QATAR UNIVERSITY

COLLEGE OF ENGINEERING

DEVELOPMENT OF EMISSIONS REDUCTION TUBE FOR DIESEL ENGINES

BY

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A Thesis Submitted to

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ABSTRACT

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Title: Development of Emissions Reduction Tube for Diesel Engines.

Supervisor of Thesis: Samer A. Fikry.

Automobile industry have grown a lot since the last century and caused a serious issue of emission releases to the atmosphere regardless of how useful it is to human beings. Compression ignition diesel engines in particular will be the main focus of this project due to the huge smoke emissions that are caused by incomplete combustion of diesel fuel.

An emissions reduction tube has been fabricated and installed at the exhaust of a single cylinder diesel engine that has a size of 230 cubic centimeters. Water and sodium hydroxide were used as absorbing mediums.

The main effect was on engine's emissions which are HC, CO, CO2, NOx and smoke. Water has reduced hydrocarbon's emissions by almost 40% but didn't affect the CO2 emissions. Sodium hydroxide solution which is 50% saturated however has reduced carbon dioxides emissions almost by 90%. Moreover, NOx emissions were reduced for both water and NaOH experiments. Smoke emissions were reduced by 80% for both constant load and constant speed experiments.

In conclusion, NaOH and water showed that it is very possible to reduce or even stop the harmful gasses from polluting the environment. An HC-CO2 reduction trade-of relation has been found when using water and NaOH solution respectively, but in general with a little bit of optimization, all emissions could be reduced to an acceptable

limit keeping the environment as safe as possibly can.

DEDICATION

This work is dedicated for all those who gave me the courage to continue my studies. I thank Al-mighty Allah and my family for the support they have given me during the program. Special thanks go to my beloved wife Nariman who stood by me throughout the report writing.

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Over and above all, I give praise to my creator Allah for his never-ending blessings in my life.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

In this chapter, a clear problem definition will be stated and addressed that would clearly justify the needs of ways, techniques and efforts that individuals and corporates are trying to study to come up with something that would stop or reduce the large and hazardous amounts of automobile exhaust gasses released from diesel engines.

1.1 Problem Definition

Automobiles play a crucial role in everyone's daily life from transportation of people to goods to trades etc. population growth has led to an increase in the number of cars and trucks used on daily basis. Industrial continuous demand and revolution came up with lots of improvements when it comes to automobiles. Hybrid and electrical cars are a great alternative to internal combustion engine cars; however, they are still not able to completely replace these highly efficient vehicles due to lack of power or the very high cost of electric cars.

Figure 1. Internal Combustion Engine [1]

Internal combustion engines use the high energy content stored in gasoline and diesel fuels and convert them into mechanical energy that drives the vehicles, figure (1). The combustion of these fuels with air results in a great deal of hazardous emissions like carbon dioxide CO2, carbon monoxide CO, unburned hydrocarbons HC, nitrogen oxides NOx and smoke. These harmful gasses are bad to both people and environment. The danger lies especially in carbon dioxide which plays a great role in global warming which is because of a phenomenon called greenhouse gas effect.

Almost all automobile companies started using an environment friendly device called the catalytic converter which is installed in the exhaust port of the vehicle. This device converts harmful gasses into less harmful gasses, figure (2).

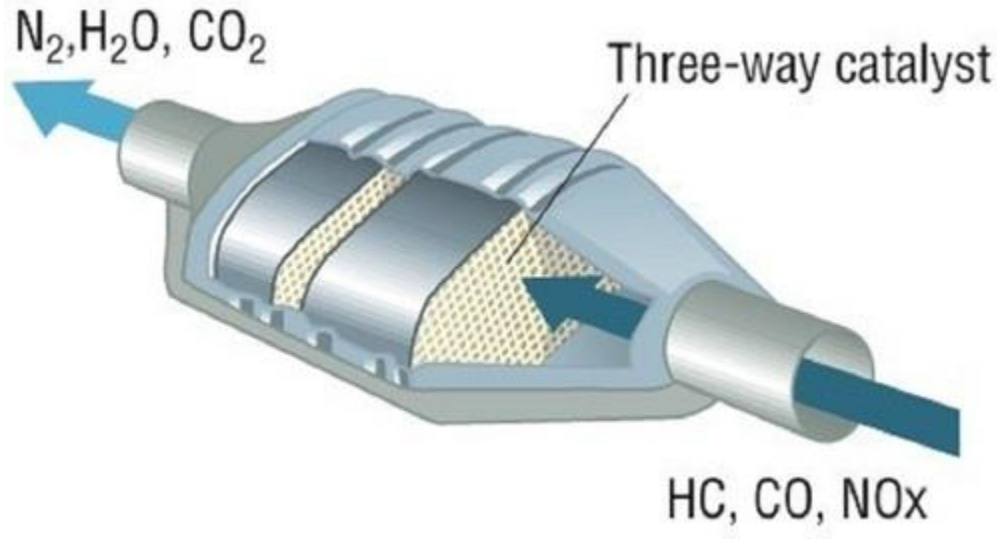


Figure 2. Three-way catalytic converter [7]

The catalytic converter or sometimes called diesel oxidation catalyst DOC in diesel engines converts HC, NOx and CO into H2O, N2 and CO2 respectively. Carbon dioxide will find its way to the atmosphere and forming some sort of a layer that traps the ultraviolet and other radiations coming from the sun inside the hemisphere. This will eventually and gradually increase the overall temperatures of the planet causing problems to all living organisms.

1.2 Harmful gasses

The expansion of human's activities reached high levels and affected the nature of the globe. The natural systems on earth are being manipulated. It's known that some gases in atmosphere, such as nitrous oxide (N_2O), methane (CH_4), tropospheric ozone (O_3), and carbon dioxide (CO_2) have been increasing in a tremendous manner in the last century. Also, other gases which are not naturally a part of the natural system, such as hydrocarbons (HC), chlorofluorocarbons and other gases are increasing as number of vehicles, factories and different human activities increases. "These gases create a thermal radiation shield; this shield reduces the amount of thermal radiation energy allowed to escape from the earth, raising slightly the average earth temperature" (Pulkrabek, 2004). This might negatively affect agriculture, sea levels, rain levels and other impacts of the increment of the earth temperature, figure (3).

