the blended fuel can be denoted by symbols such as Bx, where x is biodiesel portion. For example B5 means a mixture of 95% petro diesel and 5% biodiesel by volume.

For intake air, low levels of oxygen enrichment were used; it did not exceed 24% of the intake air in order to protect the engine, higher oxygen enrichment levels need special engine modifications because of the expected higher output temperature which is expected to be produced [7]. The intake air oxygen concentration was increased by injecting pure oxygen from a cylinder directly to the mixing chamber. The experimental setup of this part is shown in Figure 4.3.

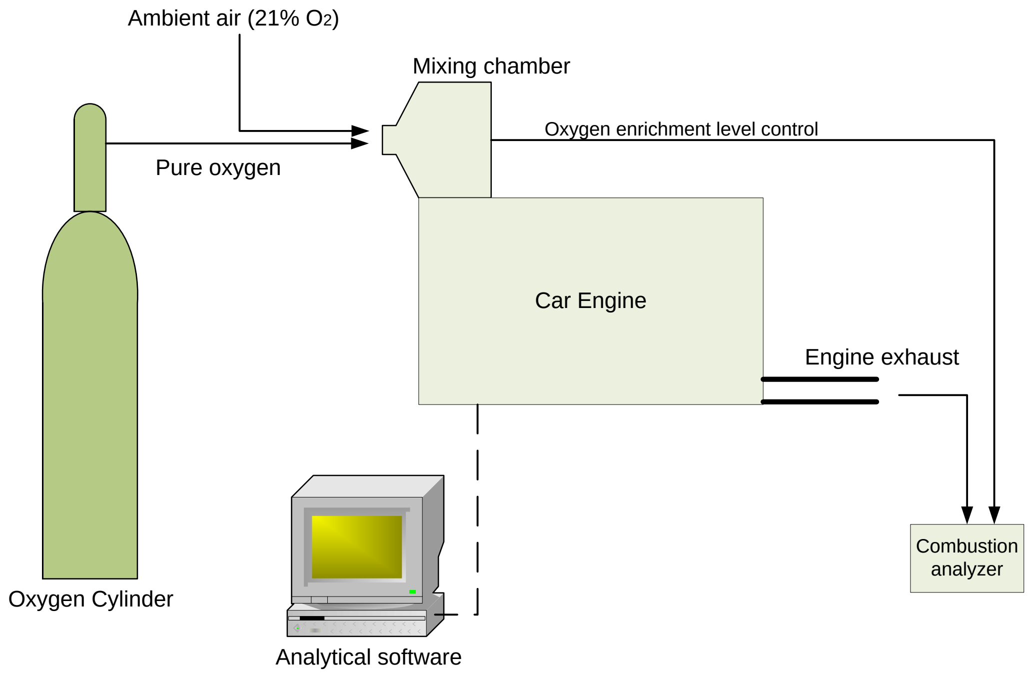


Figure (4.3): Oxygen enriched combustion with internal combustion engine experimental setup.

To ensure effective oxygen enrichment, the pure oxygen was injected directly through the mixing chamber in its inlet, and the intake air oxygen concentration was measured using the combustion analyzer at the last point that we can reach before the combustion chamber, in this way, we can ensure that the mixing process done efficiently.

Also, the data measurements were taken after 30 seconds on inserting the analyzer probe into the exhaust emissions to ensure data measurements stability.

To sum up, there are two main variables in this experimental part; these variables are the biodiesel to petro-diesel ratio, and the concentration of oxygen in intake air.

4.2 Water Heating Boiler

In this part of the experimental work, OEC was implemented with water heating boiler. Oxygen enrichment levels were controlled by injecting pure O_2 through intake air nozzle after ensuring complete closure to all of the boiler intake air body holes, the combustion analyzer was used to help in controlling the required level of oxygen concentration and in measuring exhaust gas emissions. The experimental boiler specifications are illustrated in Table 4.3.

Table (4.3): Experimental water heating boiler specifications.

Manufacturer	FERROLI
Type	LO70
Power (kW)	30 – 60
Fuel consumption (kg / hour)	2.5 – 5.1
Electric alimentation (V/50 Гц)	230 V 1N ac
Engine (kW)	0.1
Electric capacity (kW)	0.4
Weight (kg)	12
Regulation	TN

The boiler has a monitoring thermo-sensor which is designed to turn it off when reaching the required temperature. This monitoring sensor creates an obstacle in experimental work which is turning off the boiler in a short time which is not enough to monitor the oxygen concentration or measure the exhaust emissions. To overcome this obstacle, a constant continuous flow stream of water was fed to the boiler. In this way the water temperature does not elevate to the turn off temperature, so that the water temperature (heat transfer ratio) remains constant and prevents the sensor from turning the boiler off.

The boiler experimental setup is illustrated in Figure 4.4.

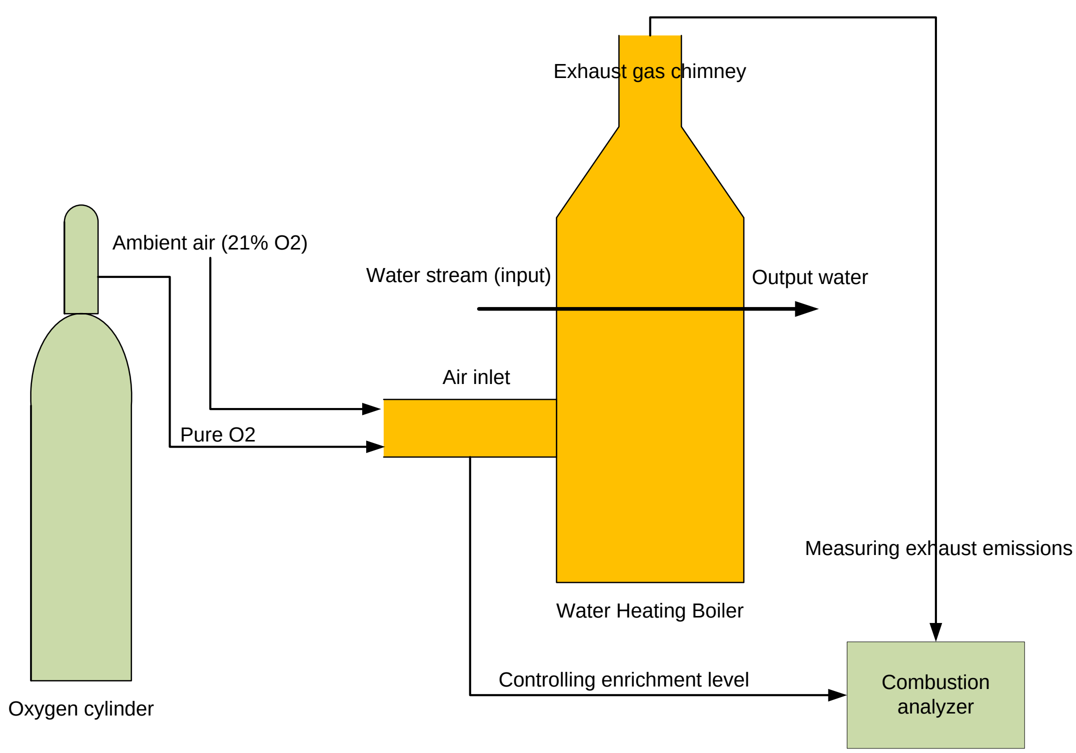


Figure (4.4): Oxygen enriched combustion with water heating boiler experimental setup.

Like the ICE part, two high emission fuels were used in different concentrations; these fuels are petro-diesel and biodiesel, and for oxygen concentrations in the inlet combustion air, it was varied from 21% to 27%, no higher oxygen concentrations were used, because higher concentrations need special modifications to the boiler to prevent any damage from the higher output temperature which is expected to be produced [7]. In contrast with ICE part, two levels of excess air were used; the first one is the optimum excess air level (19%) while the second one is the theoretical excess air level (1%) (This excess air level is the minimum level that can be measured using the combustion analyzer, so that the excess air was controlled until reaching this level and no more control was implemented to ensure the experiment accuracy).

However, all of the experimental results for both the internal combustion engine and the water heating boiler are given in appendices A and B.

Chapter Five

Results and Discussion for Internal Combustion Engine

The experimental results were measured by using both the combustion analyzer and the motor analytical software; the results were recorded after one minute of inserting the combustion analyzer probe into exhaust stack emissions to ensure stability and steady measurements. Efficiency and CO_2 concentrations were not measured using the analyzer due to the high O_2 concentration in the emissions; usually such analyzers are not capable of such measurements when the O_2 concentration exceeds 15%. However, additional variables were measured using the engine software such as fuel temperature and engine speed (RPM).

In this experimental work, three levels of oxygen enrichment were used; these levels are 21% O_2 which is the ideal air composition, 22% O_2, and 23% O_2.

In the preliminary experiments, 24% O_2 concentration was used, it was noticed that there is no need to use O_2 enrichment higher than 23%, because no significant effects were observed in comparison with 23% O_2 concentration. As a result, only three percent of oxygen concentrations were used (21%, 22%, and 23% O_2).

The main variables in this experiment are petro-diesel to biodiesel ratio and oxygen concentration in the intake air.

5.1 Effect of biodiesel and oxygen concentration on exhaust gas temperature

The exhaust gas temperature can be assumed as an indicator of combustion efficiency, generally, under the same operating conditions, the higher output temperature means the higher combustion efficiency. The effect of biodiesel and oxygen concentration on the temperature of the exhaust gas was investigated using two analytical methods.

The first one is analyzing results of output temperature when using different biodiesel concentrations at the same oxygen concentration level, it is clearly shown that using higher biodiesel portions produces higher output temperature; it happens as a result of the fact that biodiesel is an oxygenated fuel and contains about 10% of its weight as oxygen which improves the combustion efficiency [23]. These results are shown in Figures 5.1 and 5.3. In the 21% intake air oxygen concentration case, it is shown that using B15 instead of B0 can increase the exhaust output temperature about 10 ^{o}C. But when using 22% intake air oxygen concentration, there is no significant differences in the output temperature by using different biodiesel portions, these results are shown in figure 5.2.

As a conclusion, biodiesel fuel can increase the combustion efficiency because it contains about 10% of its weight of oxygen and thus can be considered as a kind of oxygenated fuel. The higher oxygen content in biodiesel improves the combustion efficiency. [23]

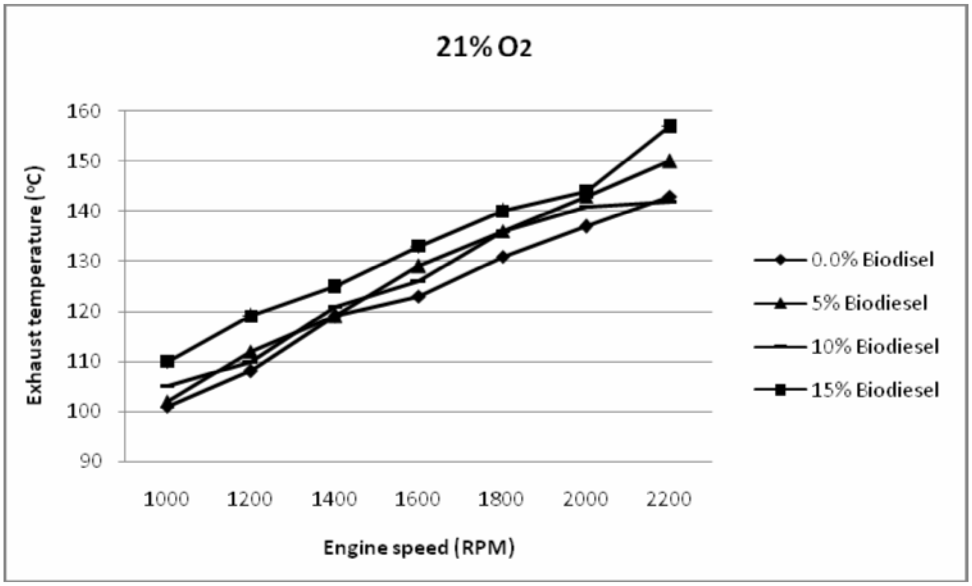


Figure (5.1): Temperature of the exhaust gas as a function of engine speed for 21% O_2 concentration and (0.0, 5, 10, and 15 %) Biodiesel concentrations.

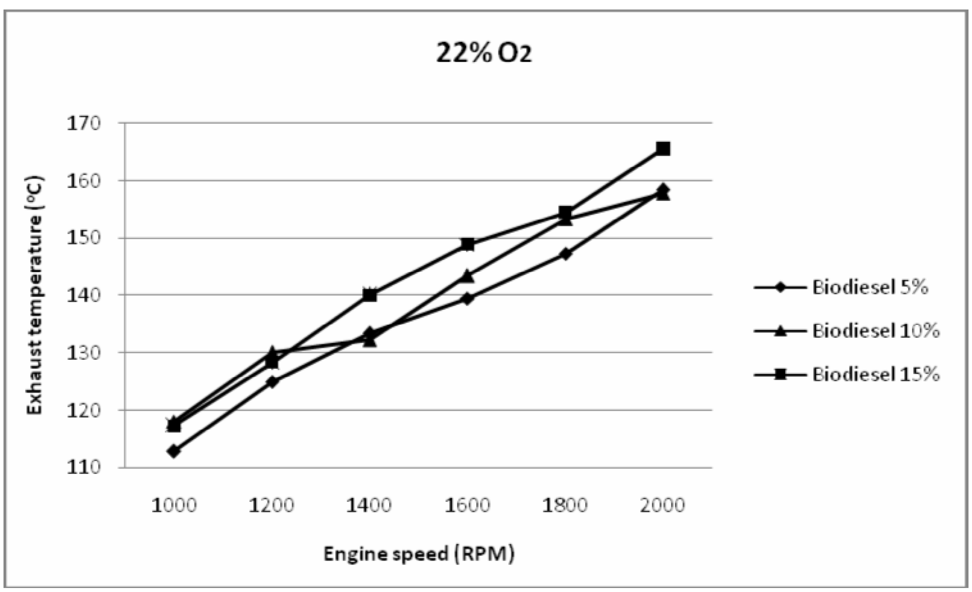


Figure (5.2): Temperature of the exhaust gas as a function of engine speed for 22% O_2 concentration and (, 5, 10, and 15%) Biodiesel concentration.

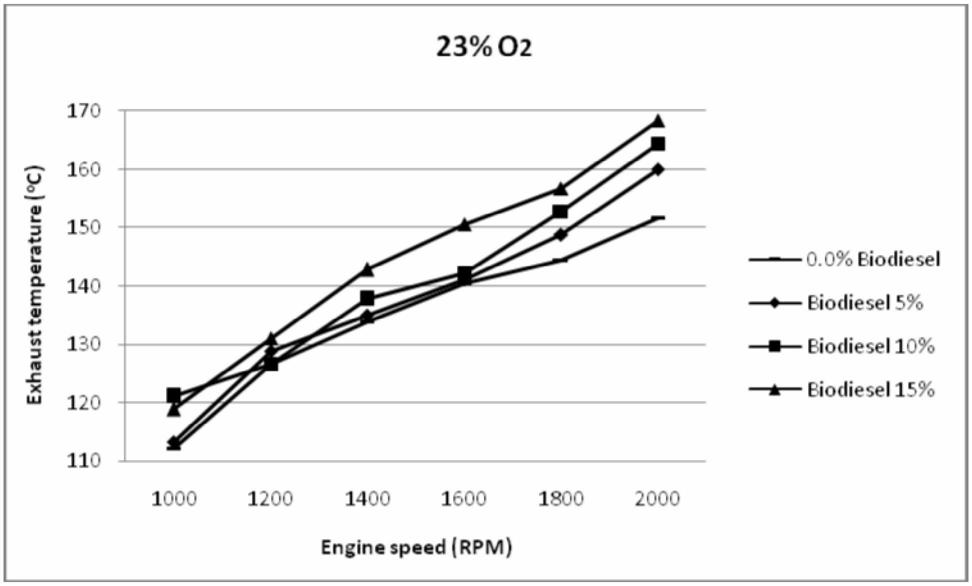


Figure (5.3): Temperature of the exhaust gas as a function of engine speed for 23% O_2 concentration and (0.0, 5, 10, and 15%) Biodiesel concentration.

The second analytical method aims to study the effect of using higher intake air oxygen concentrations at the same fuel properties, in this way, results show that using higher oxygen concentrations produce higher output temperatures, it occurs as a result of additional quantities of oxygen which enters the combustion chamber with the intake air [7]. So that, oxygen enriched combustion can be assumed as a method of improving the combustion efficiency in four stroke compression ignition internal combustion engines. These results are shown in Figures 5.4 – 5.7. In these figures, it is shown that there are no significant differences in the exhaust gas temperature when using 22%, 23%, or 24% intake air oxygen concentrations. Also, using oxygen enriched intake air with only 22% can increase the exhaust output temperature more than 10 ^{o}C.

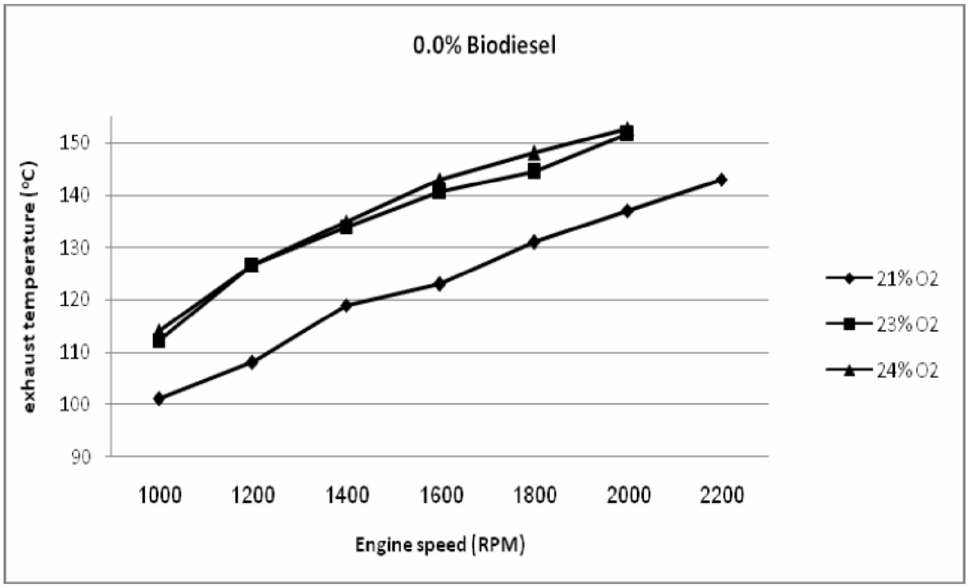


Figure (5.4): Temperature of the exhaust gas as a function of engine speed for 0.0% Biodiesel concentration and (21, 23, and 24%) oxygen concentrations.

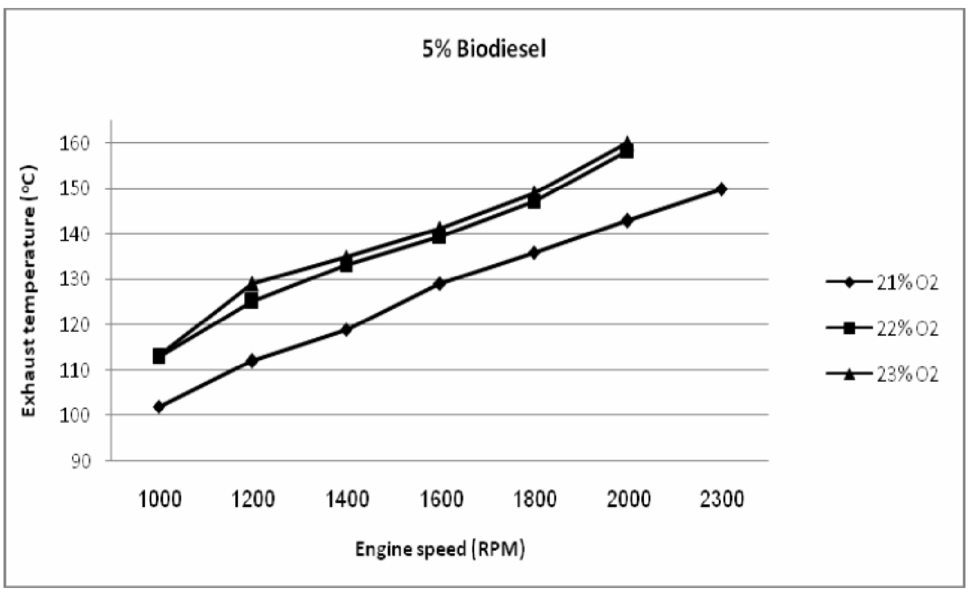


Figure (5.5): Temperature of the exhaust gas as a function of engine speed for 5% Biodiesel concentration and (21, 22, and 23%) oxygen concentrations.

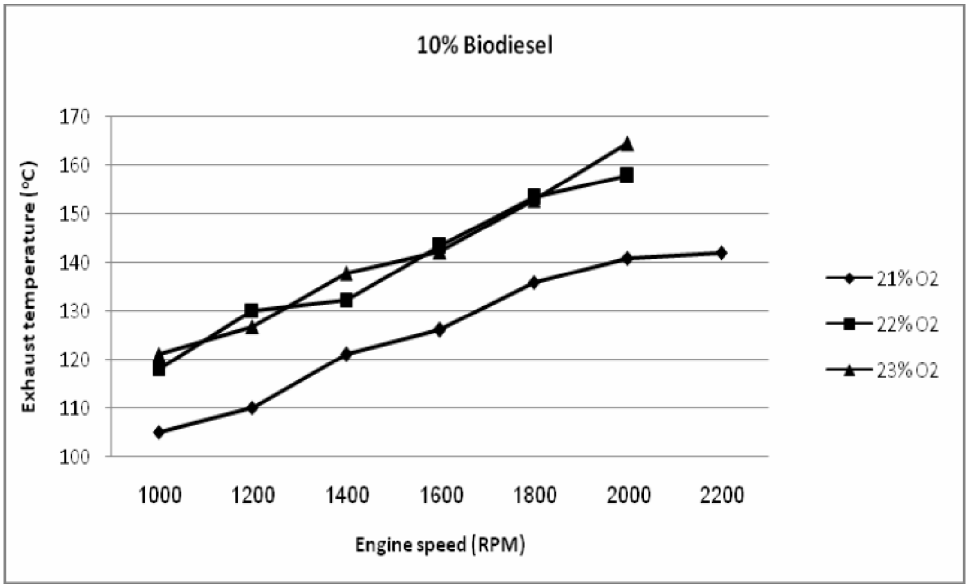


Figure (5.6): Temperature of the exhaust gas as a function of engine speed for 10% Biodiesel concentration and (21, 22, and 23%) oxygen concentration.

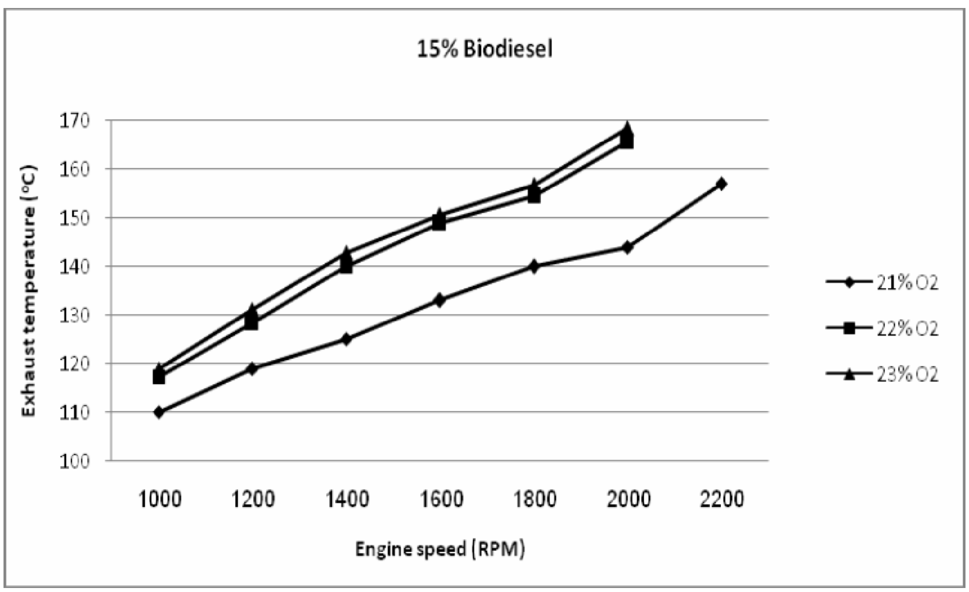


Figure (5.7): Temperature of the exhaust gas as a function of engine speed for 15% Biodiesel concentration and (21, 22, and 23%) oxygen concentrations.