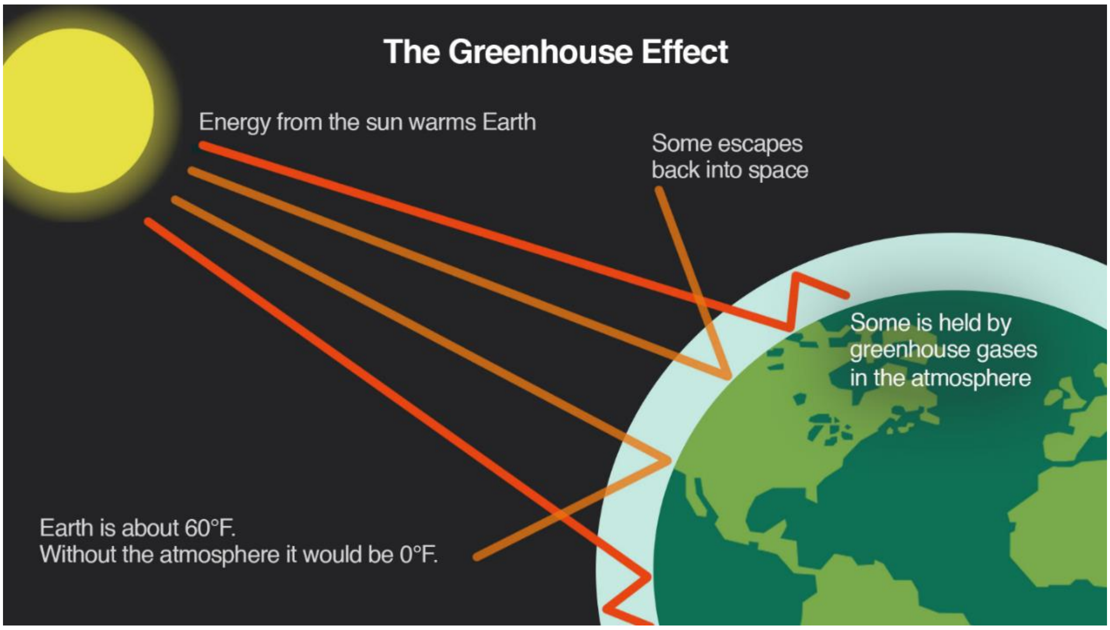


Figure 3. The greenhouse effect [2]

There are billions of vehicles on the road in whole the world. All these vehicles together produce large amount of pollution. When it's recognized that vehicles are the major contributor in this problem, the governments created emission standards that restrict the amount of pollution that vehicles can produce. Over the years, vehicle companies made many improvements and modifications in engines to keep up with these standards.

Currently, many researches investigate the most effective way to reduce carbon dioxide emissions from vehicles and other types of internal combustion engines. So far, the existed methods to reduce carbon dioxide are:

1- Using lower carbon content fuel, i.e. other than gasoline.

2- Using energy sources with low amount of carbon dioxide emissions, such as wind, nuclear energy. (Replacing the internal combustion by other natural power sources).

3- Increasing the combustion efficiency of the engine, this will burn huge amount of carbon in the fuel by allowing for better mixing and burning, i.e. enhance the combustion efficiency.

Also, some technologies are found to help in capturing carbon dioxide emissions from burning fuel, such as solvent absorption, physical absorption and adsorption, membrane systems, and other technologies. Also, there are some works still in action on finding new ways to capture carbon dioxide, and one of these researches might find a way to capture most of the carbon dioxide emissions, especially from Mobile sources.

1.3 Smoke

Smoke is one of the most critical emissions of diesel engines. It is basically a light black cloud that is formed due to incomplete combustion or oxidizing of fuel inside the engine. Its composition may vary with the fuel type or rate of consumption, or speed of engine operation. Smoke can cause lung cancer and can also lead to bladder cancer [11]. Increasing load on the engine will lead to more injection of fuel into the engine that can’t be burnt or oxidized completely due to no enough air to complete the reaction and thus exiting through the exhaust.

1.4 Diesel Engine’s emissions

Diesel engines which are also called compression ignition engines (CIE) are engines which run on diesel cycle, a combustion process of a reciprocating type. Fuel is ignited due to the high temperature caused by compressing air into the cylinder. Fuel in injected nearly at top dead center (TDC) after compression stroke. Diesel emissions are gasses which come out from the exhaust of an automobile vehicle. The oxidation of Diesel fuel result in the following by-products:

1. Nitrogen oxides (NOx), which are formed due to high temperature thermal fixation of O2 and N2 in the air/fuel mixture, or due to reaction between ambient O2 and N2-containing compounds in the fuel. The increase in temperature inside the cylinder causes high formation of NOx. Also, lean fuel mixtures can cause high formation of NOx due to slow flame speed.
2. Hydrocarbons (HC), which are formed due to incomplete combustion inside the cylinder. Hydrocarbons are organic compounds containing carbon and hydrogen atoms. Too lean and too rich fuel mixtures cause high release of HCs. Also, over penetration of fuel molecules that wets the cylinder's wall during ignition delay (ID) cause high release of HCs.
3. Carbon oxide (CO), which is mainly formed due to incomplete oxidation of fuel. Too rich mixtures cause high release in carbon monoxide. Carbon dioxide is formed in the catalytic converter or the diesel oxidation catalyst due to oxidation of CO into CO2.
4. Smoke, which is the black cloud that we mostly see from big truck's exhausts figure (4). Smoke is basically a form of unburned hydrocarbons that are light in weight. Smoke is generated mainly due to incomplete combustion of fuel and is increased with increasing load on the engine.

Figure 4. Smoke emissions from a diesel car [11]

1.5 CO2 Reduction technique

Sodium hydroxide also known as caustic soda is an inorganic compound that is composed of both sodium positive ions and hydroxide negative ions. It is prepared by adding the solid NaOH pellets or powder into water with different percentages and molarities depending on the need. About 1.1 kg of NaOH is required to dissolve completely in 1 Liter of water figure (5), this is called 100% saturated NaOH solution. The reaction between solid NaOH and water is exothermic so care must be taken while preparing the solution. NaOH has a great capability to react with CO2; as will be seen later in the literature, or in other words absorbing it and not allow it to escape to the atmosphere. Na2CO3 is called Sodium carbonate and it is the by-product of the absorption reaction. It can be used in the manufacture of glass, paper, rayon, soaps, and detergents.

$$\mathbf{NaOH \rightarrow Na^{+} + OH^{-} + HEAT}$$

$$\mathbf{NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O}$$

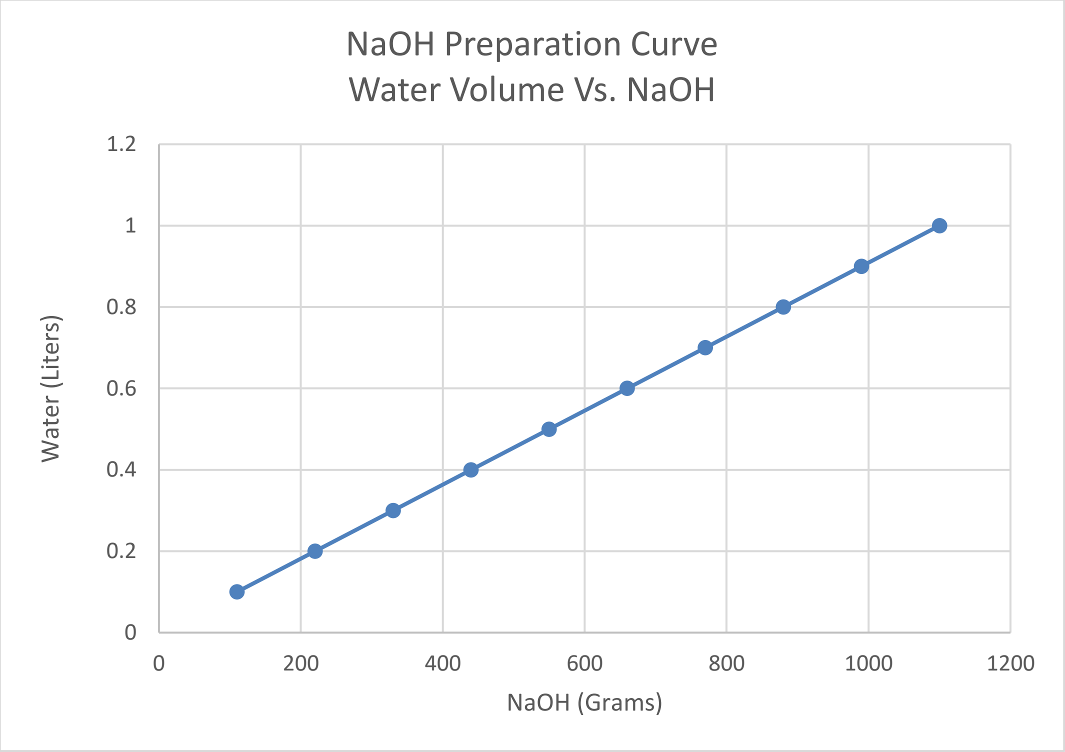


Figure 5. Saturation Curve for NaOH [7]

1.6 Objectives

The main motivation or driving force to do this project is to come up with a device that can be easily installed at the back of an automobile's exhaust that would absorb or reduce all the less harmful gasses which are CO2, HC, NOx and smoke after the diesel oxidation catalyst. For that, a simple cylindrical device with a special designed dispenser or distributor were fabricated as per the nominal size of any exhaust tailpipe and connected at the exhaust port of a single cylinder diesel engine that will be elaborated more in the experimental methods section.

This device will be tested three times for three different experiments.

The objectives are as follows:

1. Develop an emission reduction tube that can be installed easily with the current exhaust pipe of diesel vehicles.
2. Test the emissions reduction tube on a single cylinder diesel engine when filled with water and NaOH solution and observe the exhaust gasses concentrations.
3. Compare the engine performance and emissions of the engine when using the developed tube with the reference parameters of the engine without using the tube.

All of these 3 experiments will be done twice, for constant load-variable speed and constant speed-variable load. The experiment with NaOH will be done as a function of time in order to see how much the alkaline solution can last before it can’t absorb any more CO2

In this project, the unused portion of the exhaust tailpipe will be utilized to install the cylindrical device and thus not adding to the overall mass or volume of the automobile’s exhaust system as can be seen in figure (6)

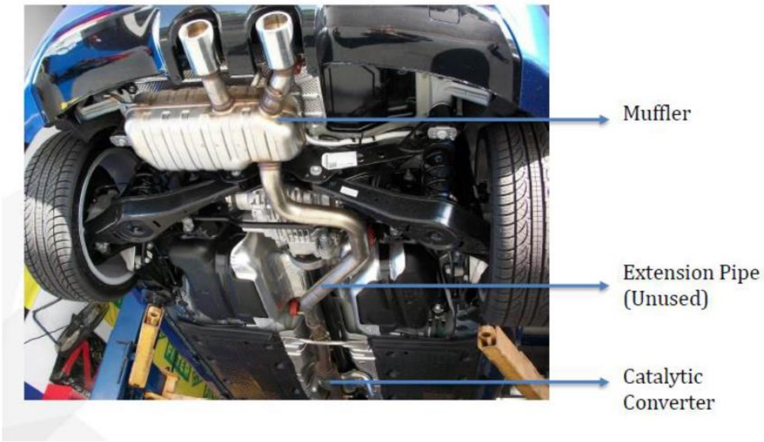


Figure 6. Car's exhaust system [10]

CHAPTER 2: LITERATURE REVIEW

In this part of the research, detailed studies that have been executed in the past will be mentioned and discussed. The whole idea of carbon dioxide capturing was limited to industries and power plants to be exact since “limiting pollution” has become a viral part of the environmental sectors of governments in most of the developed countries if not all. Nowadays, this idea has been extended to automobiles as well because of its non-negligible amount of carbon dioxide release. In the following sub-chapters, the evolving idea of carbon dioxide capturing in automobiles will be reviewed thoroughly.

2.1 Global Warming

2.1.1 Problem definition

Unanimously, this problem would be global warming. Global warming is the rise in the overall temperature of earth’s atmosphere due to the greenhouse effect. This is caused by some hazardous gasses released to the air’s mixture. The main contributor is a gas called carbon dioxide or CO_2. Earth’s average temperature raised about 0.8^oC since the 1880s, with approximately two-thirds of the increase happening since 1980’s [1].

Recent statistics conducted by NASA’s Goddard Institute for Space Studies (GISS) and the National Climatic Data center showed that 2005 and 2010 were the warmest year of planet earth [2]. Carbon dioxide blocks earth’s radiation back space. Sun radiates it at near infrared. However, earth radiates out at far infrared.

2.1.2 Qatar’s Role and Vision

The state of Qatar has, and still is, witnessing a large growing economy in terms of oil and gas profit. This growth of course comes with side effects. One of these major side effects is the release of CO2 to the atmosphere which the ministry of environment is trying to regulate and control.

According to Qatar National Vision 2030:

“The State shall preserve the environment and its natural balance in order to achieve comprehensive and sustainable development for all generations” [3]

The need for developing in terms of environment has been set as a major pillar on which the future of Qatar is based and depending on. Also the need of address the global environmental issues of Global Warming has been directly highlighted in the 2030 vision.

Qatar is one of the largest producers of Natural Gas and CO2 is one of the byproducts of this process. Whitson and Kuntadi [4] have stated, in a conference held in Qatar, that the annual production of 2.54 million metric tons of CO2 in Qatar. Along with this, there is significant amount of CO2 being produced in burning of fossil fuel and coal for the production of electricity, cement production and many other industrial processes.

For time being, this research is focusing on how to minimize CO2 levels from reaching out to the atmosphere until Qatar and other countries could find an alternative to fossil fuels.

2.2 Emissions from ICE

Vehicles, trucks and other motors continue to play a leading role in increasing the air pollution rates in the world today. It is the main source of volatile organic compounds (VOCs), nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC), diesel particulate, and chlorofluorocarbons (CFCs).

In European countries, the vehicles are the largest source of emissions, such as CO, NOx and HC. Researchers predicted that vehicles will remain the main source of emissions for sometimes in the near future. “Currently, road vehicles account for 74%

of the nitrogen oxides and 94% of black smoke emissions in London"[5].

The vehicles are also considered as the main emission source in US and Japan. "In overcrowded areas in US where the air pollution is severe, Environment Protection Agency (EPA) has projected that vehicles will be the main source of 38% of NOx and 22% of total VOC in 2005" [5]

2.2.1 Particulate (PM)

Particulate is a mixture of liquid drops and solid particles found in the air. It includes dirt, smoke and liquid drops. These particulates can be emitted by natural sources and human made sources, such as dust from the wind, vehicles, industrial sites, and fires. Also, it can be formed in the atmosphere by condensation or conversion of emitted gases, such NOx, VOCs, and Sulphur dioxide SO2. These particulates are considered one of the main reasons of lung cancer and other health symptoms.