As a conclusion, using biodiesel fuel in four stroke internal combustion engine improves the combustion efficiency; biodiesel is an oxygenated fuel which means it contains oxygen within its composition; it improves the combustion efficiency and produces higher output temperature. In the same way, using higher oxygen concentration as an intake air produces higher output temperature, again, the additional oxygen quantities improve the combustion efficiency, which means that oxygen enriched combustion can be assumed as a method of improving combustion efficiency and producing higher output temperature. These conclusions are illustrated briefly in Table 5.1 which shows the engine output temperature at 1000 and 2000 engine speed in each case.

Table (5.1): Summarized exhaust gas temperature using different intake air oxygen concentrations with different biodiesel ratios

Oxygen enrichment	Exhaust gas temperature (^oC)							
	B0		B5		B10		B15	
	Engine speed		Engine speed		Engine speed		Engine speed	
	1000	2000	1000	2000	1000	2000	1000	2000
21%	101	137	102	143	105	141	110	144
22%	N.A	N.A	113	158	118	158	117	166
23%	112	152	113.3	160	121	164	119	168

To evaluate this improvement in exhaust gas temperature, an improvement percentage was calculated with respect to reference operating condition, these reference conditions are pure petro-diesel fuel when calculating the effect of using higher biodiesel fuel concentrations and ambient air oxygen concentration (21% O_2) when calculating the effect of using higher intake air oxygen enrichment.

When calculating the temperature improvement of using higher intake air oxygen concentration Equations (5.1) and (5.2) are used:

$$TI_O\ (\%) = ((T_2 - T_1) / T_1) * 100 \ldots\ldots\ldots\ldots (5.1)$$

Where:

TI_O = temperature improvement (%) by using higher intake air oxygen concentration and Y% biodiesel fuel concentration at Z engine speed.

T_1 = exhaust temperature when using ambient air oxygen concentration (21%) and Y% biodiesel fuel concentration at Z engine speed (RPM).

T_2 = exhaust temperature when using X% intake air oxygen concentration and Y% biodiesel fuel concentration at Z engine speed (RPM).

Assuming the 21% intake air oxygen concentration as a reference point. Then, Equation (5.1) will calculate the exhaust temperature improvement (%) at each engine speed measuring point, and equation (5.2) is used to determine the average exhaust temperature improvement (%).

$$TI\ \%_{\,(XX\%\ O2)} = \text{Average}\ (TI_O\ \%_{\,(Z1)} + \ldots\ldots\ldots + TI_O\ \%_{\,(Zn)}) \ldots\ldots\ (5.2)$$

Where:

$TI\ \%_{\,(XX\%\ O2)}$ = the average temperature improvement when using X% intake air oxygen concentration and Y% biodiesel fuel concentration.

$TI_O\ \%_{\,(Z1)}$ = the exhaust temperature improvement (%) when using X% O_2 concentration and Y% biodiesel fuel concentration at Z1 engine speed (RPM).

$TI_O\ \%_{\,(Zn)}$ = the exhaust temperature improvement (%) when using X% O_2 concentration and Y% biodiesel fuel concentration at Zn engine speed (RPM).

For example: to evaluate the temperature improvement of using 23% intake air oxygen concentration and B0 fuel. First, the temperature improvement at each engine speed measuring point should be calculated using equation (5.1), then the average of these temperature improvements is calculated. These calculations are summarized in Table 5.2.

Table (5.2): Exhaust gas temperature improvement when using 23% intake air oxygen concentration and B0 fuel.

Engine speed (RPM)	23% O_2 Temperature improvement %	Average improvement %
1000	11	12.7
1200	17.3	
1400	12.5	
1600	14.3	
1800	10.3	
2000	10.73	

Also, similar method is used to evaluate the effect of using higher biodiesel concentrations, the reference in this case is when using B0 fuel, to do so, Equations (5.3) and (5.4) are used:

$$TI_B\ (\%) = ((T_2 - T_1) / T_1) * 100 \ldots\ldots\ldots\ldots\ldots(5.3)$$

Where:

TI_B = temperature improvement (%) when using X% biodiesel concentration and Y% intake air oxygen enrichment at Z engine speed.

T_1 = the exhaust temperature when using B0 fuel and Y% intake air concentration at Z engine speed (RPM).

T_2 = the exhaust temperature when using X% biodiesel concentration and Y% intake air oxygen concentration at Z engine speed.

Equation (5.3) will evaluate the temperature improvement (%) at each engine speed measuring point. Then Equation (5.4) computes the average of these exhaust temperature improvements.

$$TI\ \%_{(BX\%)} = \text{Average}\ (TI\ \%_{(Z1)} + \ldots\ldots\ldots + TI\ \%_{(Zn)}) \ldots\ldots\ldots (5.4)$$

Where:

$TI\ \%_{(BX)}$ = the average temperature improvement when using Bx fuel concentration and Y% intake air oxygen concentration.

$TI\ \%_{(Z1)}$ = the exhaust temperature improvement (%) when using Bx fuel and Y% O_2 concentration at Z1 engine speed.

$TI\ \%_{(Zn)}$ = the exhaust temperature improvement (%) when using Bx fuel and Y% O_2 concentration at Zn engine speed.

For example: to evaluate the temperature improvement of using B5 fuel at 21% intake air oxygen concentration, first the exhaust temperature improvement at each engine speed measuring point should be calculated using equation (5.3), then the average of these temperature improvements is calculated. These calculations are summarized in Table 5.3.

Table (5.3): Exhaust gas temperature improvement when using B5 fuel and 21% O_2 enrichment.

Engine speed (RPM)	B5 Temperature improvement %	Average improvement %
1000	1	3
1200	3.7	
1400	0	
1600	4.9	
1800	3.8	
2000	4.4	

Using previous methods, the average temperature improvement (%) is calculated, these results are summarized in Table 5.4. It is obvious that using higher biodiesel portion by 5% can improve the output temperature between 2% to 4.5%, and when using higher oxygen concentration, it is shown that only 1% oxygen enrichment (using 22% O_2 instead of 21% O_2) can improve the output temperature between 10% to 13%.

Table (5.4): Summarized exhaust gas temperature improvement (%) when using different intake air oxygen concentrations and/or different biodiesel concentrations

Oxygen enrichment	Exhaust temperature improvement %		
	B5	B10	B15
21%	3	2.8	7.4
22%	N.A	N.A	N.A
23%	2.1%	4.4	7.1
Oxygen enrichment	**Exhaust temperature improvement %**		
	22% O_2	23% O_2	24% O_2
B0	N.A	12.7	14
B5	10.2	11.7	N.A
B10	13	14.4	N.A
B15	10.6	12.4	N.A

In previous studies, many of investigators such as Tsolakis [35], Senatore et al. [36], Shaheed and Swain [37], Graboski et al. [38], Canakci and Van Gerpen [39], Canakci [40], Lapuerta et al. [41], and Monyem and Van Gerpen [42] acknowledged that no variations in thermal efficiency when using different types of biodiesel fuels. A few investigators stated that they observed some improvement in thermal efficiency, although this is not confirmed by the data provided.

Puhan et al. [43] stated measuring increases in efficiency when using ethyl ester from mahua oil as compared with that obtained with diesel fuel (and explained using composition and density differences).

A minor number of earlier studies have also been found to report some improvement or some decrease in thermal efficiency when using biodiesel fuels.

Kaplan et al. [44] explained that they observed increase in efficiency by means of an improved combustion, giving no further reasons.

In the Handbook of Biodiesel, it is asserted that an improvement in thermal efficiency occurs when 20% blends are used, thereby compensating for the loss of heating value. However, no references are cited to support this statement.

Agarwal and Das [45] tested linseed-oil biodiesel differently blended with high sulfur diesel fuel in a single cylinder 4 kW portable engine widely used in the agricultural sector and showed increases in thermal efficiency, especially at low load. Conversely, Lin et al. [46] found a decrease in efficiency (they reported increases in energy consumption) when using palm-oil biodiesel, pure and in 20% blends, in a 2.8 L indirect injection engine, although the small differences (below 2.3% in all cases) can hardly be considered significant.

Some authors have found positive and negative results when blending biodiesel. Labeckas and Slavinskas [47] tested a 4.75 L engine under different steady modes using 5%, 10%, 20%, 35% blends and pure rapeseed-oil biodiesel. The thermal efficiency appeared to reach a maximum for 5–10% blends. Ramadhas et al. [48] tested a 5.5kW single-cylinder engine with 10%, 20%, 50%, 75% blends and pure biodiesel from Indian rubber seed oil. They obtained maximum efficiencies for 10% and 20% blends. This improved efficiency was explained by the increased lubricity of these blends as compared to their pure components. However, the reported 25% efficiency increase in the case of the 10% blend lessens credibility to this study. To the contrary, Murillo et al. [49] found negative results. These authors tested different blends of conventional diesel fuel and biodiesel from used cooking oil, at full load, in a marine outboard 3-cylinder naturally aspirated engine. With blends of 10%, 30% and 50% of biodiesel, efficiency was lower than that obtained with petro-diesel fuel, but the highest efficiency was found with pure biodiesel.

5.2 Effect of Biodiesel and Oxygen Concentration on Exhaust NOx Emissions

NOx is produced as a by-product from most of the combustion processes, it is poisonous for humans and in long exposure cases can be fatal, also, due to its acidity it contributes in forming acid rain which destroys agriculture and pollutes water resources [7]. So that, effective solutions should be implement to reduce its emission.

By analyzing experimental results with respect to specific intake oxygen concentration, its seen that when using ambient air oxygen concentration (21% O_2), there is no significant difference in NOx emissions with respect to different biodiesel ratios as shown in Figure 5.8. In contrast, Cherng-Yuan Lin and Shiou-An Lin found that due to the higher oxygen content in biodiesel (about 10% of its weight), it improves the combustion efficiency and produces larger NOx formation [23].

Although most of the related literatures show a slight increase in NOx emissions when using biodiesel fuel, other investigators found different results, using biodiesel fuel in engines can be classified into four groups from NOx formation point view:

1. Group I: some investigators found that using biodiesel produces higher NOx formation, an experimental work carried out in a 7.3 L Navistar engine running the 13-mode US Heavy-Duty test cycle using different soybean-oil biodiesel blends, the increases in NOx emissions obtained were in proportion to the concentration in biodiesel, 8% NOx formation increase was reached in the case of pure biodiesel [50]. Schumacher et al. [51] tested a 200kW 6-cylinder at 1200 and 2100 RPM and 50% and 100% load with 10%, 20%, 30% and 40% soybean-oil biodiesel blends. The NOx emissions increased up to 15% in the case of the 40% blend. Marshall et al. [52] tested a Cummins L10E engine under transient

conditions with diesel fuel and 20% and 30% biodiesel blends. They observed an increase in NOx emissions of 3.7% with the 20% blend while only a 1.2% with the 30% blend. Other experiments measuring increases in NOx emissions were also collected. For example, Police et al. measured increases around 20%, while Rantanen et al. found 4–10% increases, in both cases operating heavy-duty engines under the ECE R49 test cycle with pure rapeseed-oil biodiesel. [53]

2. Group II: other investigators concluded that the effect of biodiesel on NOx emissions depends on the type of engine and its operating conditions. Serdari et al. [54], measured on-road emissions from three different vehicles using high sulfur diesel fuel (1800 ppm) and 10% sunflower-oil biodiesel blends. They found both increases and decreases in NOx emissions, and attributed such differences to the different engine technology and maintenance conditions. Krahl et al. [55], collected different European experiments with rapeseed oil biodiesel and obtained an average increase of 15% in NOx emissions. However, they recorded some cases, mainly those testing indirect injection diesel engines under transient cycles, where the NOx emissions were similar with diesel and biodiesel fuels. McCormick [56, 57], measured NOx emission reductions around 5% when using 20% soybean-oil biodiesel blends.
3. Group III: some investigators found that there are no significant differences between using biodiesel or petro-diesel from NOx

formation point view. Durbin et al. [58], tested four different engines with diesel, pure biodiesel and a 20% biodiesel blend. The engines were chosen to represent a wide variety of heavy duty engines: turbocharged and naturally aspirated, direct and indirect injection. Small differences in NOx emissions were found and the authors concluded they were not significant. The same conclusion was reached by these authors when they used these fuels in seven different vehicles. Wang et al. [59], tested nine vehicles with diesel and 35% soybean-oil biodiesel blends. They also concluded that differences in NOx emissions were not significant.

4. Group IV: A minor number of papers have reported decreases in NOx emissions when using biodiesel fuels. Peterson and Reece [60] used several blends of diesel fuels with both ethyl and methyl esters from rapeseed oil in vehicles equipped with similar 5.9 L engines. They measured reductions in NOx emissions of around 10% both with ethyl and methyl ester blends. McDonald et al. [53], obtained NOx decreases of 5–10% from their transient tests with pure soybean-oil biodiesel in a Caterpillar engine. Dorado et al. [61], recorded reductions above 20% from testing biodiesel from waste olive oil in an eight-mode cycle. Lapuerta et al. [62], observed a small decrease in NOx emissions from an indirect injection 1.9 L engine operating in five selected steady modes with pure and blended biodiesel from sunflower and cardoon oils.

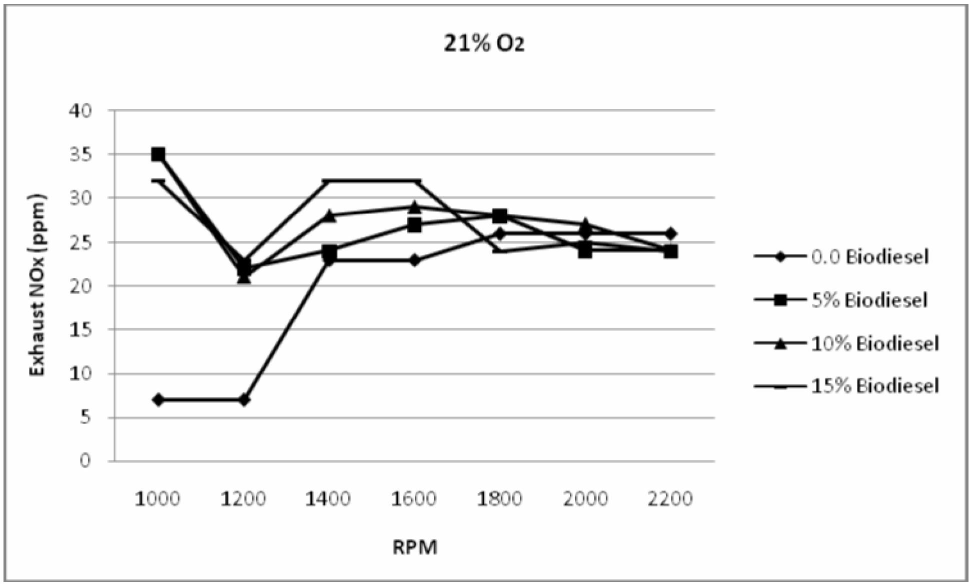


Figure (5.8): Exhaust NOx concentration as a function of engine speed for 21% O_2 concentration and B0, B5, B10, and B15 biodiesel concentrations.

But when using higher oxygen concentration, biodiesel reduce NOx emissions, it happened as a result of the additional oxygen quantities enter the process from both of biodiesel and intake air, it affects the combustion process and improves its completeness by combining effectively with fuel molecules [2, 5, 7, 23], these results are shown in Figures 5.9 and 5.10.

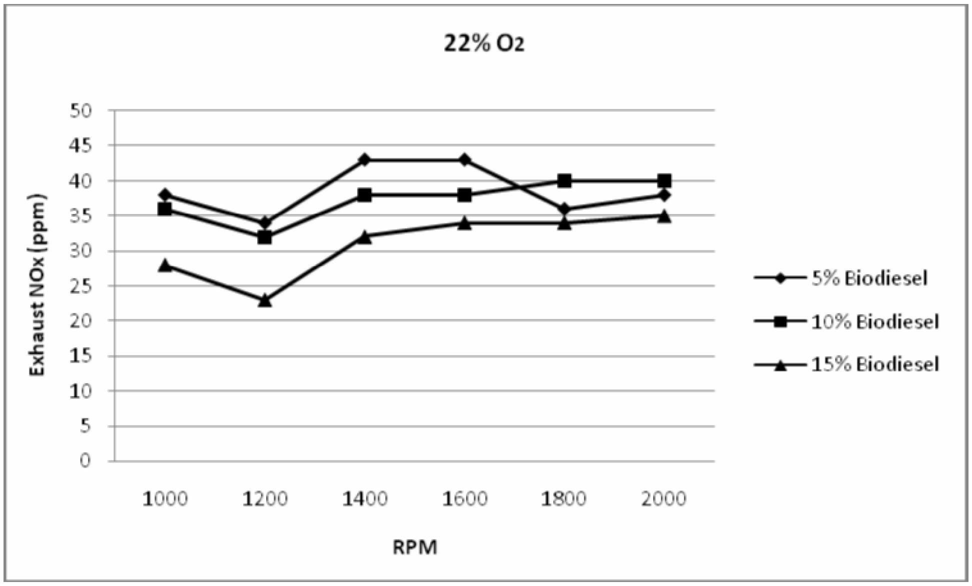


Figure (5.9): Exhaust NOx concentration as a function of engine speed for 22% O_2 concentration and B5, B10, and B15 biodiesel concentrations.

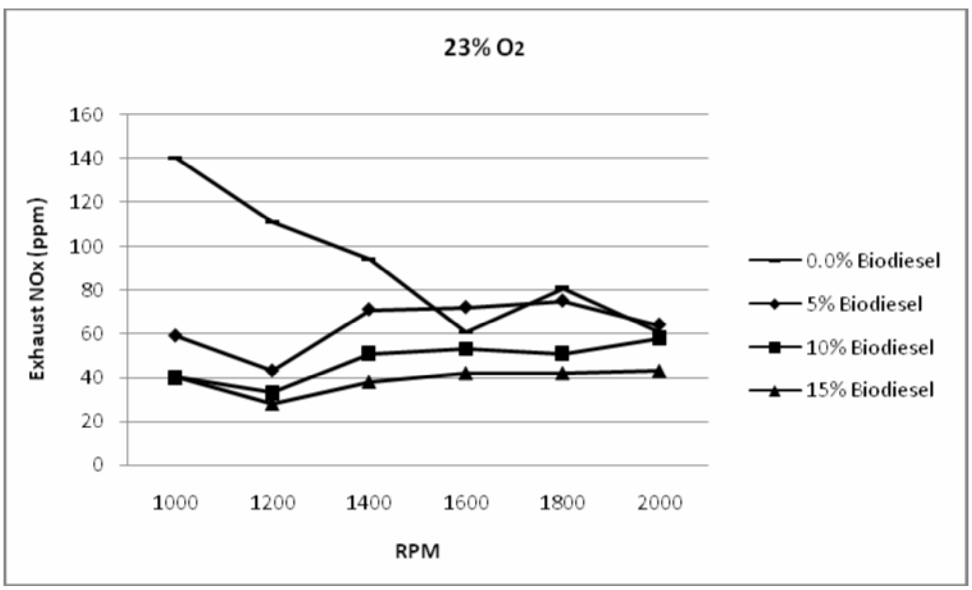


Figure (5.10): Exhaust NOx formation as a function of engine speed for 23% O_2 concentration and B0, B5, B10, and B15 biodiesel concentrations.

So that, biodiesel fuel is recommended to be used with higher intake air oxygen concentrations in order to reduce NOx formation.

In order to determine the effect of using higher oxygen concentrations on NOx formation, results were analyzed with respect to specific biodiesel ratios, and its found that using higher oxygen concentration produces higher NOx emissions, these results are shown in Figures 5.10 -5.13. the higher NOx production came as a result of prompt formation, prompt NOx forms by the relatively fast reaction between nitrogen, oxygen, and hydrocarbon radicals, it’s a very complicated process consists of hundreds of reactions, the hydrocarbon radicals are intermediate species formed during the combustion process. Prompt NOx formation is generally happened at relatively low temperature combustion processes. [7]

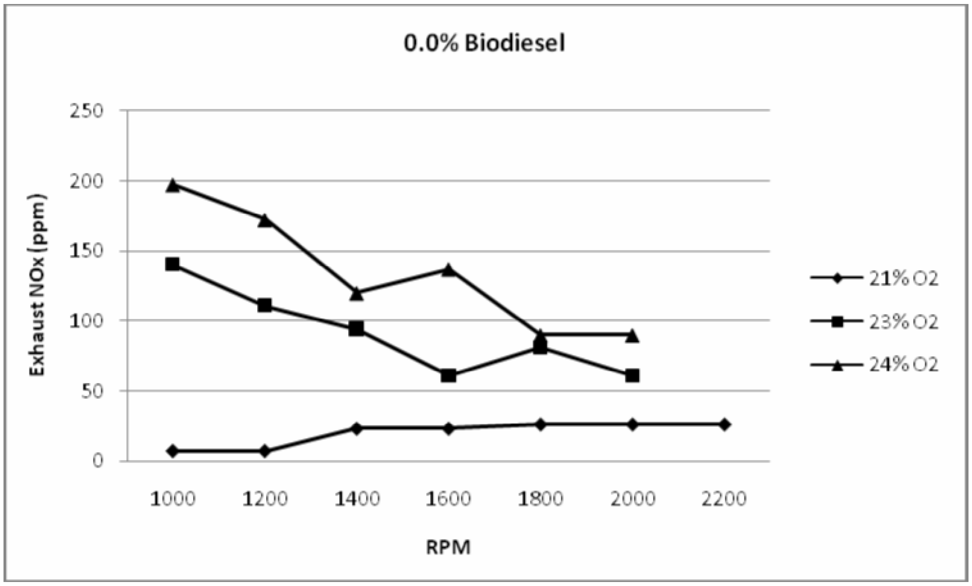


Figure (5.11): Exhaust NOx concentration as a function of engine speed for B0 and 21%, 23%, and 24% O_2 concentrations.

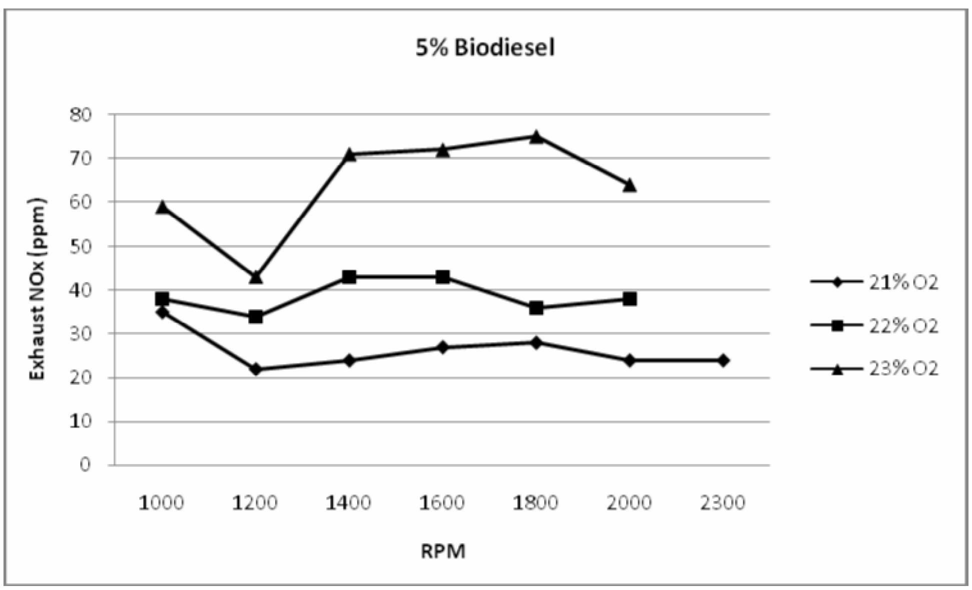


Figure (5.12): Exhaust NOx concentration as a function of engine speed for B5 and 21%, 22%, and 23% O_2 concentrations.