2.2.2 Oxides of nitrogen emissions:

Under high temperature and pressure conditions in the engine, oxygen and nitrogen atoms in the air reacts to form what is called nitrogen oxides (NOx). These nitrogen oxides are one of the reasons of the acid rains and contribute in the destruction of the ozone. In a study done by A. Avinash, P. Sasikumar to comprehensively study on the emission. The variation of the specific brake oxides of the nitrogen emissions (in g/kWh) with respect to the load (%) for several pre-mixed ratios is shown in figure 7. The concept of premixing fuel and air in the inlet port of admission has reduced the temperature of the mixture and this pre-cooling effect could be the reason for the reduction of the combustion temperatures in the cylinder. In addition, improved homogeneity due to premixing ensured that more air is now applied by the fuel. In fact, this factor could have paved way to reduce the level of nitrogen oxides for premixed fuel-air mixtures. Therefore, it was also observed from the experimental observations that the range of the nitrogen oxides reduction is approximately 43% at 25% load to approximately 48% at full load for 30% the premixed fraction when compared to diesel base. As shown in figure 7, the emission values of nitrogen oxides at full load (100%) are lower for all premixed ratios as compared to neat diesel. This tendency apparently discloses the cooling effect of the ethanol addition on the gas temperature in the premixed charge compression ignition cylinder

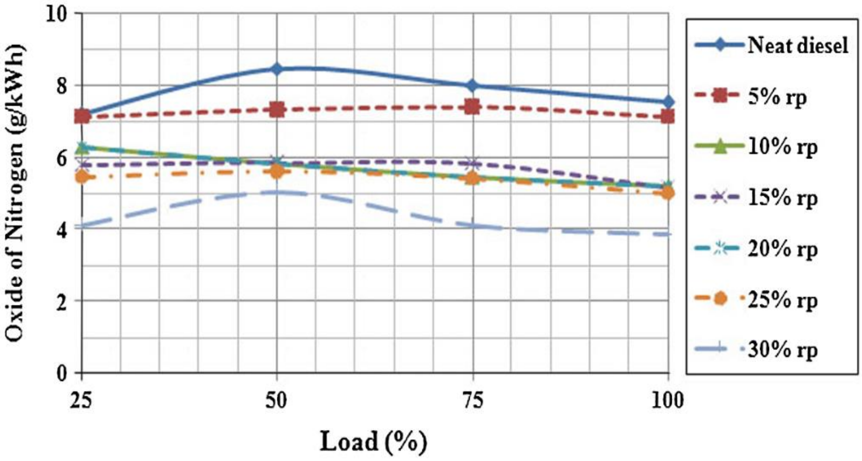


Figure 7. Specific NOx Vs. Load Percentage [12]

2.2.3 Hydrocarbons and carbon monoxides emissions:

Hydrocarbon emissions are produced when the fuel molecules in the vehicle do not burn or only burn partially. When the nitrogen oxide and sunlight are available, hydrocarbons particles make a reaction and form “ground level ozone”. High levels of ozone during smog build-up can cause difficulty to people with respiratory ailments like emphysema and asthma. Carbon monoxide (CO) is created due to incomplete combustion, and it occurs when the carbon content in the fuel is not fully oxidized into carbon dioxide (CO2). It causes few health problems, such as reduction of oxygen flow in the blood stream. The variation of unburned hydrocarbons with respect to the load for various premixed ratios is shown in figure 7. In this work, the unburned hydrocarbons increased with the increase of the fractions premixed by the reduction of the excess air with the increase of the fractions of the premix. The maximum value of unburned hydrocarbons was observed for 30% of the premixed ratio. In addition, hydrocarbons unburned were higher at lower loads (especially at 25% load) by an over-leaning of the mixture, which no power sustained combustion since it is beyond the flammability limit. Therefore, the premixed loading at lower loads could have undergone poor combustion. However, at higher loads, the higher temperature inside the combustion chamber could have contributed to better combustion during the premixed loading mode. In general, the unburnt hydrocarbon from the premixed charging operation is even greater than the diesel-based operation. The similar trend observed with unburned hydrocarbons at the loads was evidently observed for the emission of carbon monoxide as shown in figure 8. However, the trend was reversed at higher loads due to the presence of oxygen in ethanol already. Higher temperature in cylinders and higher loads. However, there was an increase in the emission of carbon monoxide with the increase of the premix fraction. This increase can be explained by the latent high heat of ethanol and another possible reason could be the effect of longer ignition delay due to the addition of ethanol.

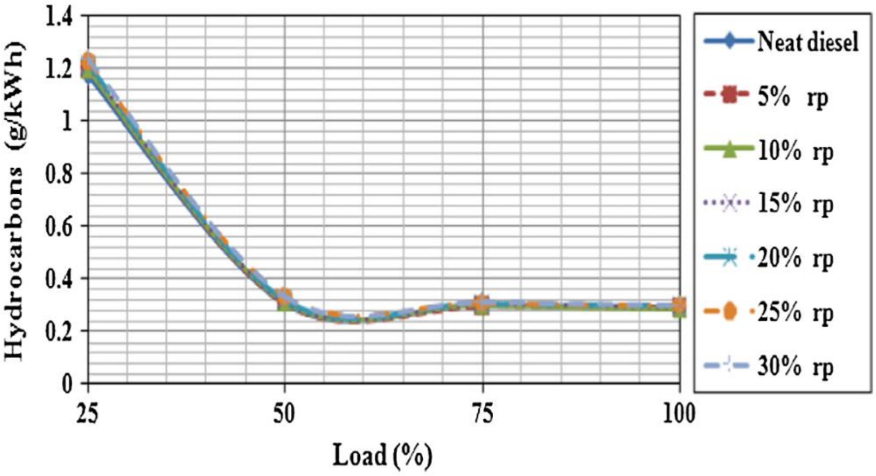
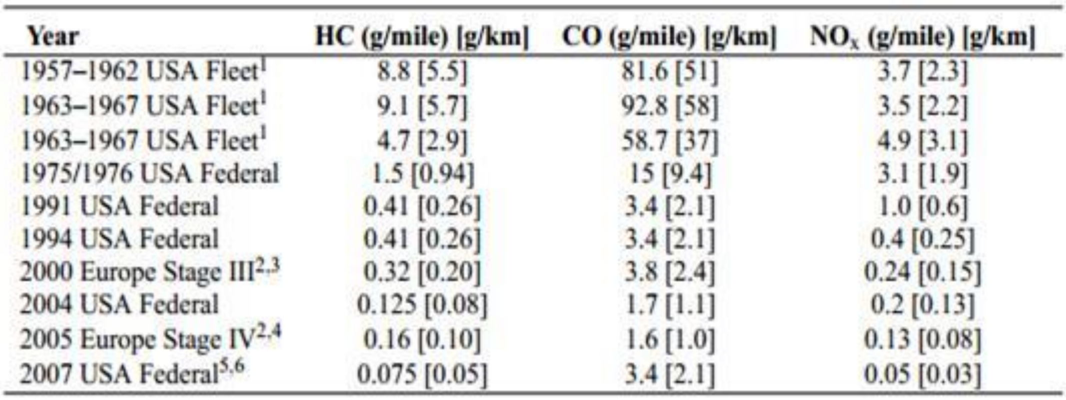


Figure 8. Specific HC Vs. Load Percentage [12]

2.2.4 HC, CO and NOx reduction

Recognition of the role of vehicle exhausts in the formation of greenhouse gases led to the implementation of regulations controlling vehicle emissions starting in the 1960s in US. The development of control technology for vehicle emissions over the past 5 decades has led to large decreases in the emissions as illustrated in Figure 9.



Year	HC (g/mile) [g/km]	CO (g/mile) [g/km]	NO_x (g/mile) [g/km]
1957–1962 USA Fleet^{1}	8.8 [5.5]	81.6 [51]	3.7 [2.3]
1963–1967 USA Fleet^{1}	9.1 [5.7]	92.8 [58]	3.5 [2.2]
1963–1967 USA Fleet^{1}	4.7 [2.9]	58.7 [37]	4.9 [3.1]
1975/1976 USA Federal	1.5 [0.94]	15 [9.4]	3.1 [1.9]
1991 USA Federal	0.41 [0.26]	3.4 [2.1]	1.0 [0.6]
1994 USA Federal	0.41 [0.26]	3.4 [2.1]	0.4 [0.25]
2000 Europe Stage III^{2,3}	0.32 [0.20]	3.8 [2.4]	0.24 [0.15]
2004 USA Federal	0.125 [0.08]	1.7 [1.1]	0.2 [0.13]
2005 Europe Stage IV^{2,4}	0.16 [0.10]	1.6 [1.0]	0.13 [0.08]
2007 USA Federal^{5,6}	0.075 [0.05]	3.4 [2.1]	0.05 [0.03]

Figure 9. Historical data on HC, CO & NOx emissions [12]

The data for the 1957–1962 Fleet and 1963-1967 Fleet in Figure 9 are collected from several hundred vehicles tested in the laboratories. The more recent data are collected after applying the regulatory standards that must new vehicles met. It is clear

from increasing the regulatory standards and the huge difference between the latest standards and the measured emissions from the 1957–1962 Fleet and 1963-1967 Fleet that each vehicle per km basis has experienced major reduction in HC, CO, and NOx emissions over the past 50 years. Even if the on-road vehicles number are increasing dramatically these days, the total emissions of pollutants (i.e., HC, CO,
NOx, and PM) are projected to decline significantly in the coming decades. On a global basis, the emissions of HC, CO, NOx in 2004 from light duty vehicles were approximately 27, 160, and 8 Tg.

2.3 Carbon Dioxide Emissions

Recently, the Environmental Protection Agency (EPA) in US has started to consider carbon dioxide, a product of “perfect” combustion, as a pollution source. Carbon dioxide does not directly harm human health, but it is a “greenhouse gas” that traps the earth’s heat and contributes in global warming phenomena.

As well as, according to a new study by the Europe authorities, carbon dioxide emissions intensity (g CO_2\km) of new passenger vehicles in Europe was determined by the Europe authorities by 2009. As the diesel – gasoline CO_2 emission difference is small, and as the diesel have greater carbon fuel intensity, and emissions of carbon dioxide per kilometer are related to the fuel intensity of passenger vehicles by multiplying fuel/km times the carbon content of fuel, and it allows for normalized comparison of diesel and gasoline vehicles and the aggregate emissions intensity.

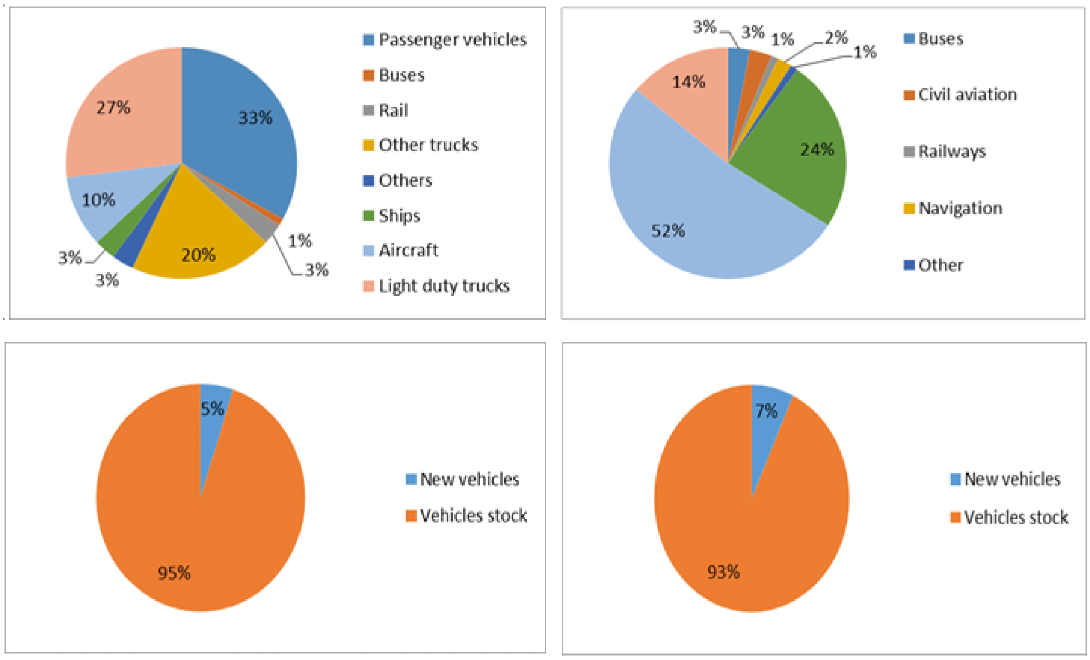


Figure 10. Regional Distribution of CO2 emissions in USA & Europe [13]

Figure 10 show the regional distribution of CO_2 emissions in US and Europe in 2004, which was taken from energy information administration [13]. The CO_2 emissions which produced by different transportation sectors in US and Europe. Figure 10 shows the CO_2 emissions produced by passenger vehicles which classified as new vehicles and stock vehicles. Based on newer study by Europe authorities which is consisting of 12 countries (EU12), through 8 countries data can be accredited, the fuel emissions-intensity of diesel and gasoline have been calculated through years, and released until 2008. The average vehicle in Europe release a 146.5 g of CO_2 for each kilometer driven [13]

2.4 Previous studies on capturing CO2

CO2 capture means trapping the CO2 at its emission source, transporting it to a storage location, and isolates it. CO2 can be captured by three ways, post-combustion, pre- combustion and oxy-fuel combustion.

In post-combustion, the CO2 is captured after the fuel is burned. This burning produces different types of emissions, such as CO2, water vapor, sulfur dioxide and nitrogen oxides. This process uses a filter to remove CO2 from other emissions. This filter is basically a solvent that absorbs CO2. The solvent can be later heated, which will release water vapor and leave concentrated CO2 behind. This process can prevent 80 % to 90% of CO2 emissions from reaching the atmosphere.