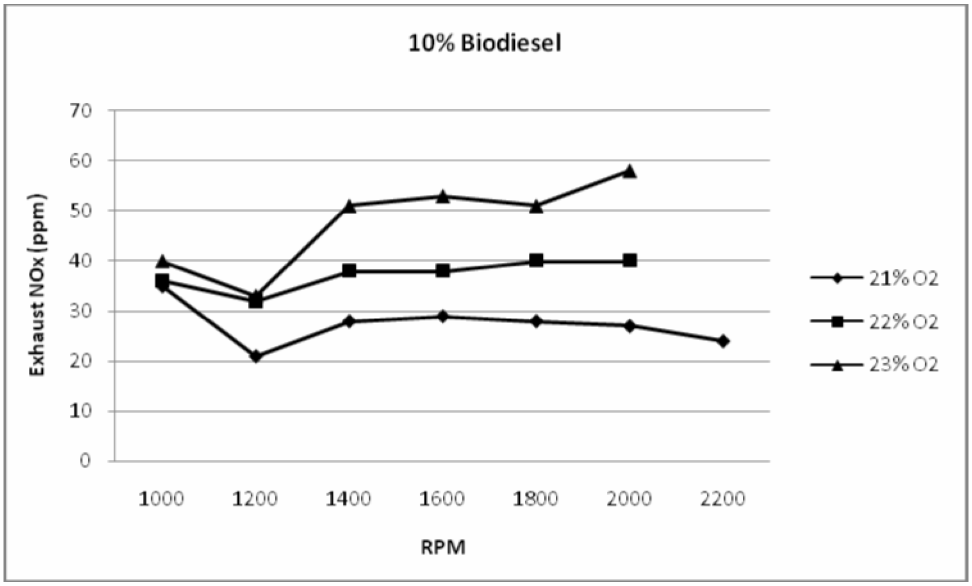


Figure (5.13): Exhaust NOx concentration as a function of engine speed for B10 and 21%, 22%, and 23% O_2 concentrations.

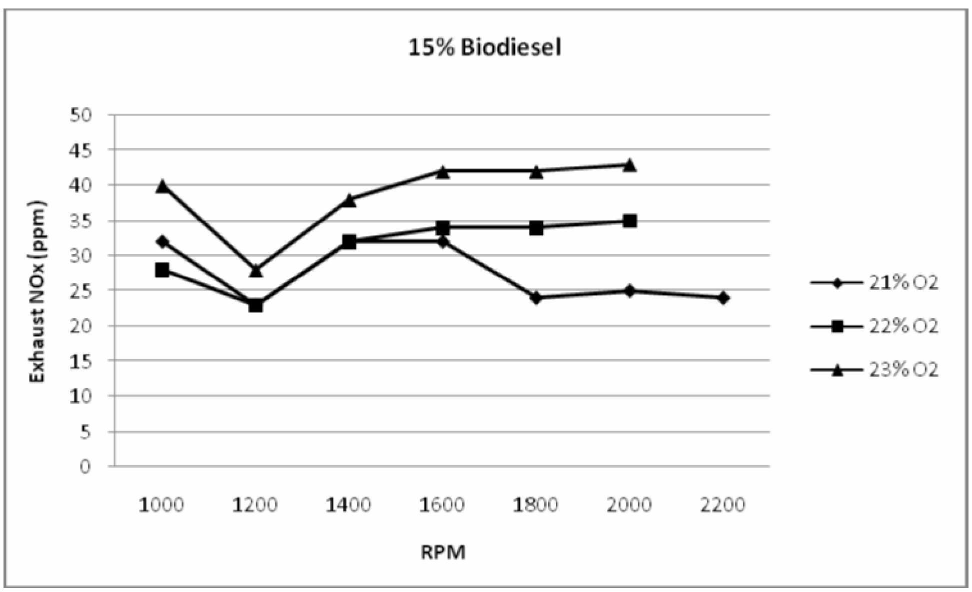


Figure (5.14): Exhaust NOx concentration as a function of engine speed for B15 and 21%, 22%, and 23% O_2 concentrations.

In previous studies, investigators found that NOx emission increases when using either biodiesel or higher oxygen concentrations. Schmidt and Van Gerpen [63], observed that NOx emission increases when using oxygen enriched intake air as when using biodiesel with standard air, with the same additional oxygen content in both cases. Iida et al. [64], observed that enriching air with oxygen from 21% to 29% led to an exponential increase in NOx emissions. Song et al. [65], showed that both the intake oxygen enrichment and the use of oxygenated fuels increase NOx emissions. This increase was higher when oxygen enrichment was used rather than when using oxygenated fuels.

As a conclusion, oxygen enriched combustion technology contributes in generating higher NOx emissions due to prompt formation in internal combustion engines. These results are summarized in Table 5.5.

Table (5.5): Summarized NOx concentration using different oxygen concentrations with different biodiesel ratios

Oxygen enrichment	NOx concentration (ppm)							
	B0		B5		B10		B15	
	Engine speed		Engine speed		Engine speed		Engine speed	
	1000	2000	1000	2000	1000	2000	1000	2000
21%	7	26	35	24	35	27	32	25
22%	N.A	N.A	38	38	36	40	28	35
23%	140	61	59	64	40	58	40	43

In order to determine the amount of NOx formation which happens due to use higher biodiesel or oxygen concentrations, the percent amount of change in NOx formation were calculated using the same method of calculating the percent amount of change in exhaust gas temperature, its found that using higher biodiesel concentration produces higher NOx emissions at ambient air oxygen concentration, these results are shown in Table 5.6. Using B15 fuel with 23% O_2 intake air concentration can reduce the NOx emissions about 52.4% in comparison of using 23% O_2 intake air concentration with pure petro-diesel fuel.

Table (5.6): Summarized NOx concentration change% using different biodiesel and intake air oxygen concentrations.

Oxygen enrichment	Exhaust NOx increasing %		
	B5	B10	B15
21%	106	110	108.7
22%	N.A	N.A	N.A
23%	-21.3	-40.4	-52.4
Oxygen enrichment	Exhaust NOx increasing %		
	22% O_2	23% O_2	24% O_2
B0	N.A	701	1080
B5	48.1	143.5	N.A
B10	35.5	72.2	N.A
B15	12.6	40.6	N.A

The (-) sign means that there is a reduction in the NOx formation about X%.

As a conclusion, using higher biodiesel portions with higher oxygen concentrations reduce the NOx formation, and when using ambient air oxygen concentration, there is no significant differences in NOx formation by using different biodiesel portions.

5.3 Effect of Biodiesel and Oxygen Concentration on Exhaust CO Emissions

Carbon monoxide is one of the most important combustion emissions, it gives an indicator of the process completeness, efficient or complete combustion processes means lower CO emissions. In contrast, poor efficiency or incomplete combustion process leads to higher CO emissions.

Analyzing experimental results at ambient air oxygen concentration show that using blended fuel (biodiesel with petro-diesel) reduces CO emissions at different engine speeds, the additional oxygen contained in the biodiesel improves the combustion process completeness, which leads to lower CO emissions; these results are shown in Figure 5.14.

With regard to most of the literature reviewed, a decrease in CO emissions when substituting diesel fuel with biodiesel can be considered as the general trend. Krahl et al. [66], after testing biodiesel from rapeseed oil, obtained approximately a 50% decrease with respect to both low and ultra-low sulfur diesel fuels. Peterson and Reece [60] fuelled a turbocharged engine with diesel and several biodiesel fuels, pure and differently blended. They concluded that the decrease in CO emissions with biodiesel was almost 50%. Alam et al, [67], reported a higher decrease in CO emissions when using biodiesel at low load.

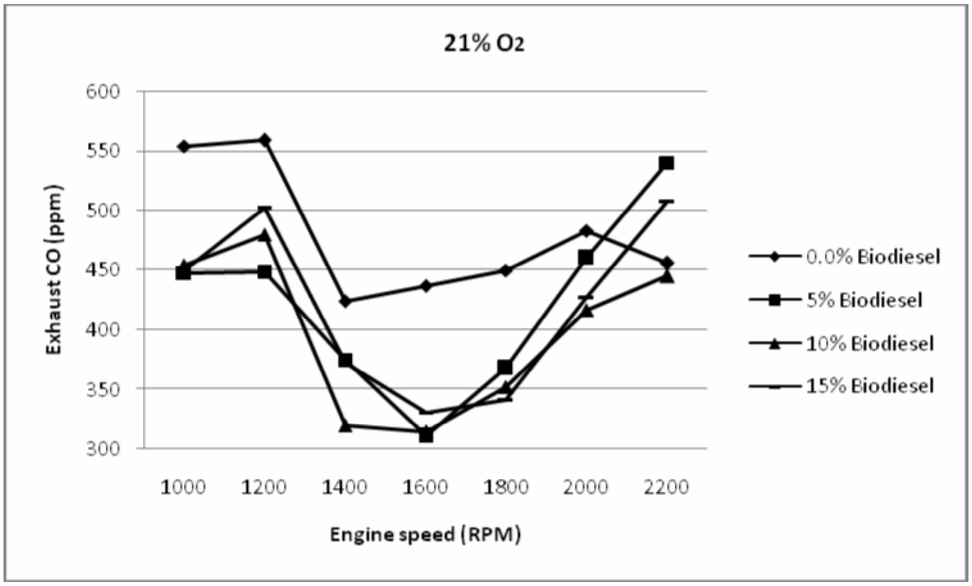


Figure (5.15): Exhaust gas CO emissions as a function of engine speed for 21% O_2 concentration and B0, B5, B10, and B15 fuel concentrations.

But when using intake air with higher oxygen concentrations, CO emissions increased by increasing biodiesel concentration, it happens due to the prompt formation as a result of the existence of hydrocarbons and radicals especially at low temperature conditions. Also, higher exhaust temperature due to the higher oxygen concentration in the intake air or biodiesel fuel could also cause fuel dissociation and higher CO emissions [7]. These results are shown in Figures 5.15 and 5.16.

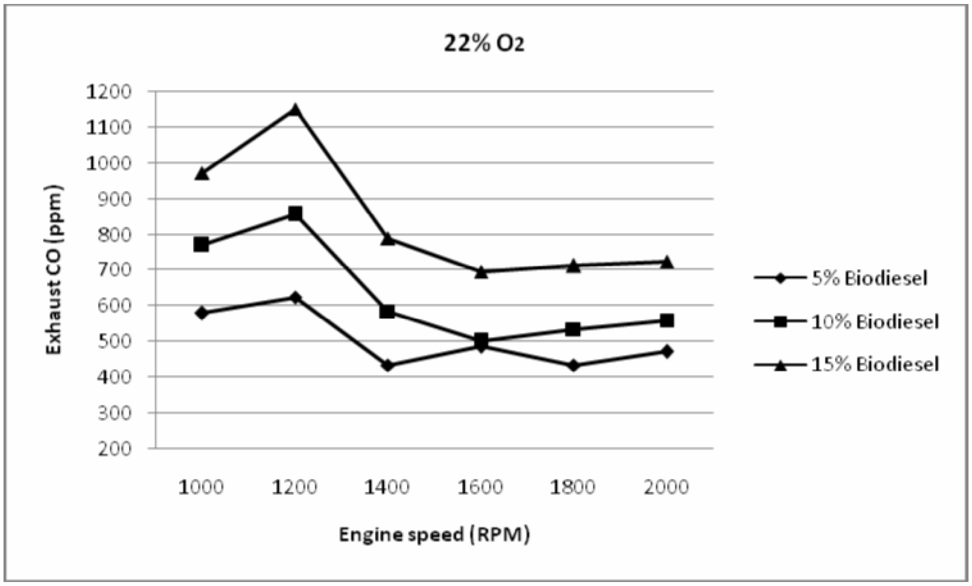


Figure (5.16): Exhaust gas CO emissions as a function of engine speed for 22% O_2 concentration and B5, B10, and B15 fuel concentrations.

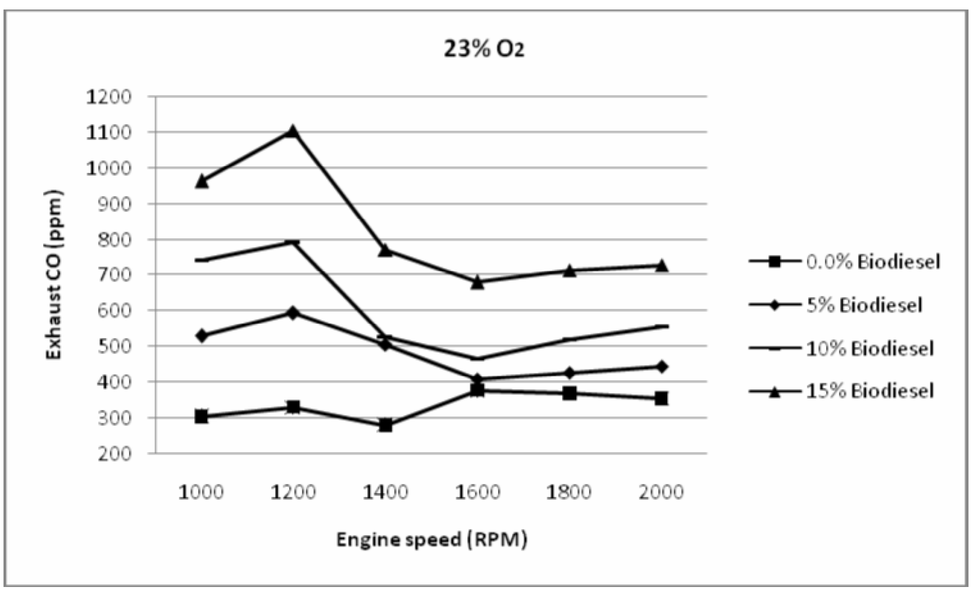


Figure (5.17): Exhaust gas CO emissions as a function of engine speed for 23% O_2 concentration and B0, B5, B10, and B15 fuel concentrations.

And for the effects of using higher oxygen concentrations on CO emissions, results were analyzed at specific biodiesel concentrations. It's shown that when using pure petro-diesel, oxygen enriched air can reduce the CO emissions, it happens due to the additional oxygen quantities which improve the combustion process completeness, these results are shown in Figure 5.17.

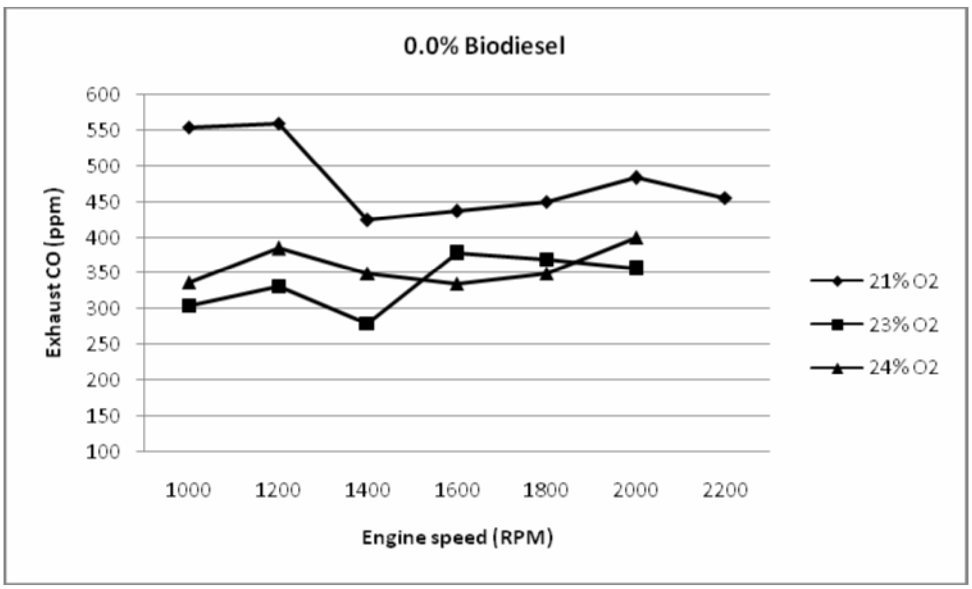


Figure (5.18): Exhaust gas CO emissions as a function of engine speed for B0 fuel concentration and 21%, 23%, and 24% O_2 concentrations.

But when using blended fuels (petro-diesel with biodiesel in different ratios), CO emissions increase by increasing the intake air oxygen concentration. This CO emissions increasing as a result of prompt formation, it happens due to the existence of hydrocarbons and radicals especially at low temperature conditions. Also, higher exhaust temperature due to the higher oxygen concentration in the intake air or biodiesel fuel could also cause fuel dissociation and higher CO emissions [7].These results are shown in Figures 5.18-5.20.

Tinaut et al. tested two vehicles under the NEDC measured CO increases when fuelling their vehicles with 5% and 10% biodiesel blends. [68]

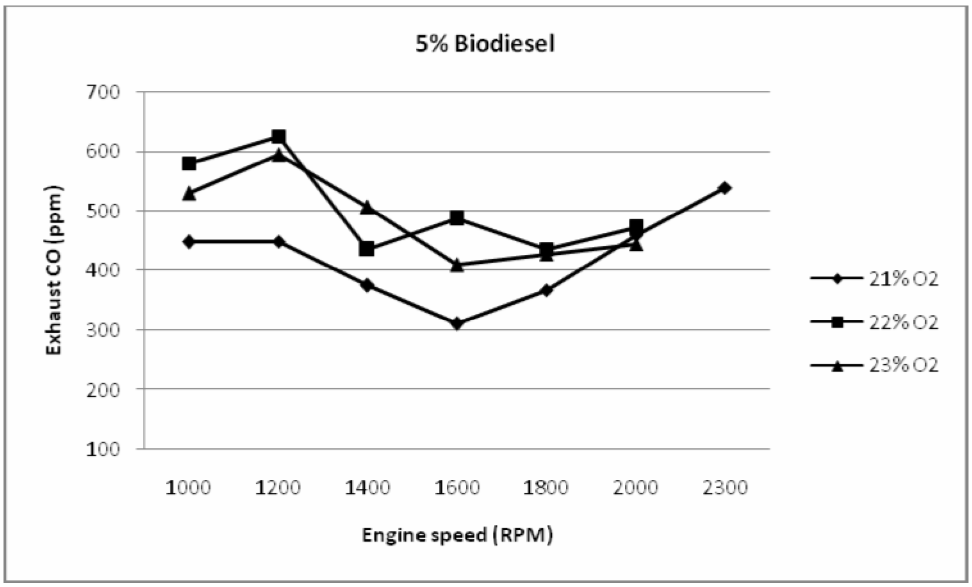


Figure (5.19): Exhaust gas CO emissions as a function of engine speed for B5 fuel concentration and 21%, 22%, and 23% O_2 concentrations.

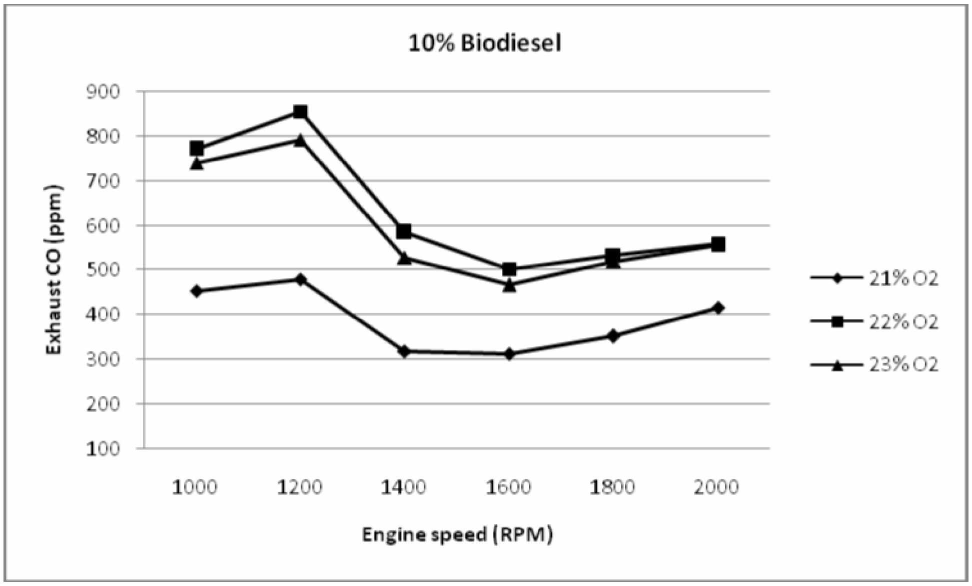


Figure (5.20): Exhaust gas CO emissions as a function of engine speed for B10 fuel concentration and 21%, 22%, and 23% O_2 concentrations.

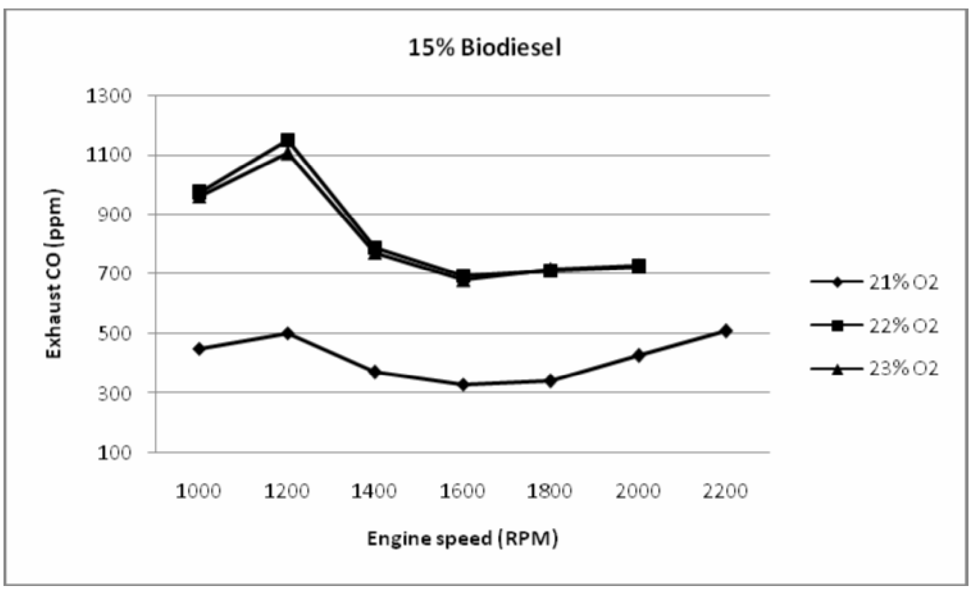


Figure (5.21): Exhaust gas CO emissions as a function of engine speed for B15 fuel concentration and 21%, 22%, and 23% O_2 concentrations.

As a conclusion, increasing the oxygen content in the process by either higher intake air oxygen concentration or higher oxygenated fuel (biodiesel) concentrations produce higher CO emissions, it happens as a result of prompt formation. Also, higher exhaust temperature due to the higher oxygen concentration in the intake air or biodiesel fuel could cause fuel dissociation and higher CO emissions [7]. These results can be shown when summarizing the exhaust gas CO emissions at minimum and maximum engine speeds experimental measuring points as in Table 5.7.

Table (5.7): Summarized CO concentration using different oxygen concentrations with different biodiesel ratios

Oxygen enrichment	CO concentration (ppm)							
	B0		B5		B10		B15	
	Engine speed		Engine speed		Engine speed		Engine speed	
	1000	2000	1000	2000	1000	2000	1000	2000
21%	554	493	448	460	454	417	450	427
22%	N.A	N.A	580	472	770	560	972	724
23%	305	356	530	445	741	557	963	728

To determine the amount of differences which happen as a result of using either higher biodiesel concentrations or higher intake air oxygen concentrations on CO emissions, the same methods of calculating exhaust gas temperature and NOx emissions (Equations a – d) increasing or reduction percent were implemented by using exhaust gas CO emissions measurement, its shown that using either higher oxygen concentration with pure petro-diesel or higher biodiesel concentrations with ambient air oxygen concentration (21%) reduce CO emissions, but higher oxygen concentration reduces CO emissions more than using higher biodiesel concentration. Also, using both of biodiesel and oxygen enriched intake air contributes in producing higher CO exhaust gas emissions. These results are shown in Table 5.8. The higher CO reduction can be achieved by using 23% O_2 intake air concentration and pure petro-diesel fuel.

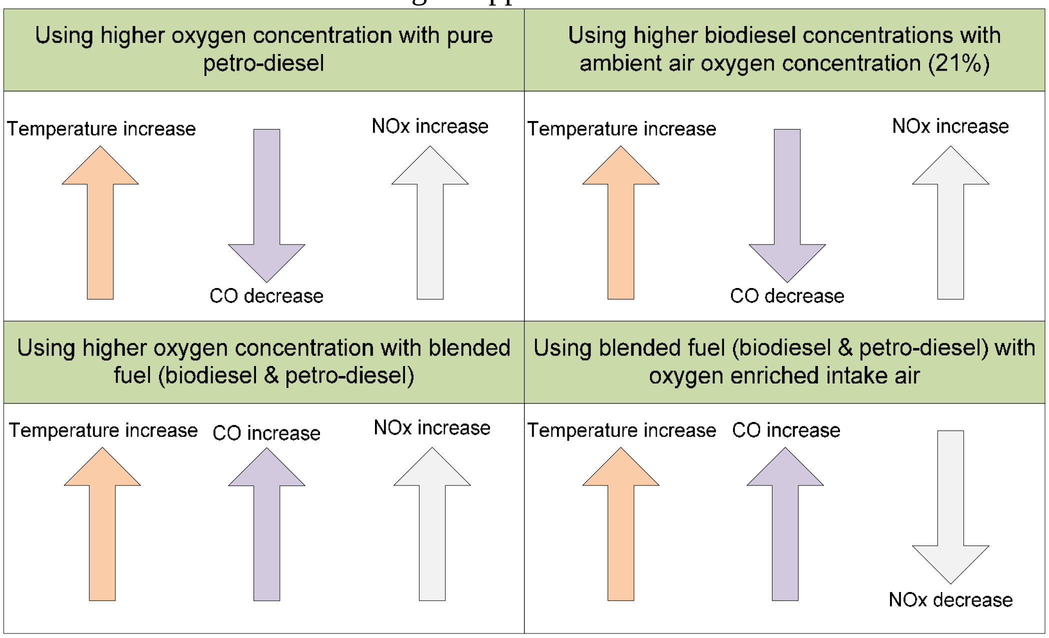
Table (5.8): Summarized exhaust gas CO concentration change % using different biodiesel and intake air oxygen concentrations.

Oxygen enrichment	Exhaust CO increasing or reduction %		
	B5	B10	B15
21%	-17	-20.1	-16.9
22%	N.A	N.A	N.A
23%	47.1	81.8	150.3
Biodiesel concentration	**Exhaust CO increasing or reduction %**		
	22% O_2	23% O_2	24% O_2
B0	N.A	-29.5	-25
B5	27.1	21.7	N.A
B10	62.8	53.9	N.A
B15	107.7	104.5	N.A

The (-) sign means that there is a reduction in the CO formation about X%.

Either higher biodiesel or intake air oxygen concentrations affects the temperature, NOx, and CO exhaust emissions by decreasing or increasing its values, Table 5.9 summarize these effects in the internal combustion engine application.

Table (5.9): Effects of using higher biodiesel and oxygen concentrations on exhaust emissions in internal combustion engine application.



5.4 Effect of Biodiesel and Oxygen Concentration on Exhaust Motor Temperature

In all internal combustion engines, motor temperature should be controlled carefully in order to maintain the engine and protect it from damage, each engine has its cooling system, when temperature reaches high limits, a stand by cooling system is turned on automatically, in most cases this stand by system is fan.

In all experimental work, the fuel temperature does not change and it remains within its average values. On the other hand, the motor temperature increases when using either biodiesel or higher oxygen concentrations, this increasing in output temperature is another indicator of the combustion process improvement by using either biodiesel or higher intake air oxygen concentrations.

5.5 Effect of Biodiesel and Oxygen Concentration on Exhaust O_2 Emissions

In the theoretical combustion process, fuel needs specific amount of oxygen in order to be burned completely, and the output exhaust gases contain 0.0% O_2. In real applications, this does not happen, so that even modern combustion systems need to operate under excess air conditions in order to ensure better combustion, and the exhaust gas contains O_2. [2, 5, 6]

Results show that when using blended fuel (biodiesel with petro-diesel), O_2% in the exhaust gas increase, this increasing happens because of the additional oxygen quantities contained in the biodiesel fuel [23]. These results are shown in Figures 5.21 – 5.23.

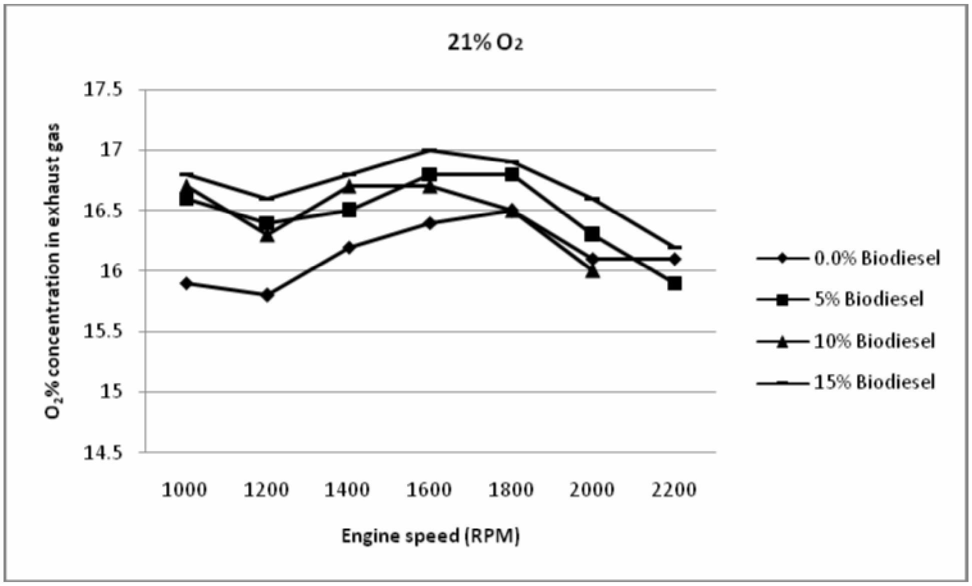


Figure (5.22): Exhaust gas O_2% as a function of engine speed for 21% O_2 air concentration and B0, B5, B10, and B15 biodiesel concentrations.

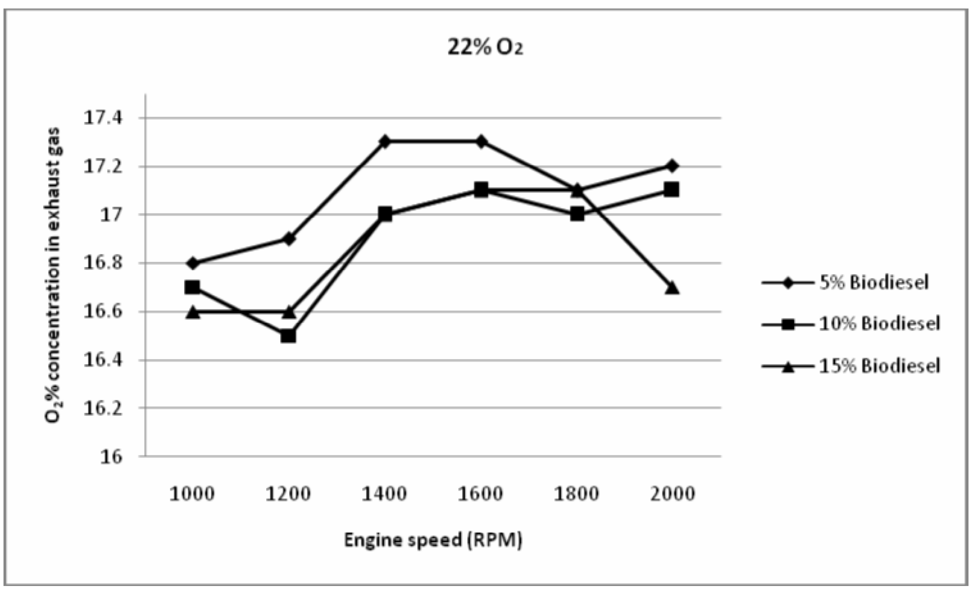


Figure (5.23): Exhaust gas O_2% as a function of engine speed for 22% O_2 air concentration and B5, B10, and B15 biodiesel concentrations.

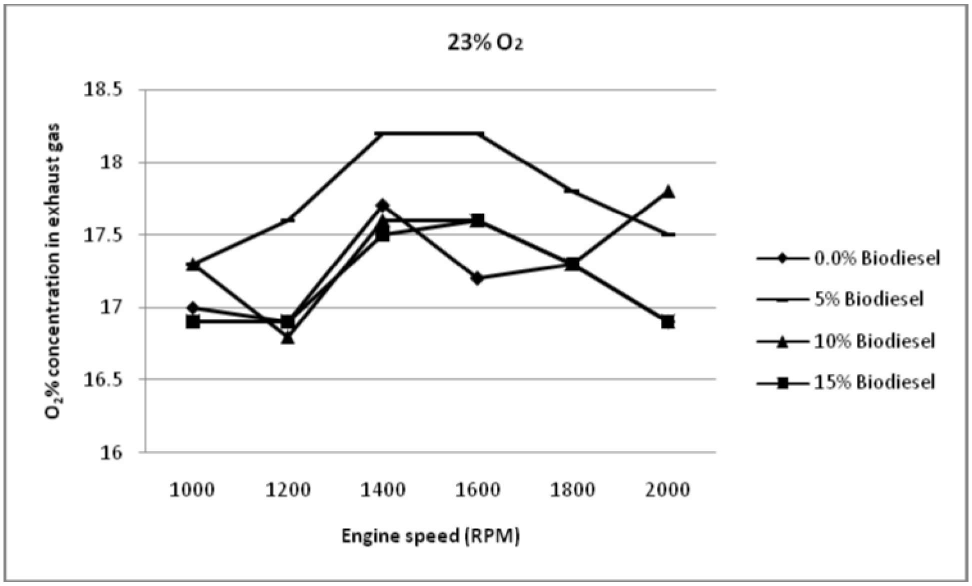


Figure (5.24): Exhaust gas O_2% as a function of engine speed for 23% O_2 air concentration and B0, B5, B10, and B15 biodiesel concentrations.

Also, using higher oxygen concentrations intake air leads to higher O_2% in the exhaust emissions. These results are clearly shown in Figures 5.24 – 5.27.

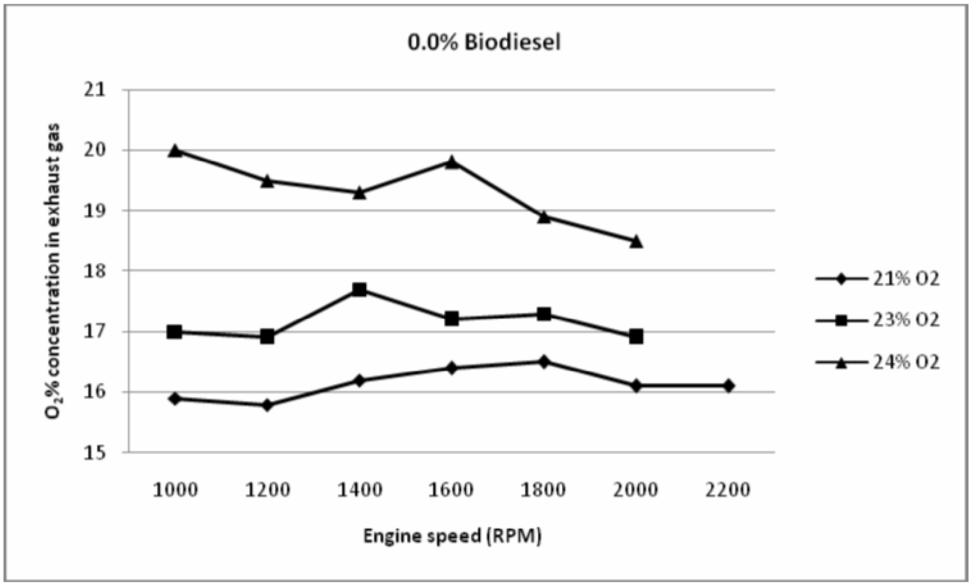


Figure (5.25): Exhaust gas O_2% as a function of engine speed for B0 fuel concentration and 21%, 23%, and 24% O_2 concentrations.

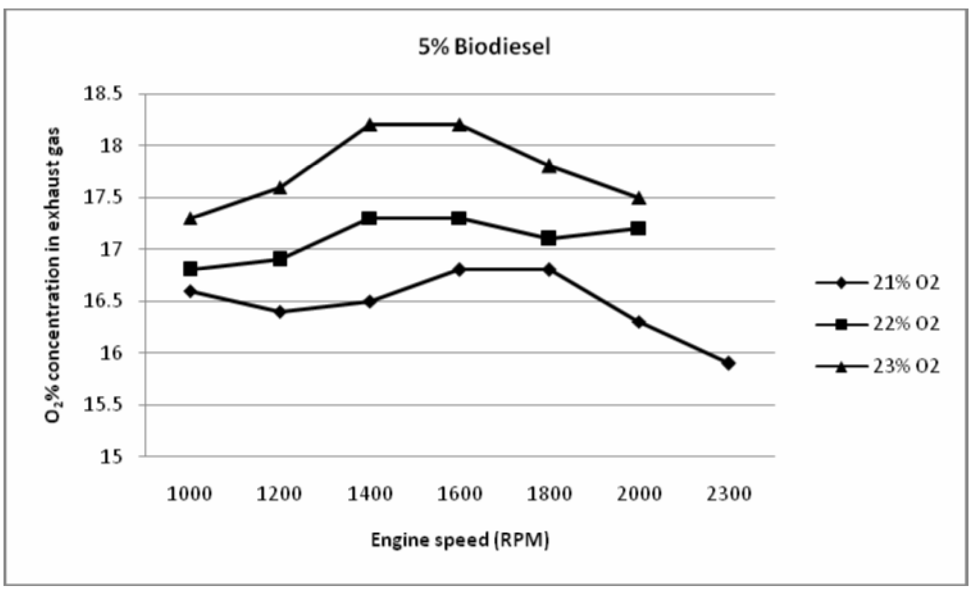


Figure (5.26): Exhaust gas O_2% as a function of engine speed for B5 fuel concentration and 21%, 22%, and 23% O_2 concentrations.

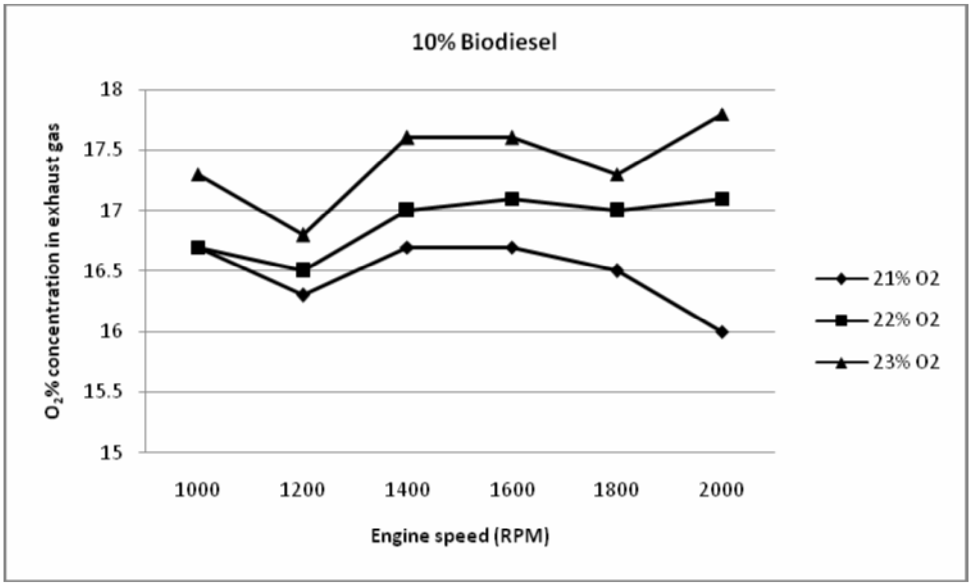


Figure (5.27): Exhaust gas O_2% as a function of engine speed for B10 fuel concentration and 21%, 22%, and 23% O_2 concentrations.

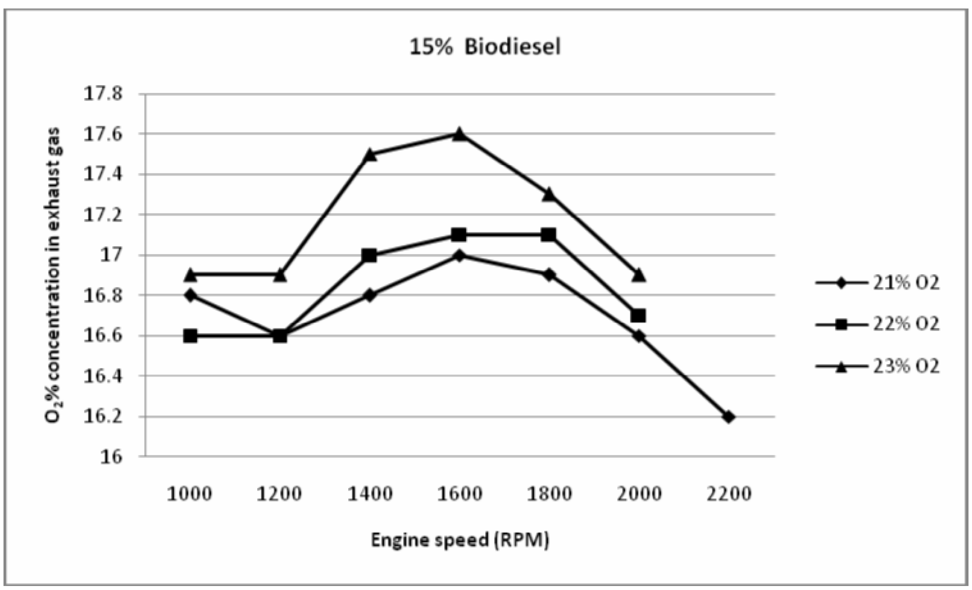


Figure (5.28): Exhaust gas O_2% as a function of engine speed for B15 fuel concentration and 21%, 22%, and 23% O_2 concentrations.

5.6 Effect of Biodiesel and Oxygen Concentration on Exhaust SO_2 Emissions

During internal combustion engine experimental work, SO_2 emissions did not change, it remains zero at all of the experimental measurements. So that, it can be concluded that using biodiesel with different concentrations from 0.0% up to 15% of the total fuel volume does not contribute in SO_2 generation. In addition, using higher oxygen concentrations with four stroke diesel internal combustion engine does not increase SO_2 emissions.

Chapter Six

Results and Discussion for Water Heating Boiler

In this section of experimental work, the experiment was implemented on water heating boiler, and the results were measured using the combustion analyzer, each recorded result was documented after suitable enough time of inserting the combustion analyzer probe into the exhaust stack emissions to ensure stability and steady measurements.

In this experimental work, seven levels of intake air oxygen enrichment were used; these levels are 21% O_2 which is the ambient air composition, 22%, 23%, 24%, 25%, 26%, and in some cases 27% O_2, no higher intake air oxygen concentrations were used in order to maintain the boiler, because higher oxygen concentrations need some modifications to protect the burner from damage as a result of the expected higher output temperature. [7]

As in the internal combustion engine section, the main variables in this experiment are biodiesel concentration and oxygen concentration in the intake air. In addition, in this section the combustion analyzer was used to monitor the burner excess air level, and experiments were performed under actual/optimum (19%) and theoretical (1%) excess air conditions.

6.1 Effect of Biodiesel and Oxygen Concentration on Exhaust Gas Temperature

It is known that exhaust gases in any combustion process carry different portions of energy contained in the fuel to the atmosphere, the amount of this wasted energy depends on many factors, one of them is the heat transfer sufficiency between the burned fuel and the load (load means the material that we aim to heat like water, air, etc…), another reason is the excess air quantity, the higher excess air quantity causes the higher energy waste. [2, 5, 29]

However, in this experimental work the boiler heat transfer area remains constant, and the water stream which is used to maintain the boiler temperature and heat transfer ratio was constant too. So that, the exhaust gas temperature can be used as an indicator about the combustion process thermal efficiency and how it is affected by higher intake air oxygen concentrations and/or higher biodiesel fuel concentrations.

As mentioned before, these experiments were performed under two excess air levels, the first one is the optimum or actual excess air (19% excess air) while the second one is the theoretical excess air (1% excess air).

Results of operating under actual excess air conditions show that the output temperature increases almost linearly by increasing the intake air oxygen concentration, it happens as a result of the additional oxygen quantities enter the combustion process; these oxygen quantities improve the combustion process and produce higher thermal energy, which means that the boiler can be modified in order to benefit from the extra output temperature, or in other words, there is an opportunity to save fuel. In similar fields, some investigators [7] achieved 50% – 60% fuel saving by implementing oxygen enriched combustion technology on boilers. Also, the output temperature increases by using higher biodiesel concentrations, the oxygen quantity which is contained in the biodiesel contributes in improving the combustion process too [23]. These results are shown in Figure 6.1. It's obviously noticed that at each biodiesel concentration, using 26% O_2 intake air concentration instead of 21% O_2 concentration increases the output temperature from 15 to 20 ^oC.

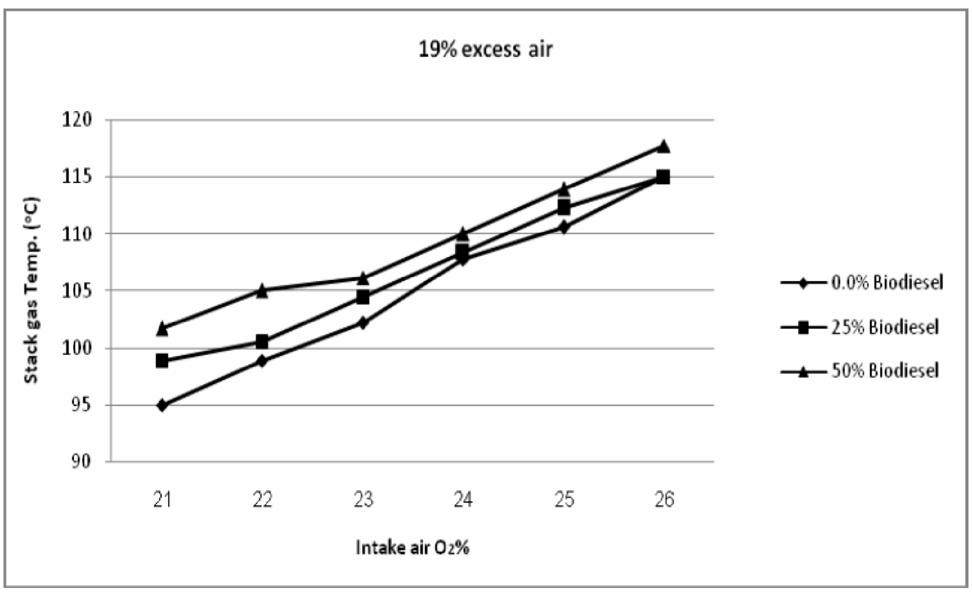


Figure (6.1): Boiler stack gas temperature (^oC) as a function of intake air oxygen concentration for B0, B25, and B50 fuel concentration and 19% excess air.