In pre-combustion, CO2 is trapped before burning the fuel. The fuel is heated in pure oxygen, producing a mixture composed of carbon monoxide and hydrogen. Then, this mixture is passed through a catalytic converter with steam, which will produce extra hydrogen atoms with CO2. These gases are fed into a flask with a chemical called amine. The amine will bond with CO2 and fall to the bottom of the flask, and the hydrogen will rise up out of the flask. Then, amine and CO2 mixture are heated, where amine drop to the bottom of the flask, and CO2 rises to the top for collection.

In oxy-fuel combustion, the fuel is burned in oxygen. This will produce a gas mixture composed mostly of steam and CO2. The steam and CO2 are separated by cooling and compressing the mixture. The oxygen required for this process is so expensive, but researchers are developing new ways to capture CO2 in a most efficient and cheap ways.

2.4.1 Spraying of NaOH

In contrast to the carbon capture systems for power plants, the system described in this work captures CO2 directly from ambient air. This has the advantages that CO2 emission that left after combustion process to be captured. The objective of this research is to determine the feasibility of a NaOH sprays for use in a CO2 capture system by estimating the energy and cost requirements per unit CO2 captured, figure (11). A prototype is constructed and tested to measure CO2 absorption, energy use, and the costs of this process.

The analysis of the system indicates that CO2 capture from air is technically practical by using NaOH spray technology. Drop coalescence apparently decreases the CO2 absorption efficiency; however, pump and fan energy requirements are still manageable. "The cost of CO2 capture by using NaOH spray in the full-scale system is 96 $/ton-CO2 in the base case, and ranges from 53 to 127 $/ton-CO2 under alternate operating parameters and assumptions regarding capital costs and mass transfer rate" [6]. This is about 26.45 $/MWh

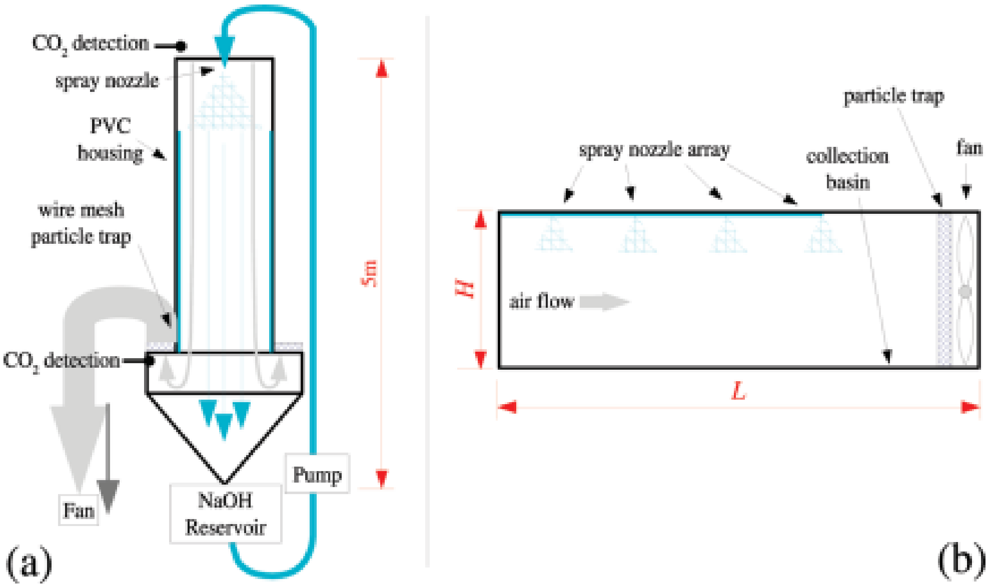


Figure 11. Spraying of NaOH method [6]

2.4.2 Carbon Dioxide Capturing from automobiles

A study by a group of people in Qatar University was conducted and considered an eye opener to absorbing carbon dioxide. They have used NAOH solution in water and subjected it to the exhaust of car's engine [7]. Actually, the true experiment only mapped the reality. Meaning that they have simulated the cars exhaust engine.

Figure (12) shows the test rig in which it was used to absorb CO2

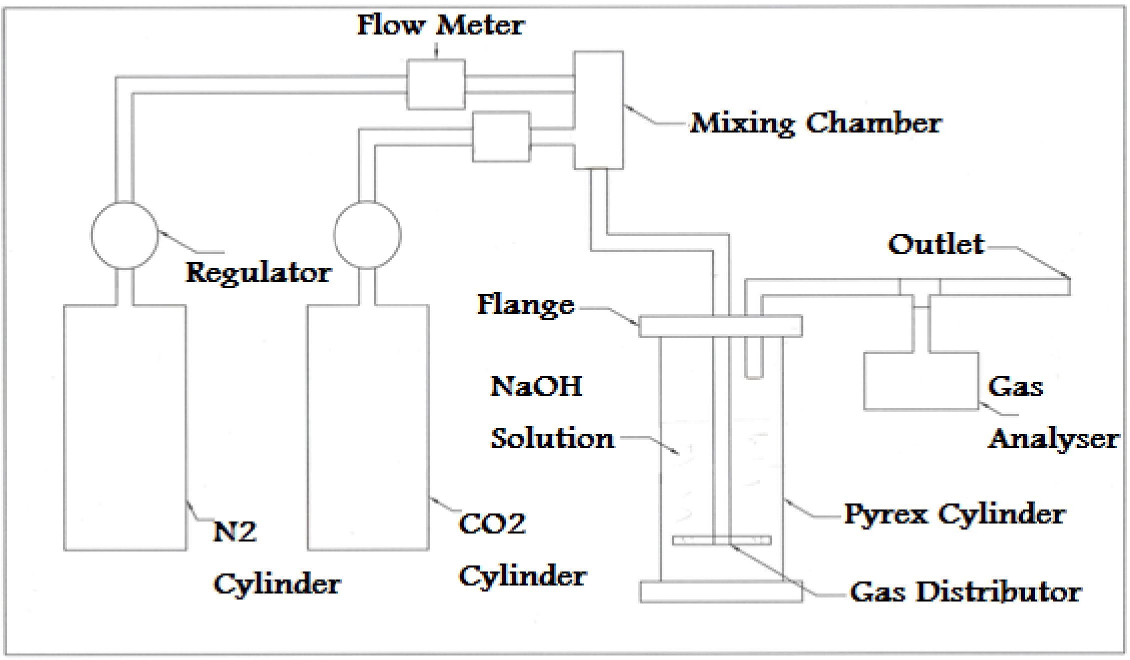


Figure 12. Test rig schematic for CO2 capture [7]

The flow rates have been adjusted to match the size of a small engine. After doing the experiment with different concentrations of NaOH dissolved in water, it was found that the 100% concentrated solution showed the best absorption results. However, it took only 3 hours for the solution to be good enough for the job. After these 3 hours the effectiveness went down to 0 and the exhaust dispenser got blocked due to formation of crystals of Sodium Carbonate. Figure (13) shows the difference between the three experiments:

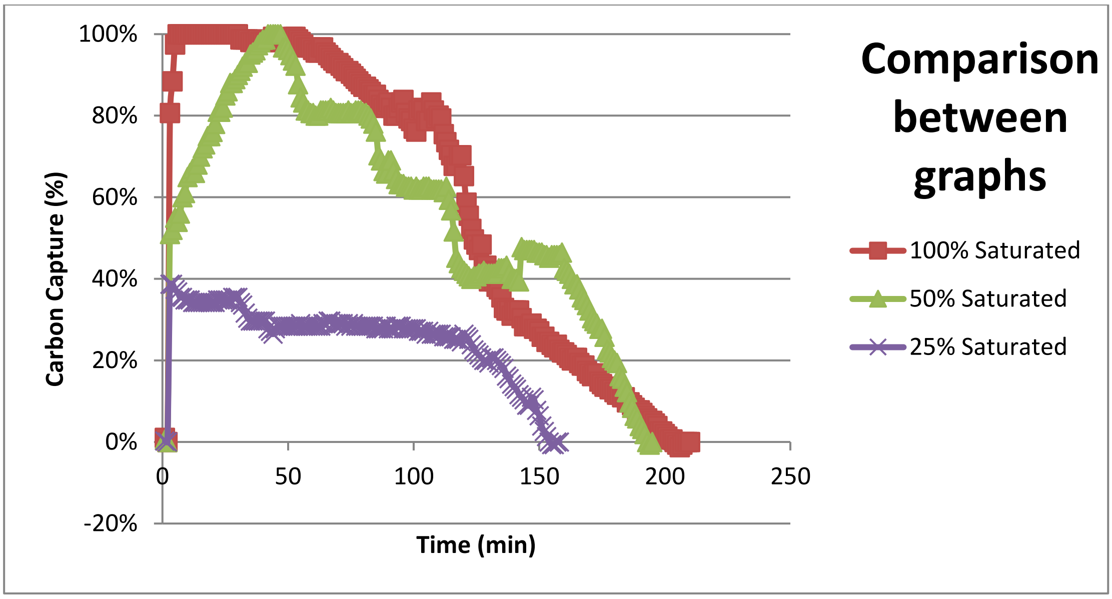


Figure 13. CO2 absorption percentage as a function of time for various saturation limits of NaOH [7]

A second trial by different group of students in Qatar University as well was conducted. This time, the distributor in which the exhaust gases exits to mix with the solution has been modified as in figure (14).

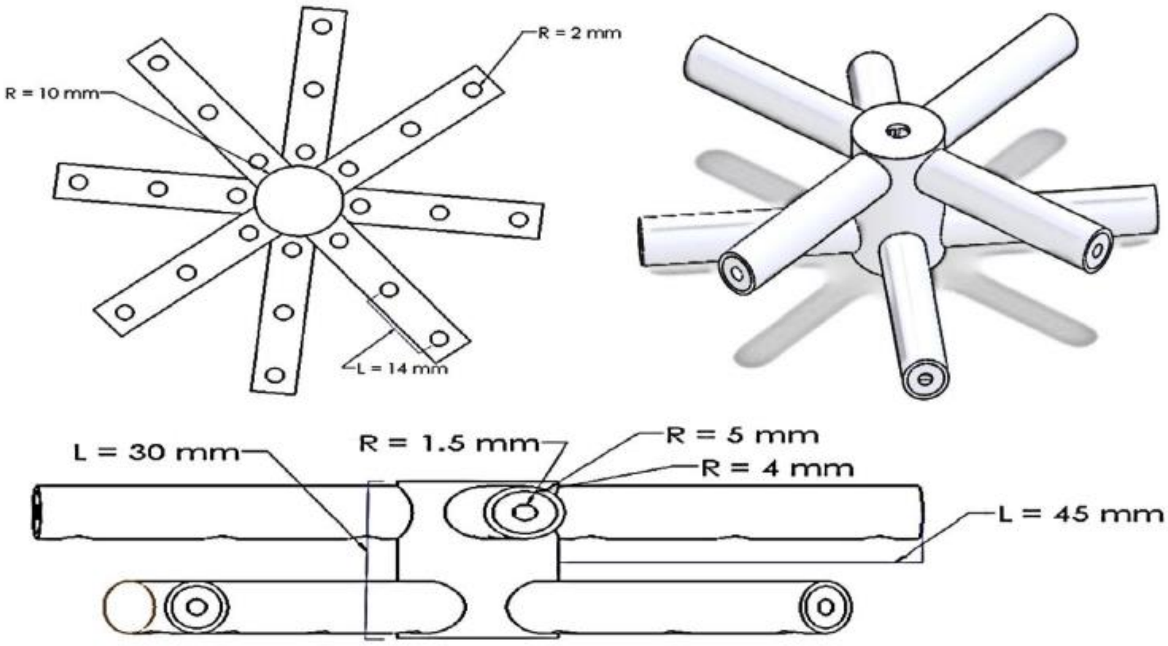


Figure 14. New designed distributor [8]

The new distributors allow for more interaction of atoms from exhaust gases and NaOH solution. This was proven after taking the CO2 levels using a gas analyzer after the exhausts leave the NaOH cylinder. The following figure (15) shows a comparison between the old study and the new one:

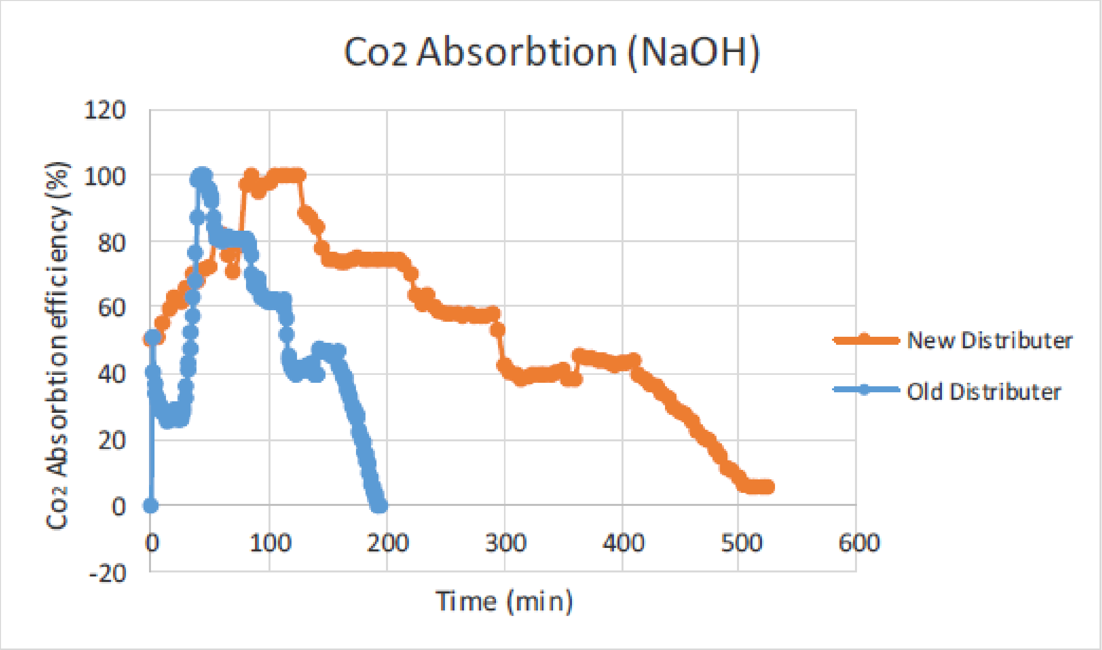


Figure 15. Difference between old and new distributor in terms of CO2 absorption [8]