In similar way, results of operating under theoretical excess air (1%) condition show that the output temperature increase by either increasing the intake air oxygen concentration or by increasing the biodiesel concentration due to the additional oxygen quantities entering the process by biodiesel or intake air which improve the combustion process and produce higher output temperature [7, 23]. These results are shown in Figure 6.2. In this case, its obviously shown that using 26% O_2 intake air concentration instead of 21% O_2 ambient air concentration increases the output temperature up to 13 ^oC.

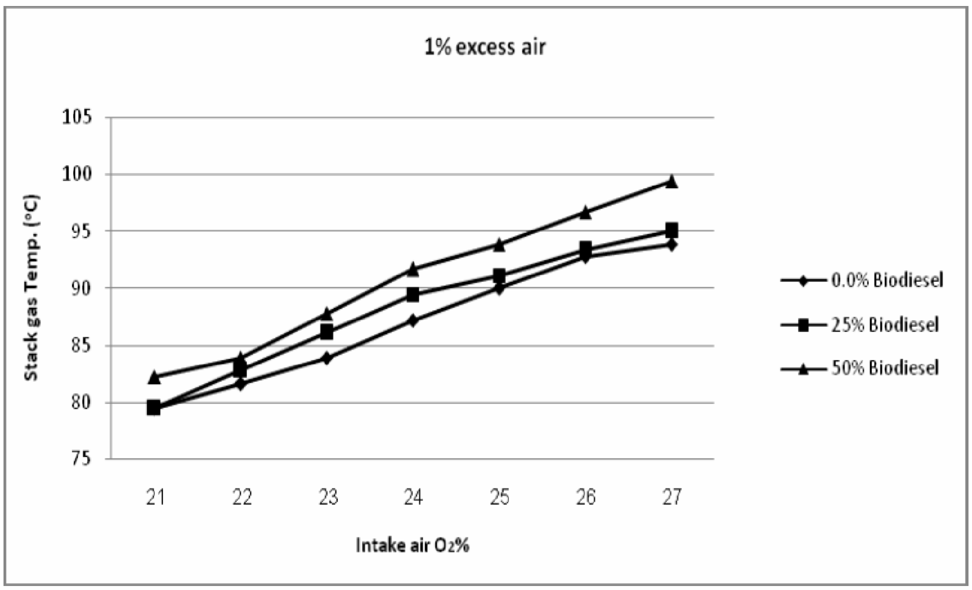


Figure (6.2): Boiler stack gas temperature (^oC) as a function of intake air oxygen concentration for B0, B25, and B50 fuel concentration and 1% excess air.

To explore differences in output temperature between the two operating cases (19% excess air and 1% excess air), results were analyzed with respect to specific biodiesel concentrations, its shown that when operating under actual excess air conditions, the output temperature is higher than when operating under theoretical excess air conditions, it happens as a result of the additional oxygen quantities enter the process in the case of 19% excess air. These results are shown in Figures 6.3 – 6.5. It's obvious from the figures that using 26% oxygen enrichment and theoretical excess air level (1%) gives the same results as 21% oxygen enrichment and optimum excess air level (19%).

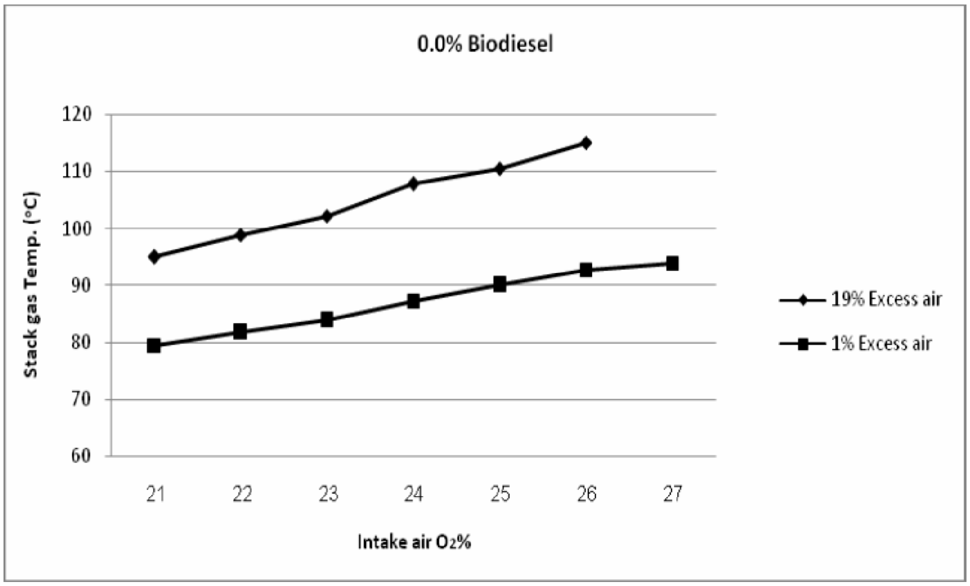


Figure (6.3): Boiler stack gas temperature (^{o}C) as a function of intake air oxygen concentration for 19% and 1% excess air B0 fuel concentration.

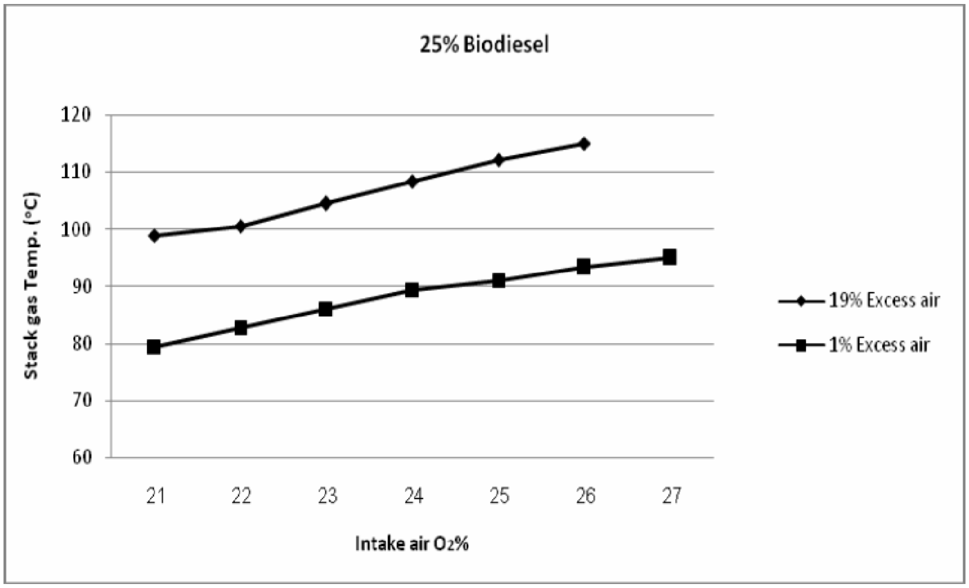


Figure (6.4): Boiler stack gas temperature (^oC) as a function of intake air oxygen concentration for 19% and 1% excess air B25 fuel concentration.

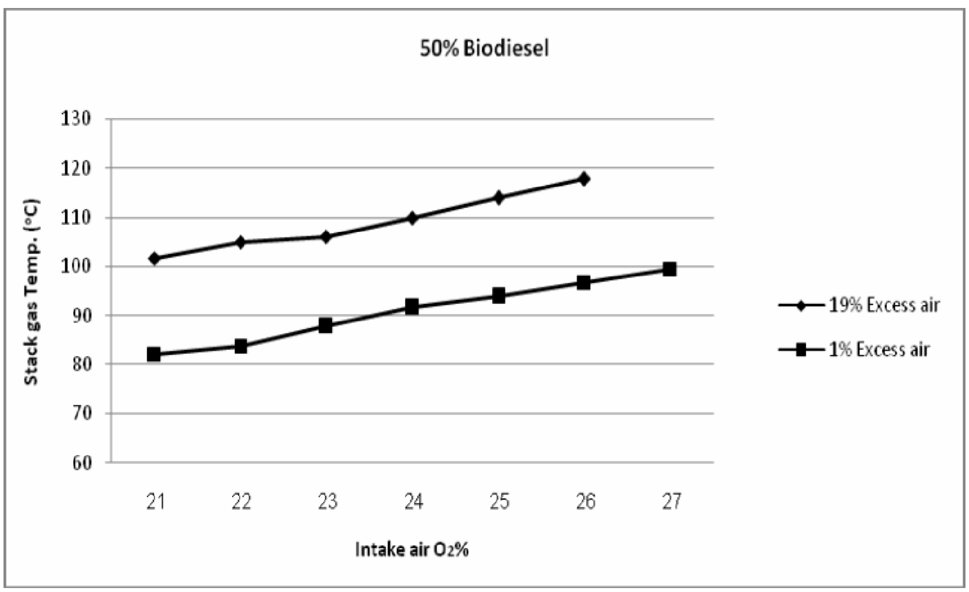


Figure (6.5): Boiler stack gas temperature (^oC) as a function of intake air oxygen concentration for 19% and 1% excess air B50 fuel concentration.

As a conclusion, the higher oxygen quantities in the intake air or the higher concentration of biodiesel fuel improve the combustion process and produce higher output temperature. These results can be summarized in Table 6.1. It's shown that using 26% O_2 intake air enrichment with B50 fuel can produce 99.4 ^{o}C output gas temperature which is higher than the output gas temperature when using 21% O_2 intake air with both of B0 and B25.

Table (6.1): Summarized boiler stack gas temperature when using different oxygen concentrations with different biodiesel ratios.

Excess air level	Stack gas temperature (^{o}C)					
	B0		B25		B50	
	O_2%		O_2%		O_2%	
	21	26	21	26	21	26
Optimum excess air (19%)	95	115	99	115	101.7	117.8
Theoretical excess air (1%)	79.4	92.8	79.4	93.3	82.2	99.4

To evaluate this improvement in stack gas temperature, an improvement percentage was calculated with respect to reference operating condition, this reference condition is pure petro-diesel fuel and ambient air oxygen concentration level (21% O_2).

When calculating the temperature improvement of using higher intake air oxygen concentration Equation (6.1) is used:

$$TI_O\ (\%) = ((T_2 - T_1) / T_1) * 100 \ldots\ldots\ldots\ldots\ldots (6.1)$$

Where:

TI_O = temperature improvement %.

T_1 = the output temperature when using ambient air oxygen concentration level (21%) and pure petro-diesel fuel.

T_2 = the output temperature when using X% intake air oxygen concentration and Y% biodiesel fuel concentration.

For example: to evaluate the temperature improvement of using 22% intake air oxygen enrichment knowing that the output temperature at this point is 99 ^oC, and the reference output temperature when using 21% intake air oxygen concentration is 95 ^oC, then the output temperature improvement can be calculated as:

$$TI\ (\%) = ((99 - 95) / 95) * 100 = 3.9\%$$

Also, similar method is used to evaluate the effect of using higher biodiesel concentrations, the reference in this case is when using B0 fuel, to do so, Equations (6.2) and (6.3) are used.

$$TI_B\ (\%) = ((T_2 - T_1) / T_1) * 100 \ldots\ldots\ldots\ldots (6.2)$$

Where:

TI_B = temperature improvement %.

T_1 = the output temperature when using X% intake air oxygen concentration level and pure petro-diesel fuel.

T_2 = the output temperature when using X% intake air oxygen concentration and Y% biodiesel fuel concentration.

Equation (6.2) will evaluate the temperature improvement at each oxygen concentration level. Then equation (6.3) computes the average of these temperature improvements.

$$TI\,\%_{(BXX)} = \text{Average}\,(TI\,\%_{(X\%\,O2)} + \text{- - - -} + TI\,\%_{(Y\%\,O2)}) \ldots\ldots\ldots \quad (6.3)$$

Where:

$TI\,\%_{(BXX)}$ = the average temperature improvement when using XX biodiesel fuel concentration at different oxygen concentration levels.

$TI\,\%_{(X\%\ O2)}$ = the temperature improvement when using Bxx at X% O_2 concentration.

$TI\,\%_{(Y\%\ O2)}$ = the temperature improvement when using Bxx at Y% O_2 concentration.

As an example: to evaluate the temperature improvement of using B25, the temperature improvement at each oxygen concentration level should be calculated, then the average of these improvements is computed as shown in Table 6.2.

Table (6.2): Example of boiler stack gas temperature improvement % calculation when using B25 fuel concentration.

Intake air O_2%	T1 (B0)	T2 (B25)	TI
21	95	99	4.1%
22	98.9	100.6	1.7%
23	102.2	104.4	2.2%
24	107.8	108.3	0.5%
25	110.6	112.2	1.5%
26	115	115	0
Average temperature improvement			**1.7%**

Implementing previous methods of calculating temperature improvement %, its found that using higher intake oxygen concentration produce higher temperature improvement, in similar way, its found also that using higher biodiesel fuel concentration produces higher temperature improvement too. These results are shown in Table 6.3. As an example, using B50 fuel instead of pure petro-diesel with different intake air oxygen concentrations and 19% excess air level can increase the boiler stack gas temperature 4.1% more than B0 fuel. Also, using 26% O_2 intake air enrichment with B0 fuel and 19% excess air level can increase the boiler stack gas temperature 21.1% more than using 21% O_2 intake air under the same conditions.

Table (6.3): Summarized boiler stack gas output temperature improvement % (^oC) when using different biodiesel concentrations and/or different intake air oxygen concentrations

Excess air %	Temperature improvement %					
	B25			B50		
19% Excess air	1.7			4.1		
1% Excess air	1.4			4.3		
Excess air % and biodiesel concentration	Temperature improvement %					
	22% O_2	23% O_2	24% O_2	25% O_2	26% O_2	27% O_2
19% excess air and B0	4.1	7.6	13.5	16.4	21.1	N.A
1% excess air and B0	2.8	5.6	9.8	13.3	16.8	18.2
19% excess air and B25	1.6	5.5	9.4	13.4	16.2	N.A
1% excess air and B25	4.2	8.4	12.6	14.7	17.5	19.6
19% excess air and B50	3.2	4.3	8.2	12	15.8	N.A
1% excess air and B50	2	6.8	11.5	14.2	17.6	20.9

6.2 Effect of Biodiesel and Oxygen Concentration on Exhaust NOx Emissions

As mentioned before, NOx emissions is one of the most poisonous combustion products, it contributes in forming acid rain which is destructive to whatever it comes in contact with, including plants, trees, and man made structures like buildings and bridges. [5, 7]

In this experimental work, results show that NOx emissions increase by using higher intake air oxygen concentration, the combustion process improvement due to additional oxygen quantity contributes in increasing NOx emissions thermal formation [7]. Also, NOx emissions increase when using higher biodiesel concentration, the additional oxygen quantities in the biodiesel improve the combustion and produce higher NOx emissions [10, 20-25]. These results are shown in Figures 6.6 and 6.7. In both excess air levels, it is shown that the increasing in NOx concentration in the stack gas emissions when using 23% O_2 intake air enrichment is higher than these emissions when using B50 fuel and 21% O_2 intake air.

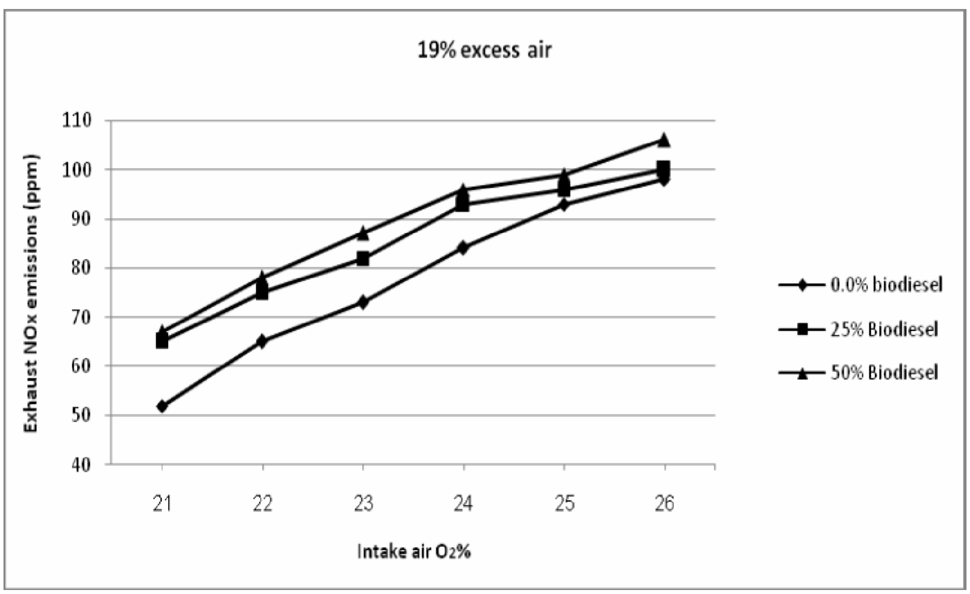


Figure (6.6): Boiler stack gas NOx emissions (ppm) as a function of intake air oxygen concentration for 19% excess air and B0, B25, and B50 fuel concentration.

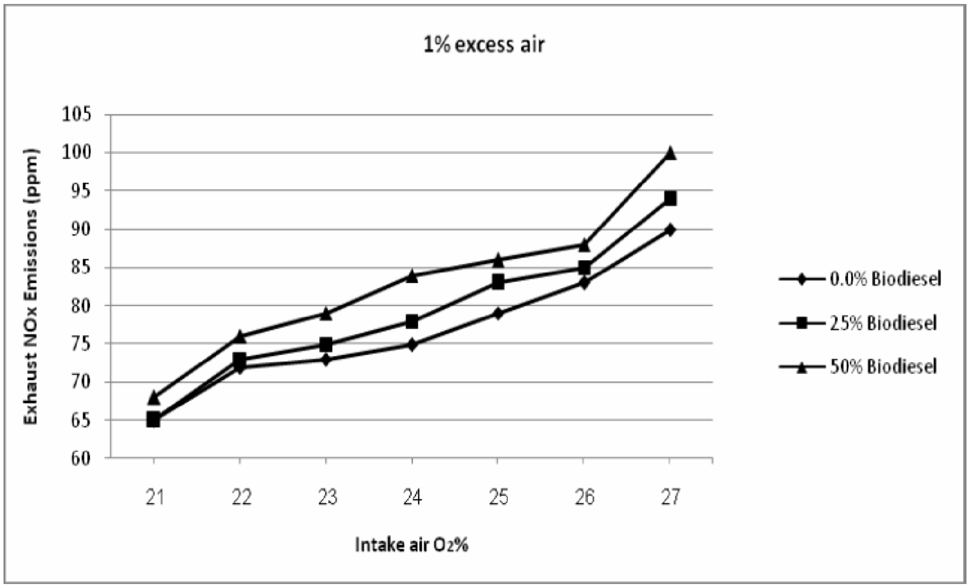


Figure (6.7): Boiler stack gas NOx emissions (ppm) as a function of intake air oxygen concentration for 1% excess air and B0, B25, and B50 fuel concentration.

In addition, experimental results show that operating under theoretical excess air conditions reduce NOx emissions, this reduction happens due to the reduction in ballast N_2 volume which is entering the combustion process with ambient air. These results are shown in Figures 6.8 – 6.10. Figure 6.8 is of special interest because at lower oxygen concentration and lower stack gas exhaust temperature, the NOx emissions when using 1% excess air is higher than when using 19% excess air. This behavior could be explained by prompt NOx formation. [7]

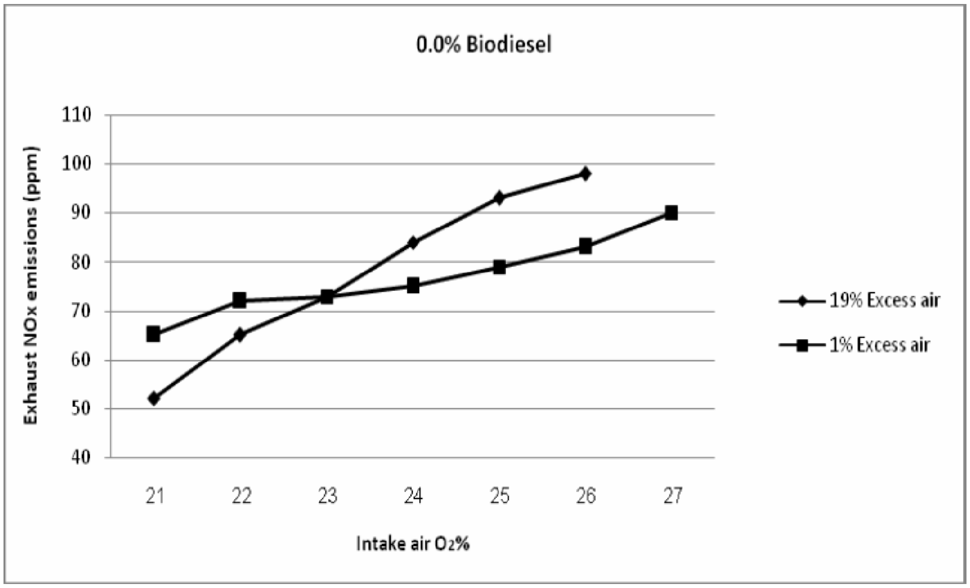


Figure (6.8): Boiler stack gas NOx emissions (ppm) as a function of intake air oxygen concentration for B0 fuel concentration and 19% and 1% excess air.

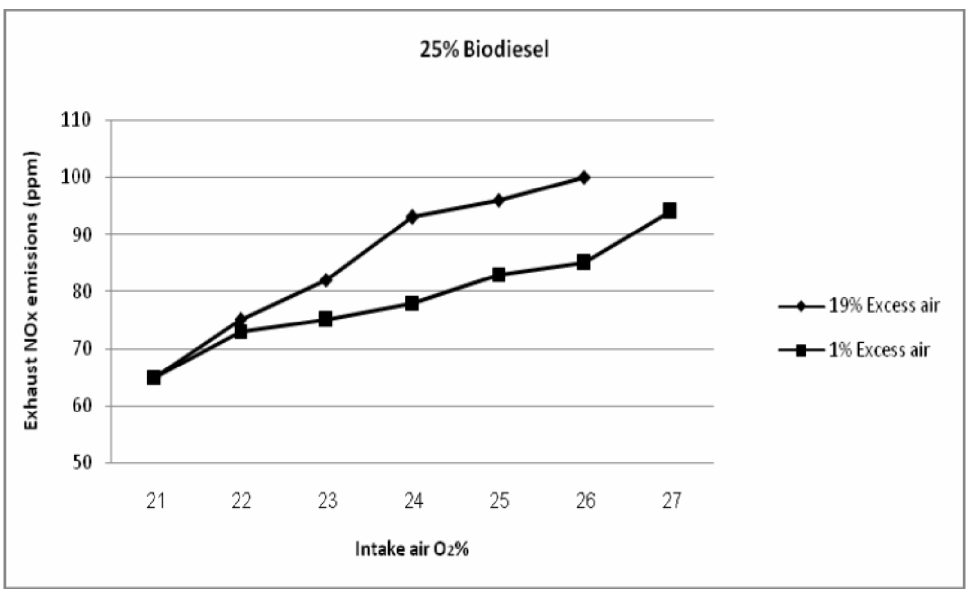


Figure (6.9): Boiler stack gas NOx emissions (ppm) as a function of intake air oxygen concentration for B25 fuel concentration and 19% and 1% excess air.

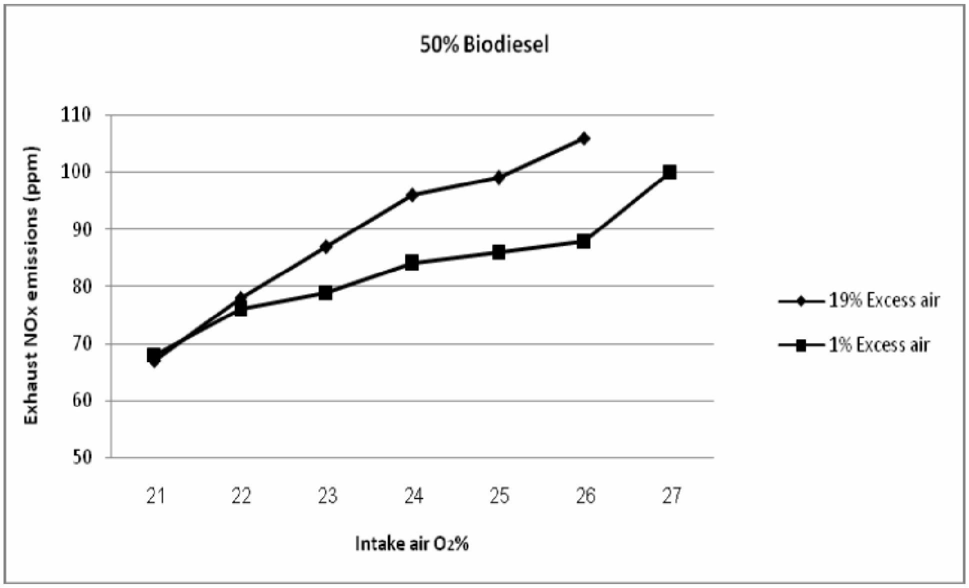


Figure (6.10): Boiler stack gas NOx emissions (ppm) as a function of intake air oxygen concentration for B50 fuel concentration and 19% and 1% excess air.

As a conclusion, NOx emissions increase when using either higher intake air oxygen or biodiesel concentrations, it happens due to the additional oxygen quantities in the biodiesel or air which improve the combustion process and increasing NOx emissions thermal formation. Also, using lower excess air quantities reduce the NOx formation due to the reduction in N_2 ballast volume entering the combustion process [7, 10, 20-25]. These results are summarized in Table 6.4.

Table (6.4): Summarized boiler stack gas NOx formation when using different oxygen concentrations with different biodiesel ratios.

Excess air level	NOx concentration (ppm)					
	B0		B25		B50	
	O_2%		O_2%		O_2%	
	21	26	21	26	21	26
Optimum excess air (19%)	52	98	65	100	67	106
Theoretical excess air (1%)	65	83	65	85	68	88

To determine the effect of using higher intake air or biodiesel concentrations as a percentage of reference case NOx emissions, NOx increasing or reduction emissions were calculated using the same method which is used to calculate the temperature improvement % (Equations e - g). In these calculations the NOx concentrations are used instead of using temperature values. The reference points were the ambient air oxygen concentration (21% O_2) and pure petro-diesel fuel conditions. These results are summarized in Table 6.5. For example, using 26% O_2 intake air concentration and B0 fuel at 19% excess air level increase NOx emissions 88.5% in comparison to using 21% O_2 intake air concentration under the same conditions.

Table (6.5): Summarized boiler stack gas NOx concentration change when using different biodiesel concentrations and different intake air oxygen concentrations

Excess air operating condition	NOx increasing %					
	B25			B25		
19% Excess air	11.5			16.2		
1% Excess air	2.9			8.1		
Excess air and biodiesel operating conditions	NOx increasing %					
	22% O_2	23% O_2	24% O_2	25% O_2	26% O_2	27% O_2
19% excess air and B0	25	40.4	61.5	78.8	88.5	N.A
1% excess air and B0	10.8	12.3	15.4	21.5	27.7	38.5
19% excess air and B25	15.4	26.2	43	47.7	53.8	N.A
1% excess air and B25	12.3	15.4	20	27.7	30.8	44.6
19% excess air and B50	16.4	29.9	43.3	47.8	58.2	N.A
1% excess air and B50	11.8	16.2	23.5	26.5	29.4	47.1

6.3 Effect of Biodiesel and Oxygen Concentration on Exhaust CO Emissions

Carbon monoxide is a toxic gas which is harmful for human and environment, and it contributes in forming smog. However, CO emissions can be used as an important indicator for combustion process completeness, higher CO emission means larger portion of the fuel does not burn completely. [5, 7]

Experimental results show that using higher intake air oxygen concentration reduces the CO emissions, additional oxygen quantities enter the combustion process improve its completeness and reduce CO emissions [7]. Also, using higher biodiesel concentration reduces CO emissions because of the oxygen quantity contained in the biodiesel; it improves the combustion process and its completeness [10, 23]. These results are shown in Figures 6.11 and 6.12. In the 19% excess air case, it is shown that there is no significant differences in CO stack gas emissions between B25 and B50 fuels especially when using intake air oxygen concentrations higher than 23%.

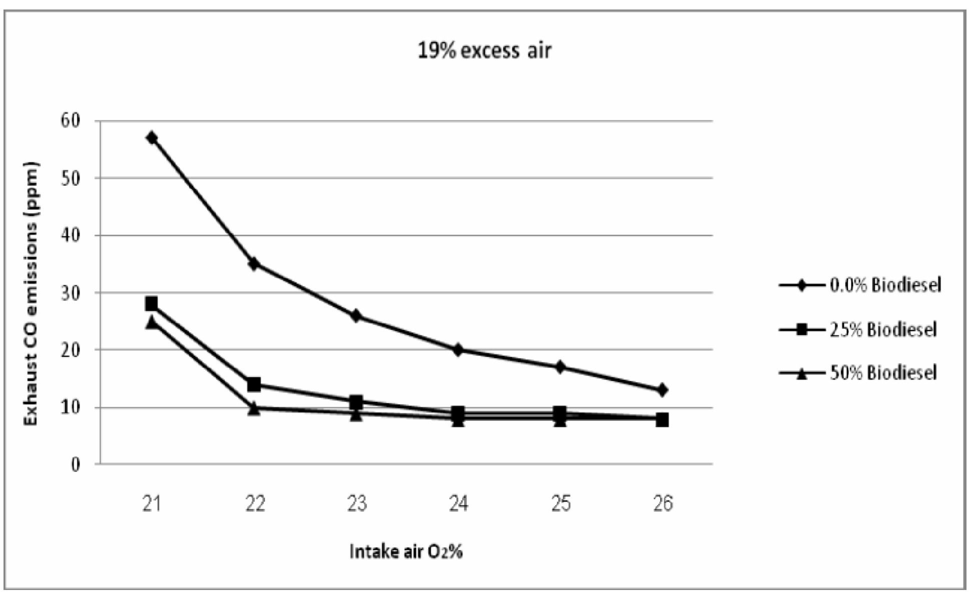


Figure (6.11): Boiler stack gas CO emissions (ppm) as a function of intake air oxygen concentration for 19% excess air and B0, B25, and B50 fuel concentrations.

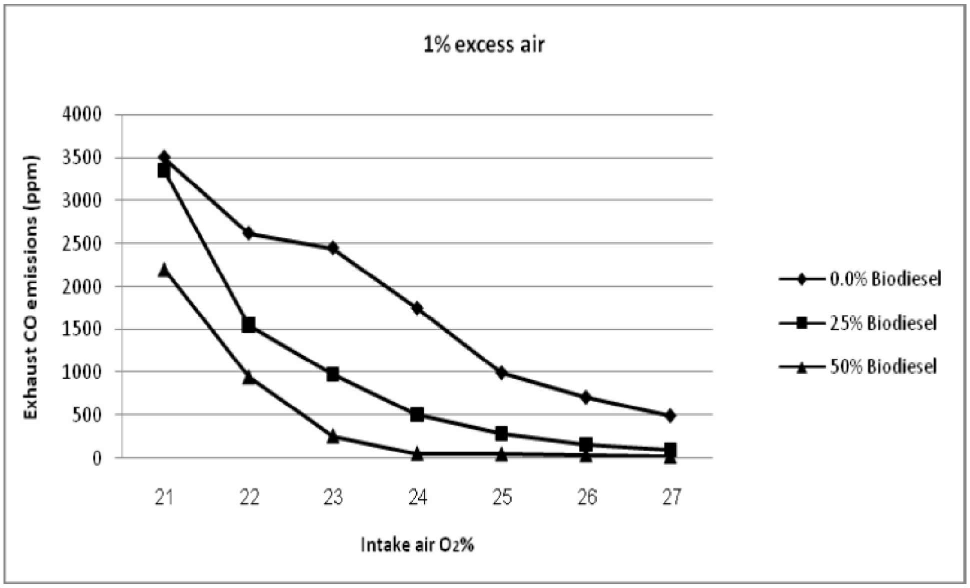


Figure (6.12): Boiler stack gas CO emissions (ppm) as a function of intake air oxygen concentration for 1% excess air and B0, B25, and B50 fuel concentrations.

As mentioned before, this experiment was performed using two excess air levels (theoretical and actual excess air levels), results show that when operating under theoretical (1%) excess air level and ambient air oxygen concentration (21% O_2), CO emissions is very higher, but when using higher intake air oxygen concentrations, CO exhaust gas emission reduces obviously, this reduction is a result of the additional oxygen quantities enter the combustion process which improve its completeness, it means that oxygen enriched combustion can be used as an effective method to reduce required excess air volumes and its related energy waste [3, 5-7]. These results are shown in Figures 6.13 – 6.15. It’s obviously shown that when using B50 fuel and intake air oxygen concentration from 24% and above, there is no significant difference in CO emissions between 19% excess air level and 1% excess air level.

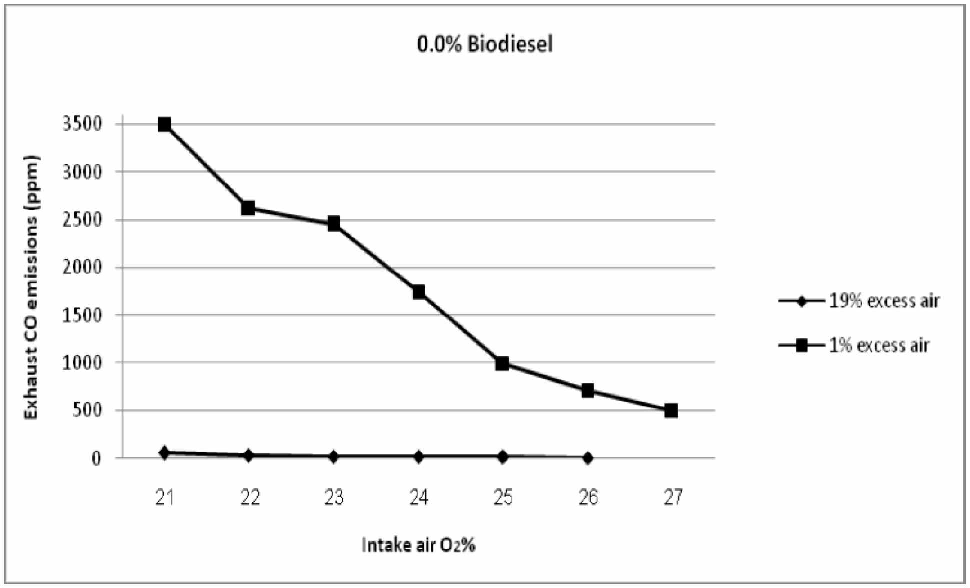


Figure (6.13): Boiler stack gas CO emissions (ppm) as a function of intake air oxygen concentration for 19% and 1% excess air and B0 fuel concentration.

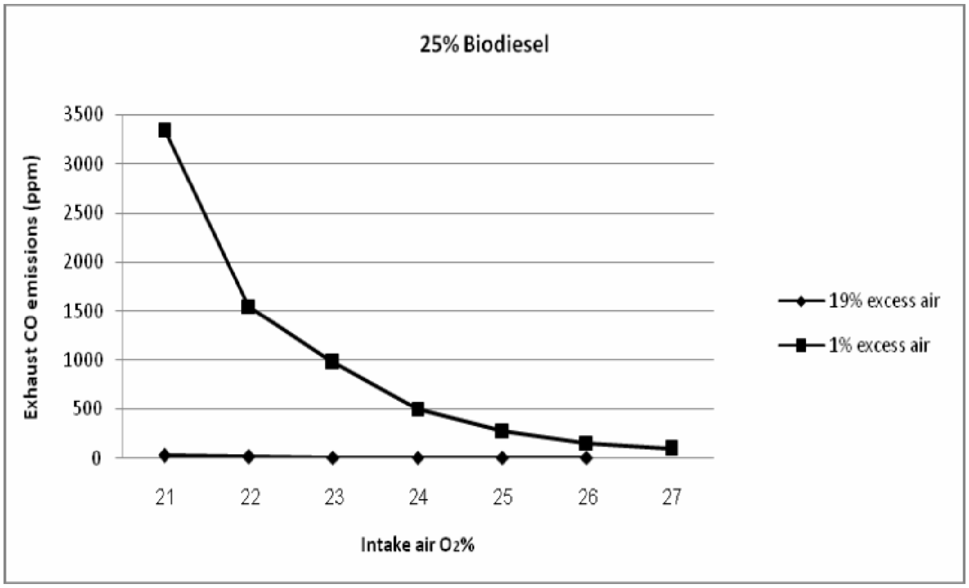


Figure (6.14): Boiler stack gas CO emissions (ppm) as a function of intake air oxygen concentration for 19% and 1% excess air and B25 fuel concentration.

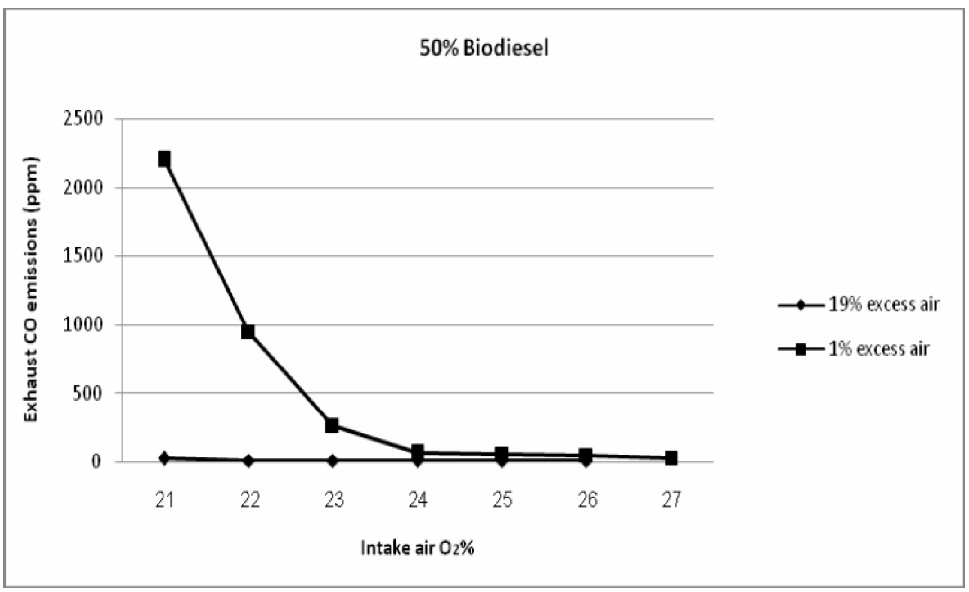


Figure (6.15): Boiler stack gas CO emissions (ppm) as a function of intake air oxygen concentration for 19% and 1% excess air and B50 fuel concentration.

As a conclusion, using either higher intake air oxygen or biodiesel fuel concentrations improve combustion process completeness and reduce CO emissions because of the additional oxygen quantities enter the process. These results are summarized in Table 6.6.

In addition, oxygen enriched combustion technology can be used with lower excess air levels; in this case, it will reduce a portion of the energy waste which happens due to the additional excess air quantities.

Table (6.6): Summarized boiler stack gas CO concentration when using different oxygen concentrations with different biodiesel ratios.

Excess air level	stack gas CO concentration (ppm)					
	B0		B25		B50	
	O_2%		O_2%		O_2%	
	21%	26%	21%	26%	21%	26%
Optimum excess air (19%)	57	13	28	8	25	8
Theoretical excess air (1%)	3500	715	3350	160	2200	29

And to evaluate the percent amount of CO emissions reduction by using higher intake air oxygen and/or biodiesel concentrations, the same method of calculating the exhaust temperature improvement and NOx increasing emissions is implemented (Equations e – g). In these calculations the CO concentrations are used instead of using temperature or NOx values. The reference points were the ambient air oxygen concentration (21% O_2) and pure petro-diesel fuel conditions. These results are summarized in Table 6.7. Its shown that the CO emissions reduction can be above 90% when using 1% excess air level and 26% intake air oxygen enrichment.

Table (6.7): Boiler stack gas CO emissions change % when using different biodiesel concentrations and different intake air oxygen concentrations

Excess air operating condition	CO reduction %	
	B25	B50
19% Excess air	-51.5	-57.4
1% Excess air	-58.1	-81.1

Excess air and biodiesel operating conditions	CO reduction %					
	22% O_2	23% O_2	24% O_2	25% O_2	26% O_2	27% O_2
19% excess air and B0	-38.6	-54.4	-64.9	-70.2	-77.2	N.A
1% excess air and B0	-25.1	-30	-50	-71.4	-79.6	-85.7
19% excess air and B25	-50	-60.7	67.9	67.9	71.4	N.A
1% excess air and B25	-53.7	-70.7	-85.1	-91.6	-95.2	-97.1
19% excess air and B50	-60	-64	-68	-68	-68	N.A
1% excess air and B50	-56.8	-87.7	-97	-97.4	-97.7	-98.7

The (-) sign means that there is a reduction in the CO formation about X%.

Either higher biodiesel or intake air oxygen concentrations affects the temperature, NOx, and CO exhaust emissions by decreasing or increasing itsvalues, Table 6.8 summarizes these effects in the water heating boiler application. In all of the performed analysis, the temperature and NOx stack gas emissions increase by increasing biodiesel fuel and/or intake air oxygen concentrations. On the other hand, CO stack gas emission decreases by using higher biodiesel fuel and/or intake air oxygen concentrations.

Table (6.8): Effects of using higher biodiesel and/or intake air oxygen concentrations on stack gas emissions in water heating boiler application.

Using higher oxygen concentrations with pure petro-diesel	Using higher biodiesel concentrations with ambient air oxygen concentration (21%)
Temperature increase CO decrease NOx increase	Temperature increase CO decrease NOx increase
Using higher oxygen concentration with blended fuel (biodiesel & petro-diesel)	**Using blended fuel (biodiesel & petro-diesel) with oxygen enriched intake air**
Temperature increase CO decrease NOx increase	Temperature increase CO decrease NOx increase

6.4 Effect of Biodiesel and Oxygen Concentration on Exhaust O_2 Emissions

To ensure as complete combustion as possible, it is necessary to operate under excess air conditions, which means higher intake air quantities containing 21% O_2 are given to the process to improve the combustion and ensure its completeness. However, although higher excess air level leads to better combustion characteristics, it has unavoidable disadvantages too; it carries a tangible amount of thermal energy by convection from combustion chamber and transfers it out to atmosphere as a waste energy with stack gases, to minimize this effect, the excess air level should be optimized at minimum points [3, 29].

In this experimental work, higher oxygen quantities can be given to the combustion process without using higher excess air levels, instead of it, enriching the intake air with higher oxygen concentrations can produce more benefits and reduce the energy waste due to higher excess air levels. [7]

Experimental results show that using higher intake air oxygen concentration increases the O_2% in the exhaust gas. Also, using higher biodiesel concentrations increase the O_2% in the exhaust gas too. These results are shown in Figures 6.16 and 6.17.

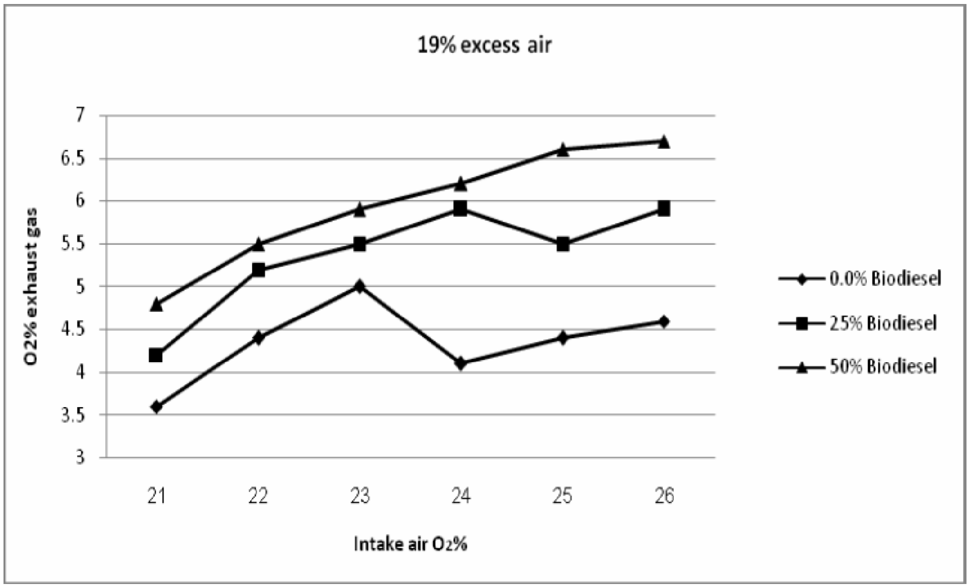


Figure (6.16): Boiler stack gas O_2% emissions as a function of intake air oxygen concentration for 19% excess air and B0, B25, and B50 fuel concentration.

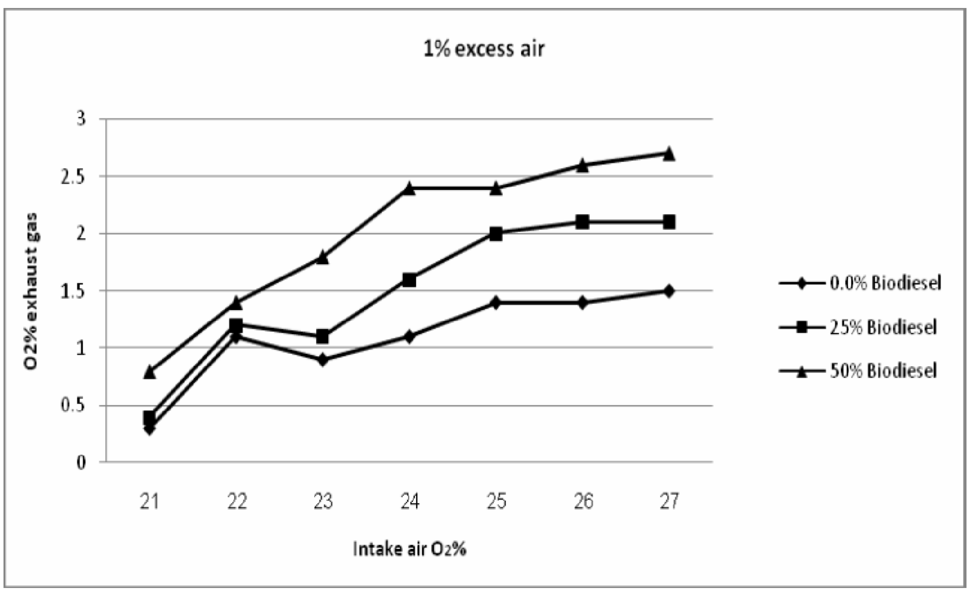


Figure (6.17): Boiler stack gas O_2% emissions as a function of intake air oxygen concentration for 1% excess air and B0, B25, and B50 fuel concentration.

In addition, comparing the experimental results of operating under two excess air levels shows that when using theoretical excess air level the exhaust O_2% is lower than when using actual (optimum) level, these results are shown in Figures 6.18 - 6.20.

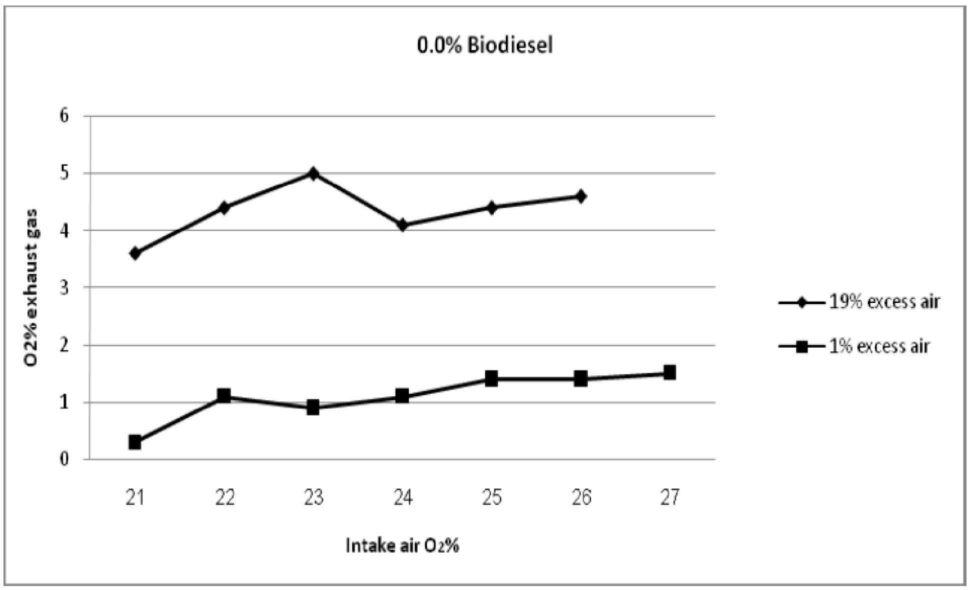


Figure (6.18): Boiler stack gas O_2% emissions as a function of intake air oxygen concentration for B0 fuel concentration and 19% and 1% excess air.

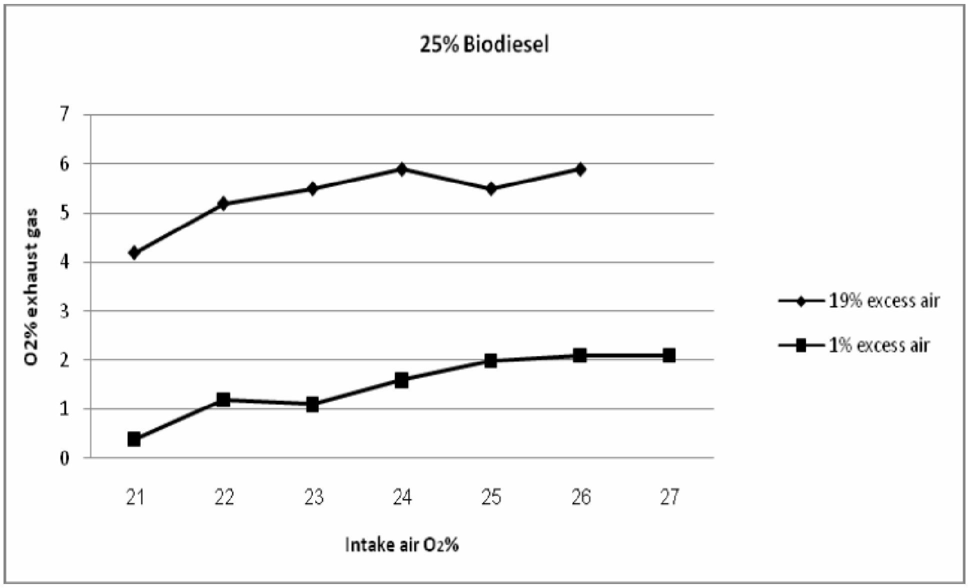


Figure (6.19): Boiler stack gas O_2% emissions as a function of intake air oxygen concentration for B25 fuel concentration and 19% and 1% excess air.

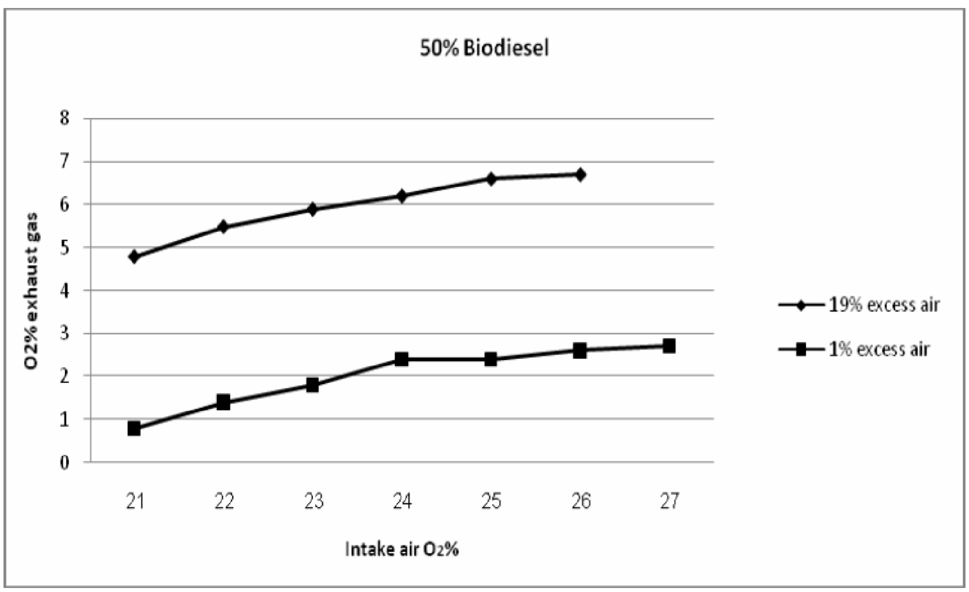


Figure (6.20): Boiler stack gas O_2% emissions as a function of intake air oxygen concentration for B50 fuel concentration and 19% and 1% excess air.

6.5 Effect of Biodiesel and Oxygen Concentration on Exhaust SO_2 Emissions

SO_2 is a poisonous gas that can be very corrosive in the presence of water. It is more destructive to plants than humans and animals; it forms acid rain when it combines with water in the atmosphere which is so destructive to the environment. [2, 7]

Experimental results show that when operating under actual (optimum) excess air level, SO_2 emissions remains zero in all of the experiments, no matter what intake air oxygen concentration or biodiesel concentration is used. But when operating under theoretical (1% excess air) level, SO_2 emissions were very high.

However, results show that SO_2 emissions can be reduced by using higher intake air oxygen concentrations, and this reduction can be maximized by using biodiesel blended with petro-diesel fuel, the intake air oxygen or biodiesel concentration leads to the higher SO_2 emission reduction that can be achieved. These results are shown in Figure 6.21. It is shown that using B50 fuel can reduce SO_2 stack gas emissions significantly when using 21% O_2 intake air concentration.

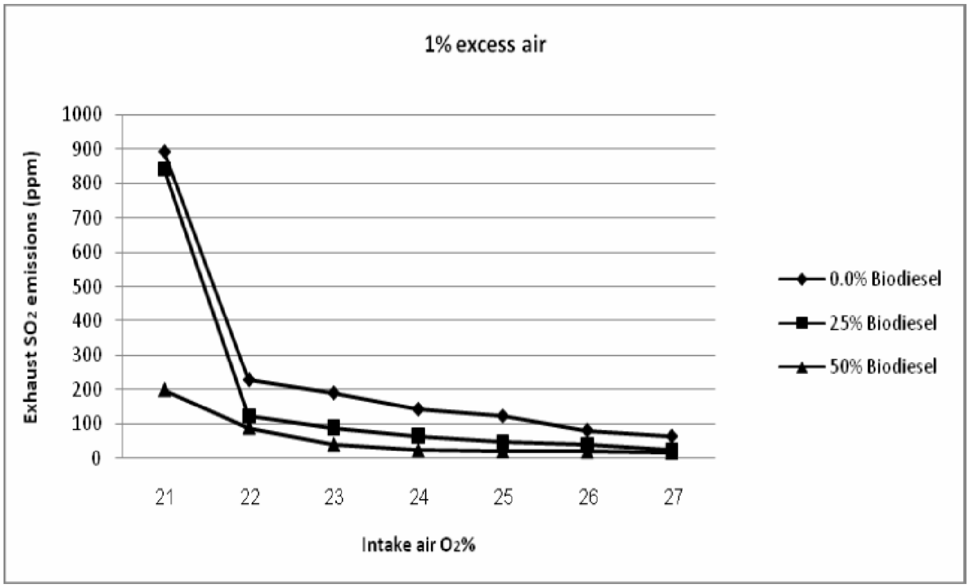


Figure (6.21): Boiler stack gas SO_2 (ppm) emissions as a function of intake air oxygen concentration for 1% excess air and B0, B25, and B50 fuel concentrations.

As a conclusion, the energy conservation advantages of low excess air levels can be achieved by supplying the combustion process with additional pure oxygen quantities to compensate the reduction in oxygen due to lower excess air levels, this oxygen can be supplied by either using higher oxygen concentration intake air or by using biodiesel fuel.

6.6 Effect of Biodiesel and Oxygen Concentration on Combustion Efficiency

Combustion efficiency can be defined as the ratio of output energy to input (stored) energy, in actual life, thermal efficiency is always below 100%, and in general most boilers are between 65% and 85% efficient, and the remaining

15% to 35% are energy waste, so that boiler efficiency can be defined simply in the following equation. [29]

$$\text{Boiler Efficiency (\%)} = 100\% - \text{Heat Losses \%}$$

In this experimental work, the increasing in stack gas temperature is an indicator of the combustion process improvement, in previous Table 6.2; it is shown that using higher intake air and/or biodiesel concentrations leads to stack gas temperature increasing, and because no modification have been made to the boiler insulation, heat transfer surfaces, or to the load, the temperature improvement can be concluded as an improvement of the exhaust gas energy portion, in general, the amount of energy in the stack gas from the stored energy of the fuel is about 18% as shown in Figure 6.22, and by knowing the percentage of temperature improvement, the efficiency improvement can be calculated by multiplying the percent temperature improvement by the stack gas energy losses (18%), as an example, the temperature improvement that can be achieved by using 26% intake air oxygen concentration and pure petro-diesel is 21.1%, so that the efficiency improvement can be calculated as (21.1% * 0.18 = 3.8%), these calculations are suitable when using optimum (19%) excess air level, but when using theoretical (1%) excess air level the stack gas carry both of thermal losses and uncombined fuel losses, these calculations of energy efficiency improvement are shown in Table 6.9. It is shown that using 26% intake air oxygen concentration with B0 fuel can improve the efficiency up to 3.8%.

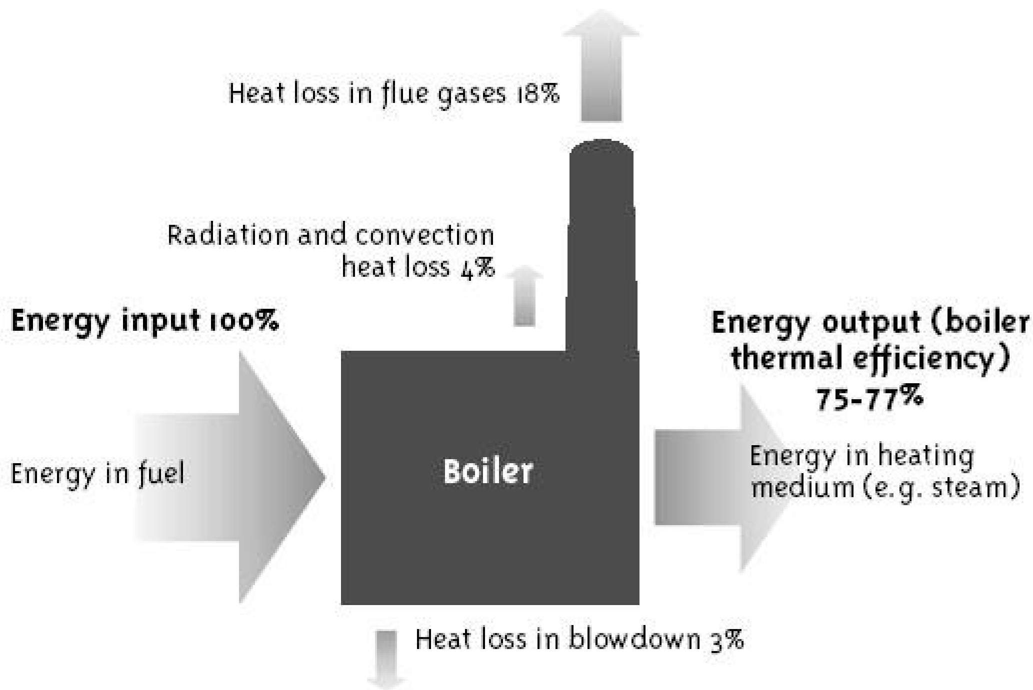


Figure (6.22): General energy losses in boilers. [5, 69]

Table (6.9): Combustion efficiency improvement indicators when using higher oxygen and/or biodiesel concentrations.

Excess air level	η improvement %			
	B25	η25	B50	η50
19% excess air	1.7%	0.31%	4.1%	0.74%

Excess air level	η improvement %									
	22% O_2	η22	23% O_2	η23	24% O_2	η24	25% O_2	η25	26% O_2	η26
B0 (19% excess air)	4.1	0.7	7.6	1.4	13.5	2.4	16.4	3	21.1	3.8
B25 (19% excess air)	1.6	0.3	5.5	1	9.4	1.7	13.4	2.4	16.2	2.9
B50 (19% excess air)	3.2	0.6	4.3	0.8	8.2	1.5	12	2.2	15.8	2.8

η: efficiency improvement %.

Chapter Seven
Conclusion

In all experiments, three main operating conditions were implemented and analyzed, these conditions are using different biodiesel concentrations with ambient intake air oxygen concentration (21% O_2), using oxygen enriched intake air (O_2 > 21%) with pure petro-diesel fuel, and using oxygen enriched intake air (O_2 > 21%) with blended fuel (petro-diesel and biodiesel) with different ratios. Results analysis uncovered obvious trends between using higher intake air oxygen and/or biodiesel concentration and the combustion process emissions.

7.1 Conclusions on Using Biodiesel Fuel and Oxygen Enriched Intake Air with Four Stroke Internal Combustion Engine.

Experimental results of using higher intake air oxygen concentration and/or higher biodiesel fuel concentration lead to a number of conclusions, in internal combustion engine, these conclusions can be classified with respect to the three operating conditions as:

7.1.1 Using higher intake oxygen concentration with pure petro-diesel fuel:

1. Exhaust gas temperature increases almost linearly by using higher intake air oxygen concentration. Also, there are no obvious differences in exhaust temperature between using 23% or 24% intake air oxygen

concentration. This exhaust temperature improvement is a result of the additional oxygen quantities enter the process and intensify the combustion.

2. Exhaust NOx emissions increase as a result of prompt formation, prompt NOx forms by the relatively fast reaction between nitrogen, oxygen, and hydrocarbon radicals, it’s a very complicated process consists of hundreds of reactions, the hydrocarbon radicals are intermediate species formed during the combustion process. Prompt NOx formation is generally happened at relatively low combustion processes temperature.
3. Exhaust CO emissions decrease when using oxygen enriched air, it happen due to the additional oxygen quantities enter the combustion process which improve reaction completeness.
4. Exhaust SO_2 emissions does not change when using higher intake air oxygen concentrations, in all experiments, SO_2 emissions were zero (ppm), on other words, using higher intake air oxygen concentration does not increase SO_2 emissions.

7.1.2 Using blended fuel (petro-diesel with biodiesel) with ambient intake air oxygen concentration (21% O_2):

1. Exhaust temperature increases when using higher biodiesel concentration, biodiesel is an oxygenated fuel, it intensifies the process and improves its completeness.
2. No significant changes in NOx emissions when using different biodiesel concentrations.
3. Using higher biodiesel fuel concentrations reduce CO exhaust emissions; the additional oxygen quantities contained in the biodiesel intensify the combustion process and improve its completeness.
4. Exhaust SO_2 emissions does not change when using higher biodiesel fuel concentrations, and SO_2 emissions were zero (ppm) in all experiments.

7.1.3 Using blended fuel (petro-diesel with biodiesel) with oxygen enriched intake air (O_2 > 21%):

1. The exhaust temperature increase when using either higher intake air oxygen concentration or higher biodiesel fuel concentration, it happens as a result of the additional oxygen quantities entering the process with either intake air or biodiesel fuel, it intensifies the combustion process and improves its completeness.

2. The NOx emissions decrease when using higher biodiesel fuel concentrations at specific intake air oxygen concentration, the higher oxygen quantities enter the process intensify it and improve its completeness. Also, using higher intake air oxygen concentration at specific biodiesel fuel concentration increase exhaust NOx emissions as a result of prompt formation, prompt NOx forms by the relatively fast reaction between nitrogen, oxygen, and hydrocarbon radicals, it's a very complicated process consisting of hundreds of reactions, the hydrocarbon radicals are intermediate species formed during the combustion process. Prompt NOx formation is generally happened at relatively low temperature combustion processes.
3. The Exhaust CO emissions increase by increasing biodiesel concentration with higher intake air oxygen concentration or by increasing intake air oxygen concentration with blended fuel (biodiesel with petro-diesel), it happens due to the existence of hydrocarbons and radicals especially at low temperature conditions. Also, higher exhaust temperature due to the higher oxygen concentration in the intake air or biodiesel fuel could also cause fuel dissociation and higher CO emissions.
4. Exhaust SO_2 emissions does not change when using higher biodiesel fuel concentrations with higher intake air oxygen concentration, and SO_2 emissions were zero (ppm) in all experiments.

7.2 Conclusions of Using Biodiesel Fuel and Oxygen Enriched Intake Air with Water Heating Boiler

Experimental results of using higher intake air oxygen concentration and/or higher biodiesel fuel concentration lead to a number of conclusions, in water heating boiler, these conclusions can be classified with respect to the three operating conditions as:

7.2.1 Using higher intake oxygen concentration with pure petro-diesel fuel:

1. Stack gas temperature increase almost linearly when using higher intake air oxygen concentrations in both of theoretical (1%) and optimum/actual (19%) excess air levels, it happens as a result of the additional oxygen quantities enter the combustion process which intensify it and improve its completeness.
2. Stack gas NOx emissions increase almost linearly when using higher intake air oxygen concentrations in both of theoretical (1%) and optimum/actual (19%) excess air levels, it happens as a result of the combustion process improvement due to additional oxygen quantity which enters the process and contributes in increasing NOx emissions thermal formation.

3. Stack gas NOx emissions can be reduced by operating under lower excess air level conditions, it happens as a result of ballast N_2 reduction.
4. Stack gas CO emissions decrease when using higher intake air oxygen concentration in both of theoretical (1%) and optimum/actual (19%) excess air levels, it happens as a result of the additional oxygen quantities which enter the combustion process, it improve its completeness and reduce CO emissions. Also, when operating under theoretical excess air level, stack gas CO emissions were very high and it reduced obviously by using higher intake air oxygen concentrations.
5. Stack gas SO_2 emissions does not change when operating under optimum (19%) excess air condition, but when operating under theoretical excess air level, SO_2 emissions were very higher, and it can be reduced by using higher intake air oxygen concentrations.

7.2.2 Using blended fuel (petro-diesel with biodiesel) with ambient intake air oxygen concentration (21% O_2):

1. Stack gas temperature increase when using higher blended fuel biodiesel concentration in both of theoretical (1%) and optimum/actual (19%) excess air levels, it happens as a result of the additional oxygen quantities contained in the biodiesel fuel which enter the combustion process and improve its completeness.

2. Stack gas NOx emissions increase when using higher blended fuel biodiesel concentration in both of theoretical (1%) and optimum/actual (19%) excess air levels, the additional oxygen quantities contained in the biodiesel intensify the combustion process and produce higher NOx emissions.
3. Stack gas CO emissions decrease when using higher biodiesel fuel concentration in both of the theoretical (1%) and optimum/actual (19%) excess air levels, the additional oxygen quantities contained in the biodiesel intensify the combustion process and reduce CO emissions. Also, when operating under theoretical excess air level, CO stack gas emissions are very high, and it can be reduced by using higher biodiesel concentration.
4. Stack gas SO_2 emissions does not change when operating under optimum (19%) excess air condition, but when operating under theoretical excess air level, SO_2 emissions were very higher, and it can be reduced by using higher biodiesel fuel concentrations.

7.2.3 Using blended fuel (petro-diesel with biodiesel) with oxygen enriched intake air (O_2 > 21%):

1. Stack gas temperature increase when using higher blended fuel biodiesel concentration with higher intake air oxygen concentration in both of theoretical (1%) and optimum/actual (19%) excess air levels, it

happens as a result of the additional oxygen quantities contained in oxygen enriched intake air biodiesel fuel which enter the combustion process and improve its completeness.

2. Stack gas NOx emissions increase when using higher biodiesel fuel with higher intake air oxygen concentration in both of theoretical (1%) and optimum/actual (19%) excess air levels, the additional oxygen quantities contained in the biodiesel intensify the combustion process and produce higher NOx emissions. Also, Stack gas NOx emissions can be reduced by operating under lower excess air level conditions, it happens as a result of ballast N_2 reduction.
3. Stack gas CO emissions decrease when using higher biodiesel fuel with higher intake air oxygen concentration in both of the theoretical (1%) and optimum/actual (19%) excess air levels, the additional oxygen quantities contained in the biodiesel fuel intensify the combustion process and reduce CO emissions. Also, when operating under theoretical excess air level, CO stack gas emissions were very high, and it can be reduced by using higher biodiesel fuel concentration with higher intake air oxygen concentration.
4. Stack gas SO_2 emissions does not change when operating under optimum (19%) excess air condition, but when operating under theoretical excess air level, SO_2 emissions were very higher, and it can be reduced by using higher biodiesel fuel concentrations with higher intake air oxygen concentrations.

Chapter Eight
Recommendations

Recommendations

Oxygen enriched combustion (OEC) technology can be considered as a new method of improving combustion processes, it has been known in the last two decades, since that time, a few number of studies were published to describe this method, its advantages, and its disadvantages. Also, most of these publications were limited to some applications like furnaces and burners.

This study analyzes the effects of using oxygen enriched combustion in both of internal combustion engine and water heating boiler, also, it was performed using both of pure petro-diesel and blended fuel (biodiesel with petro-diesel in different concentrations), it can be assumed a first step to explore the effects of implementing OEC and how it can be improved and brought into market. In order to distinguish the recommendations of each experimental part, it is divided into two groups as:

Group Number One: recommendations for implementing OEC technology on four stroke internal combustion engine with both pure petro-diesel and blended fuels (petro-diesel with biodiesel):

1. The engine fuel injection system should be modified in order to reduce the amount of fuel consumption and utilize the extra combustion thermal energy when using either biodiesel fuel or higher intake air oxygen concentration. In this way, CO emissions which happen as a result of fuel dissociation at higher temperatures may be decreased.

2. Some modifications should be done to the engine excess air level, using lower excess air levels with higher intake air concentrations or higher biodiesel fuel concentration is expected to reduce NOx emissions due to the reduction in ballast N_2 volume enters the process with the intake air.
3. Further studies should be done on internal combustion engines to investigate the effects of using higher intake air oxygen concentrations and/or higher biodiesel fuel concentrations on loaded engines.
4. The effects of using OEC technology and higher biodiesel fuel concentrations with internal combustion engines should be analyzed with respect to other exhaust emissions such as hydrocarbons (HC), N_2O, and particulates.

Group Number Two: recommendations for implementing OEC technology on water heating boiler with both of pure petro-diesel and blended fuels (petro-diesel with biodiesel):

1. Some boiler modifications should be done in order to utilize the elevation in combustion temperature which is produced as a result of using higher intake air oxygen concentrations and/or higher biodiesel fuel concentrations, to do so, the burner fuel consumption can be reduced or the internal heat transfer surfaces between the flame and the water can be redesigned to utilize the additional stack gas energy.
2. Biodiesel fuel and oxygen enriched intake air should be used to reduce the amount of stack gas CO emissions.

3. Similar studies should be done with different excess air levels after modifying the burner to operate with higher intake air oxygen concentrations, when using oxygen enriched intake air with higher concentrations (O_2 > 30%), it is expected to achieve obvious reduction in CO emissions and NOx emissions.
4. The effects of using OEC technology and higher biodiesel fuel concentrations with water heating boilers should be analyzed with respect to other exhaust emissions such as hydrocarbons (HC), N_2O, and particulates.
5. An in place oxygen production process such as membrane cell could be tested for economical analysis

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Appendixes

A. Results of Internal Combustion Engine Experimental Work

Table (A.1): Results of internal combustion engine using 21% O_2 intake air concentration and B0 fuel.

Date				7/4/2007	Diesel %	100				
Ambient Temp. ^oC				20.6	Bio-diesel %	0				
Intake Air O_2%				20.9	Experiment No.	1				
Engine Software Readings						**Combustion Analyzer Readings**				
No.	RPM	Temperatures ^oC			Fuel consumption (liter / hour)	Temperature ^oC	CO ppm	O_2%	NOx ppm	SO_2 ppm
		Fuel	Manifold	Coolant						
1	880	27.9	19.8	59.4	0.78	95	306	18.2	65	0
2	1000	33.3	22.5	72.9	1.17	101	554	15.9	7	0
3	1200	37.8	24.3	82.7	1.17	108	559	15.8	7	0
4	1400	41.4	26.1	86.4	1.17	119	424	16.2	23	0
5	1600	45.9	28.8	91.8	1.56	123	437	16.4	23	0
6	1800	49.5	29.7	100	1.56	131	450	16.5	26	0
7	2000	54	31.5	104.4	1.56	137	483	16.1	26	0
8	2200	60.3	33.3	101.7	1.95	143	456	16.1	26	0

Table (A.2): Results of internal combustion engine using 21% O_2 intake air concentration and B5 fuel.

Date	7/4/2007	Diesel %	95
Ambient Temp. ^oC	20.6	Bio-diesel %	5
Intake Air O_2%	20.9	Experiment No.	2

Engine Software Readings						**Combustion Analyzer Readings**				
No.	RPM	Temperatures ^oC			Fuel consumption (liter / hour)	Temperature ^oC	CO ppm	O_2%	NOx ppm	SO_2 ppm
		Fuel	Manifold	Coolant						
1	880	55.5	29.7	93.6	0.78	98	208	18.4	97	0
2	1000	56.7	29.7	96.3	0.78	102	448	16.6	35	0
3	1200	57.6	29.7	99	0.78	112	449	16.4	22	0
4	1400	58.5	30.6	103.5	1.17	119	375	16.5	24	0
5	1600	59.4	30.6	107.1	1.17	129	311	16.8	27	0
6	1800	61.2	31.5	N.A	1.56	136	368	16.8	28	0
7	2000	69.3	32.4	N.A	1.56	143	460	16.3	24	0
8	2200	65.7	34.2	N.A	1.95	150	540	15.9	24	0

Table (A.3): Results of internal combustion engine using 21% O_2 intake air concentration and B10 fuel.

Date				7/4/2007	Diesel %	90				
Ambient Temp. ^oC				20.6	Bio-diesel %	10				
Intake Air O_2%				20.9	Experiment No.	3				
Engine Software Readings						**Combustion Analyzer Readings**				
No.	RPM	Temperatures ^oC			Fuel consumption (liter / hour)	Temperature ^oC	CO ppm	O_2%	NOx ppm	SO_2 ppm
		Fuel	Manifold	Coolant						
1	880	60.3	29.7	92.7	0.78	100	212	18.3	101	0
2	1000	60.3	29.7	95.4	0.78	105	454	16.7	35	0
3	1200	61.2	30.6	98.1	1.17	110	480	16.3	21	0
4	1400	61.2	30.6	100.8	1.17	121	320	16.7	28	0
5	1600	63	30.6	107.1	1.56	126	314	16.7	29	0
6	1800	64.8	31.5	Fan	1.56	136	352	16.5	28	0
7	2000	66.6	32.4	Fan	1.95	141	417	16	27	0
8	2200	66.6	32.5	Fan	1.95	142	445	16	24	0

Table (A.4): Results of internal combustion engine using 21% O_2 intake air concentration and B15 fuel.

Date					24/4/2007	Diesel %	85				
Ambient Temp. ^oC					20.6	Bio-diesel %	15				
Intake Air O_2%					20.9	Experiment No.	4				
Engine Software Readings							**Combustion Analyzer Readings**				
No.	RPM	Temperatures ^oC			Fuel consumption (liter / hour)		Temperature ^oC	CO ppm	O_2%	NOx ppm	SO_2 ppm
		Fuel	Manifold	Coolant							
1	880	64.8	31.5	99	0.78		104	202	18.5	98	0
2	1000	65.7	30.6	100.8	0.78		110	450	16.8	32	0
3	1200	67.5	30.6	103.5	0.78		119	502	16.6	23	0
4	1400	69.3	32.4	fan	1.17		125	372	16.8	32	0
5	1600	70.2	32.4	fan	1.17		133	331	17	32	0
6	1800	72.9	33.3	fan	1.17		140	341	16.9	24	0
7	2000	75.6	34.2	fan	1.56		144	427	16.6	25	0
8	2200	77.4	35.1	fan	1.95		157	508	16.2	24	0

Table (A.5): Results of internal combustion engine using 23% O_2 intake air concentration and B0 fuel.

Date					8/7/2007	Diesel %	100				
Ambient Temp. ^oC					84 F	Bio-diesel %	0				
Intake Air O_2%					23	Experiment No.	5				
Engine Software Readings							**Combustion Analyzer Readings**				
No.	RPM	Temperatures ^oC			Fuel consumption (liter / hour)		Temperature ^oC	CO ppm	O_2%	NOx ppm	SO_2 ppm
		Fuel	Manifold	Coolant							
1	880	44.5	32.4	87.3	0.78		107.2	212	18.7	158	0
2	1000	60.3	35.1	99.9	0.78		112.2	305	17	140	0
3	1200	67.5	38.7	Fan	0.78		126.7	332	16.9	111	0
4	1400	70.2	40.5	Fan	1.17		134	280	17.7	94	0
5	1600	74.7	40.5	Fan	1.17		140.6	378	17.2	61	0
6	1800	76.5	41.5	Fan	1.56		144.4	370	17.3	81	0
7	2000	78.3	41.4	Fan	1.56		151.7	356	16.9	61	0

Table (A.6): Results of internal combustion engine using 22% O_2 intake air concentration and B5 fuel.

Date				29/7/2007		Diesel %	95				
Ambient Temp. ^oC				32.2		Bio-diesel %	5				
Intake Air O_2%				22		Experiment No.	6				
Engine Software Readings							**Combustion Analyzer Readings**				
No.	RPM	Temperatures ^oC			Fuel consumption (liter / hour)		Temperature ^oC	CO ppm	O_2%	NOx ppm	SO_2 ppm
		Fuel	Manifold	Coolant							
1	880	44.1	33.3	Fan	0.78		110	275	18.8	111	0
2	1000	50.4	34.2	Fan	0.78		112.8	580	16.8	38	0
3	1200	53.1	36	Fan	1.17		125	625	16.9	34	0
4	1400	55.8	37.8	Fan	1.17		133.3	435	17.3	43	0
5	1600	57.6	38.7	Fan	1.17		139.4	487	17.3	43	0
6	1800	60.3	38.7	Fan	1.56		147.2	436	17.1	36	0
7	2000	63	39.6	Fan	1.56		158.3	472	17.2	38	0

Table (A.7): Results of internal combustion engine using 22% O_2 intake air concentration and B10 fuel.

Date				29/7/2007	Diesel %	90				
Ambient Temp. ^oC				32.2	Bio-diesel %	10				
Intake Air O_2%				22	Experiment No.	7				
Engine Software Readings						**Combustion Analyzer Readings**				
No.	RPM	Temperatures ^oC			Fuel consumption (liter / hour)	Temperature ^oC	CO ppm	O_2%	NOx ppm	SO_2 ppm
		Fuel	Manifold	Coolant						
1	880	59	36.9	Fan	0.78	111	277	19.1	110	0
2	1000	58.5	37	Fan	0.78	118	770	16.7	36	0
3	1200	58.5	37.1	Fan	0.78	130	855	16.5	32	0
4	1400	58.5	37.8	Fan	1.17	132.2	585	17	38	0
5	1600	60.3	39.6	Fan	1.17	143.3	502	17.1	38	0
6	1800	65.7	40.5	Fan	1.56	153.3	535	17	40	0
7	2000	62.1	40.5	Fan	1.56	157.8	560	17.1	40	0

Table (A.8): Results of internal combustion engine using 22% O_2 intake air concentration and B15 fuel.

Date				1/8/2007		Diesel %	85				
Ambient Temp. ^oC				33		Bio-diesel %	15				
Intake Air O_2%				22		Experiment No.	8				
Engine Software Readings							**Combustion Analyzer Readings**				
No.	RPM	Temperatures ^oC			Fuel consumption (liter / hour)		Temperature ^oC	CO ppm	O_2%	NOx ppm	SO_2 ppm
		Fuel	Manifold	Coolant							
1	880	54.9	36.9	Fan	0.78		115.6	304	19	101	0
2	1000	54	35.1	Fan	0.78		117.2	972	16.6	28	0
3	1200	54	35.1	Fan	1.17		128.3	1150	16.6	23	0
4	1400	54.9	36.9	Fan	1.17		140	790	17	32	0
5	1600	58.5	38.7	Fan	1.17		149	696	17.1	34	0
6	1800	62.1	40.5	Fan	1.56		154.4	713	17.1	34	0
7	2000	64.8	41.4	Fan	1.56		165.6	724	16.7	35	0

Table (A.9): Results of internal combustion engine using 24% O_2 intake air concentration and B0 fuel.

Date					8/7/2007	Diesel %	100				
Ambient Temp. °C					84 F	Bio-diesel %	0				
Intake Air O_2%					24	Experiment No.	9				
Engine Software Readings							**Combustion Analyzer Readings**				
No.	RPM	Temperatures °C			Fuel consumption (liter / hour)		Temperature °C	CO ppm	O_2%	NOx ppm	SO_2 ppm
		Fuel	Manifold	Coolant							
1	880	73.8	39.7	Fan	0.78		113.9	158	20.8	270	0
2	1000	73.8	38.7	Fan	0.78		113.9	337	20	197	0
3	1200	74.7	39.6	Fan	0.78		126.7	385	19.5	172	0
4	1400	75.6	40.5	Fan	0.78		135	350	19.3	120	0
5	1600	76.5	41.4	Fan	1.17		143	336	19.8	137	0
6	1800			Fan	1.56		148	350	18.9	90	
7	2000	78.3	41.4	Fan	1.56		152.8	400	18.5	90	0

Table (A.10): Results of internal combustion engine using 23% O_2 intake air concentration and B5 fuel.

Date				29/7/2007		Diesel %	95				
Ambient Temp. ^oC				32.2		Bio-diesel %	5				
Intake Air O_2%				23		Experiment No.	10				
Engine Software Readings							**Combustion Analyzer Readings**				
No.	RPM	Temperatures ^oC			Fuel consumption (liter / hour)		Temperature ^oC	CO ppm	O_2%	NOx ppm	SO_2 ppm
		Fuel	Manifold	Coolant							
1	880	47.7	34.3	Fan	0.78		110	253	19.7	158	0
2	1000	51.3	35.1	Fan	0.78		113.3	530	17.3	59	0
3	1200	54	36.9	Fan	1.17		128.9	594	17.6	43	0
4	1400	56.7	37.8	Fan	1.17		135	506	18.2	71	0
5	1600	59.4	38.7	Fan	1.17		141.1	410	18.2	72	0
6	1800	61.2	39.6	Fan	1.56		148.9	428	17.8	75	0
7	2000	63.9	40.5	Fan	1.56		160	445	17.5	64	0

Table (A.11): Results of internal combustion engine using 23% O_2 intake air concentration and B10 fuel.

Date				29/7/2007		Diesel %	90				
Ambient Temp. °C				32.2		Bio-diesel %	10				
Intake Air O_2%				23		Experiment No.	11				
Engine Software Readings							**Combustion Analyzer Readings**				
No.	RPM	Temperatures °C			Fuel consumption (liter / hour)		Temperature °C	CO ppm	O_2%	NOx ppm	SO_2 ppm
		Fuel	Manifold	Coolant							
1	880	59.4	36,9	Fan	0.78		115	270	19.5	137	0
2	1000			Fan	0.78		121.1	741	17.3	40	0
3	1200	58.5	36.9	Fan	1.17		126.7	792	16.8	33	0
4	1400	58.5	38.7	Fan	1.17		137.8	528	17.6	51	0
5	1600	59.4	38.7	Fan	1.56		142.2	467	17.6	53	0
6	1800	66.6	40.5	Fan	1.56		152.8	520	17.3	51	0
7	2000	64.8	40.5	Fan	1.95		164.4	557	17.8	58	0

Table (A.12): Results of internal combustion engine using 23% O_2 intake air concentration and B15 fuel.

Date				1/8/2007	Diesel %	85				
Ambient Temp. ^oC				33	Bio-diesel %	15				
Intake Air O_2%				23	Experiment No.	12				
Engine Software Readings						**Combustion Analyzer Readings**				
No.	RPM	Temperatures ^oC			Fuel consumption (liter / hour)	Temperature ^oC	CO ppm	O_2%	NOx ppm	SO_2 ppm
		Fuel	Manifold	Coolant						
1	880	54.9	36	Fan	0.78	116.7	277	19.8	150	0
2	1000	54	35.1	Fan	0.78	118.9	963	16.9	40	0
3	1200	54.9	36	Fan	1.17	131.1	1105	16.9	28	0
4	1400	56.7	37.8	Fan	1.17	142.8	772	17.5	38	0
5	1600	60.3	39.6	Fan	1.17	150.6	680	17.6	42	0
6	1800	63	40.5	Fan	1.56	156.7	715	17.3	42	0
7	2000	65.7	41.4	Fan	1.56	168.3	728	16.9	43	0

B. Results of Water Heating Boiler Experimental Work

Table (B.1): Results of water heating boiler using B0 fuel and 19% excess air level.

Date	12/11/2007		Experiment number			13		
Ambient Temperature ^oC	21		Diesel %			100		
Excess air %	19		Biodiesel %			0		
Oxygen Enrichment %	NOx (ppm)	SO_2 (ppm)	Temperature ^oC	CO (ppm)	O_2%	Efficiency %	CO_2 %	EA%
21	52	4	95	57	3.6	85.2	12.9	19
22	65	4	99	35	4.4	85.4	12.3	24
23	73	2	102.2	26	5	84.6	11.9	29
24	84	0	107.8	20	4.1	86	12.5	23
25	93	0	110.6	17	4.4	86	12.4	24
26	98	0	115	13	4.6	86	12.2	26

Table (B.2): Results of water heating boiler using B25 fuel and 19% excess air level.

Date	12/11/2007		Experiment number			14		
Ambient Temperature ^oC	21		Diesel %			75		
Excess air %	19		Biodiesel %			25		
Oxygen Enrichment %	NOx (ppm)	SO_2 (ppm)	Temperature ^oC	CO (ppm)	O_2%	Efficiency %	CO_2 %	EA%
21	65	0	99	28	4.2	86.8	12.5	23
22	75	0	100.6	14	5.2	86.1	11.8	29
23	82	0	104.4	11	5.5	85.9	11.6	33
24	93	0	108.3	9	5.9	83.8	11.3	36
25	96	0	112.2	9	5.5	86.1	11.5	33
26	100	0	115	8	5.9	85.7	11.2	36

Table (B.3): Results of water heating boiler using B50 fuel and 19% excess air level.

Date	12/11/2007		Experiment number			15		
Ambient Temperature ^oC	21		Diesel %			50		
Excess air %	19		Biodiesel %			50		
Oxygen Enrichment %	NOx (ppm)	SO_2 (ppm)	Temperature ^oC	CO (ppm)	O_2%	Efficiency %	CO_2 %	EA%
21	67	0	101.7	25	4.8	86.6	12	27
22	78	0	105	10	5.5	86.3	11.5	31
23	87	0	106.1	9	5.9	85.8	11.2	35
24	96	0	110	8	6.2	85.5	11	38
25	99	0	113.9	8	6.6	85.7	10.7	40
26	106	0	117.8	8	6.7	85.5	10.6	42

Table (B.4): Results of water heating boiler using B0 fuel and 1% excess air level.

Date	13-11-2007		Experiment number			16		
Ambient Temperature ^oC	24		Diesel %			100		
Excess air %	1		Biodiesel %			0		
Oxygen Enrichment %	NOx (ppm)	SO_2 (ppm)	Temperature ^oC	CO (ppm)	O_2%	Efficiency %	CO_2 %	EA%
21	65	891	79.4	3500	0.3	86.1	15.4	1
22	72	229	81.7	2620	1.1	86.6	14.8	4
23	73	191	83.9	2450	0.9	87	14.9	3
24	75	143	87.2	1750	1.1	87.3	14.7	4
25	79	123	90	1000	1.4	87.9	14.6	6
26	83	82	92.8	715	1.4	88	14.3	5
27	90	65	93.9	500	1.5	88.3	14.8	6

Table (B.5): Results of water heating boiler using B25 fuel and 1% excess air level.

Date	13-11-2007		Experiment number			17		
Ambient Temperature ^oC	24		Diesel %			75		
Excess air %	1		Biodiesel %			25		
Oxygen Enrichment %	NOx (ppm)	SO_2 (ppm)	Temperature ^oC	CO (ppm)	O_2%	Efficiency %	CO_2 %	EA%
21	65	840	79.4	3350	0.4	87.1	15.3	1
22	73	123	82.8	1550	1.2	86.8	14.6	4
23	75	89	86.1	980	1.1	87.1	14.7	4
24	78	65	89.4	500	1.6	88.1	14.4	7
25	83	47	91.1	280	2	88.1	14.1	8
26	85	39	93.3	160	2.1	88.1	14	10
27	94	25	95	98	2.1	88	14.3	10

Table (B.6): Results of water heating boiler using B50 fuel and 19% excess air level.

Date	13-11-2007		Experiment number			18		
Ambient Temperature ^oC	24		Diesel %			50		
Excess air %	1		Biodiesel %			50		
Oxygen Enrichment %	NOx (ppm)	SO_2 (ppm)	Temperature ^oC	CO (ppm)	O_2%	Efficiency %	CO_2 %	EA%
21	68	200	82.2	2200	0.8	88.1	11.9	4
22	76	91	83.9	950	1.4	88.2	12.4	6
23	79	41	87.8	270	1.8	88.2	14.3	8
24	84	25	91.7	67	2.4	88.1	13.8	12
25	86	22	93.9	58	2.4	88.2	13.7	12
26	88	21	96.7	50	2.6	88.4	13.7	13
27	100	18	99.4	29	2.7	88.3	13.5	13

جامعة النجاح الوطنية
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إعداد
محمد فهد محمد السيد

إشراف
د. عبد الرحيم أبو صفا

قدمت هذه الأطروحة استكمالا لمتطلبات نيل درجة الماجستير في هندسة الطاقة النظيفة واستراتيجية الترشيد بكلية الدراسات العليا في جامعة النجاح الوطنية نابلس فلسطين.

2008

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إعداد

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الملخص

إن الهدف الأساسي من إجراء هذه الدراسة هو التحقق من أثر استخدام الهواء الغني بالاكسجين في عملية احتراق الوقود كثير الانبعاثات (الديزل والديزل الحيوي بنسب مختلفة) داخل محرك احتراق داخلي من انتاج شركة فولكس فاجن passat وبويلر تدفئة منزلية، في كلتا الحالتين، تمت زيادة نسبة الاكسجين في الهواء الداخل إلى عملية الاحتراق من خلال استخدام أسطوانة أكسجين خارجية وحقنه بشكل مباشر في الهواء الداخل للعملية، وقد استخدمت نسب هواء مشبع بالاكسجين لغاية 24% و27% في كل من محرك الاحتراق الداخلي والبويلر على التوالي. ولمعايرة نسب الأكسجين المطلوبة ودراسة تأثير الهواء على الغازات المنبعثة تم استخدام جهاز فحص الانبعاثات الناتجة من عملية الاحتراق (Bacharach) موديل 300.

لقد بينت نتائج تحليل انبعاثات عملية الاحتراق في محرك الاحتراق الداخلي عند استخدام كل من الديزل أو النسب المختلفة من الديزل والديزل الحيوي وزيادة نسبة الاكسجين في الهواء الداخل على العملية بأن درجة حرارة الهواء العادم تزداد بشكل ملحوظ وتصل 14% في بعض القراءات والتي تم الحصول عليها عند استخدام هواء غني بالاكسجين بنسبة 24% ووقود ديزل تقليدي دون استخدام الديول الحيوي، والسبب الرئيسي الذي أدى إلى هذه

الارتفاع في درجات الحرارة هو الاكسجين الزائد الذي دخل للعملية والذي أدى إلى تحسين فاعلية الاحتراق ورفع كفائته. كما وبينت النتائج بأن استخدام الديزل الحيوي وبنسبة 15% مع الهواء الجوي (غير الغني بالاكسجين) قد أدى إلى ارتفاع درجة الحرارة بنسبة 14% لنفس السبب المذكور سابقاُ. وعند تطبيق التجربة على البويلر المنزلي فقد تم الحصول على نتائج مشابهة حيث تم الحصول على 21.1% ارتفاع في درجة حرارة الهواء العادم عند استخدام هواء غني بالاجسجين بنسبة 26% وديزل بنسبة 100% (والتي تقدر بحوالي 3.8% تحسن في كفاءة الاحتراق).

كما وبينت النتائج بأن استخدام الهواء الغني بالأكسجين في عملية احتراق الوقود كثير الانبعاثات له تأثير على هذه كميات وتركيبة الانبعاثات في كل من محرك الاحتراق الداخلي وبويلر التسخين المنزلي، ففي حالة محرك الاحتراق الداخلي، تزداد نسبة ال NOx عند استخدام هواء غني بالاكسجين وخليط من وقود الديزل والديزل الحيوي. أما في حالة البويلر المنزلي، فإن كمية انبعاث ال NOx تنخفض عند التشغيل تحت ظروف الاحتراق المثالي نتيجة خفض نسبة ال N_2 الداخل للعملية.

وبشكل مشابه، فإن نسبة ال SO_2 في الغازات المنبعثة لا تتغير عند استخدام الهواء الغني بالأكسجين أو خليط الوقود، ولكنها ترتفع وبشدة في حال تشغيل البويلر تحت ظروف الاحتراق المثالية ويمكن السيطرة عليها وخفضها باستخدام الهواء الغني بالأكسجين أي بتزويد العملية بالكميات الضرورية لها من عنصر الأكسجين.

وخلصت الدراسة إلى وجود متغيرات إيجابية عند استخدام الهواء الغني بالأكسجين في عملية الاحتراق لكل من الديزل الحيوي والديزل العادي مثل الطاقة الإضافية التي تنتج عن العملية والتي يستدل عليها من درجات حرارة الغازات المنبعثة وما يمكن أن ينتج عن استغلالها من توفير في كميات الاستهلاك، ولكنها بحاجة إلى إجراء دراسات أخرى للتخلص من بعض الآثار السلبية التي ظهرت مثل ارتفاع معدل انبعاث بعض الغازات الضارة.

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