2.4.3 Activated Charcoal

Another study done by “Ramesh Thiruvenkatachari”[9] discuss the “Application of carbon fiber composites to CO2 capture from flue gas”. Activated carbon fiber materials are known for good thermal and mechanical properties and the ability of formability. In this study the simulated flue gas is composed of CO2, O2 and N_2. Moreover, the concentration of the inlet simulated flue gas (at 298 K) was about 13% CO2 (partial pressure 13 kPa), 5.5% O2 and the balance N2. Air and pure CO2 were mixed in specific ratios through mass flow controllers. Simulated flue gas initially bypasses the columns and flows directly to the sensors to record the inlet gas concentration before the start of the adsorption process. The adsorbent material used was a large size honeycomb carbon fiber composite fabricated by mixing petroleum pitch carbon fiber and phenolic resin. The diameter and the dimensions of the absorbent can be determined based on the application. The adsorbent material contains a series of flow-through gas channels for the passage of flue gas and other set of channels of different diameter to indirectly heat and cool the absorbent for regeneration (stain steel can be used). Also, Triscar 3000 is used to determine the characteristics of the absorbent such as the CO2 capture capacity. Two test columns to house the adsorbent material. A stainless-steel column is placed inside the large column with the space between the two columns filled with vacuum for insulation. Then, the absorbent material is wrapped with Teflon and placed inside the inner diameter [9].

At the beginning of the process the CO2 entered the system with constant CO2 concentration and that is due to initial adsorbents regeneration but after about 14s the sorbents begin to capture about 98% of CO2. However, near the breakthrough time the CO2 uptake decreases as the column became fully saturated. As the flow rate increases the viscous flow starts to increase resulting on earlier breakthrough time and a lower CO2 capture. The study showed that the pore size distribution (PSD) is directly proportional to the CO2 adsorption capacity as CO2 molecules are adsorbed mostly in small micro-pores at 298 K and 760 mmHg,. The PSD is obtained from equilibrium isotherms that show the mass transfer of CO2 through the porous solid. Follow are the main results of this study:

- The CO2 adsorption capacities of the activated carbon composite at 298 K were about 2.65 and 0.73 mmol/g at 760 and 99 mmHg, respectively.
- High gas separation ratio for CO2 from its mixture with N2.
- The carbon fiber composite has high adsorption heat which indicates high CO2 adsorption capacity.

The large size honeycomb shaped carbon fiber composite (HMCFC) absorbents showed very high average CO2 adsorption capacity of 11.9 % (at 293 K and a1 atm), figure (16). Also, CO2 capture efficiency was over 98 % before the absorbent become fully saturated (breakthrough). Higher pore space than activated carbon fiber.

Increasing flow rate results in decreasing the CO2 adsorption. Adsorption capacity and breakthrough were lower at high adsorption temperature.

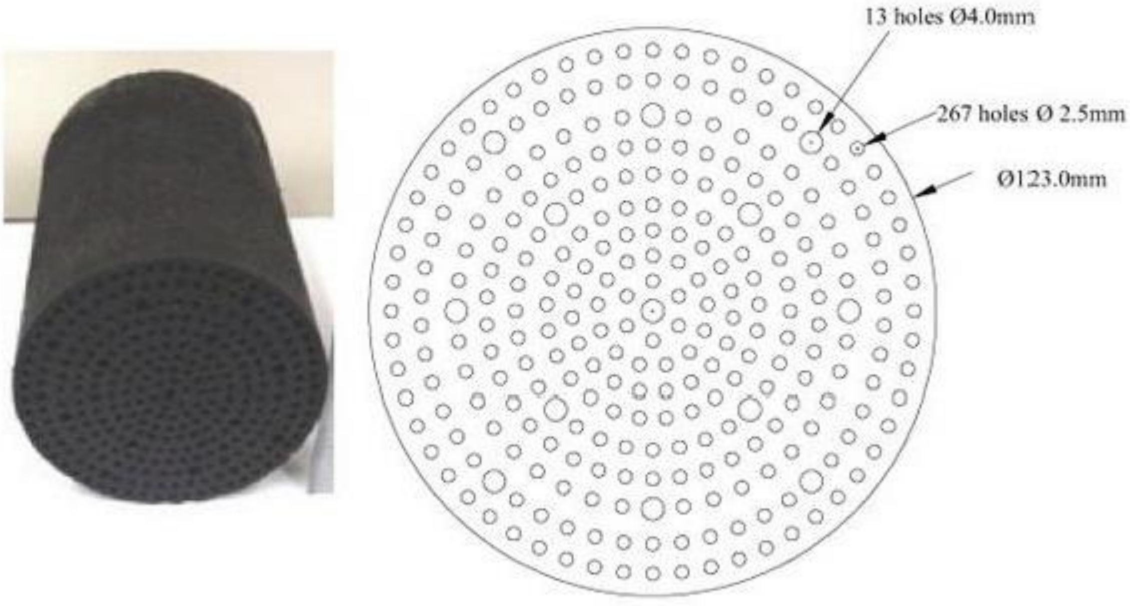


Figure 16. Honeycomb design for CO2 capturing [9]

2.4.4 The Use of Solid Zeolite

Another work is conducted by Ahmad Numan, Ahmad Sakr, and Omar Amira [15]. to develop carbon dioxide capture device for mobile system. Carbon dioxide produces from human as bi-product of respiration, factories and anywhere there is combustion reaction. Carbon dioxide itself in not harmful, but high level of it is harmful because it is the main cause of greenhouse effect. This project is to design a system that can be implemented in the automobiles, so it will minimize the pressure drop and maximize the reaction area, as a result it will reduce the carbon dioxide emission. This system is consisting of pipe of length 1m and diameter 50 mm that will be implemented after the catalytic converter. This pipe contains small solid particles that it will absorb the carbon dioxide from the gas outlet of the catalytic converter. This pipe is designed to minimize the pressure drop; thus, it cannot harm the engine or its component. As the material inside the pipe is solid, so it will work as adsorbent for the carbon dioxide that is produced by the engine. There are many materials can be used to work as carbon capture material, whoever only three materials have been chosen in this project which are Silica-Aluminas (ERS-8(II)), Zeolite 13X, Metal Organic frameworks (Ru), Sodium Hydroxide (NaOH), and mix of Sodium Hydroxide and Calcium Hydroxide (NaOH + Ca(OH)2).

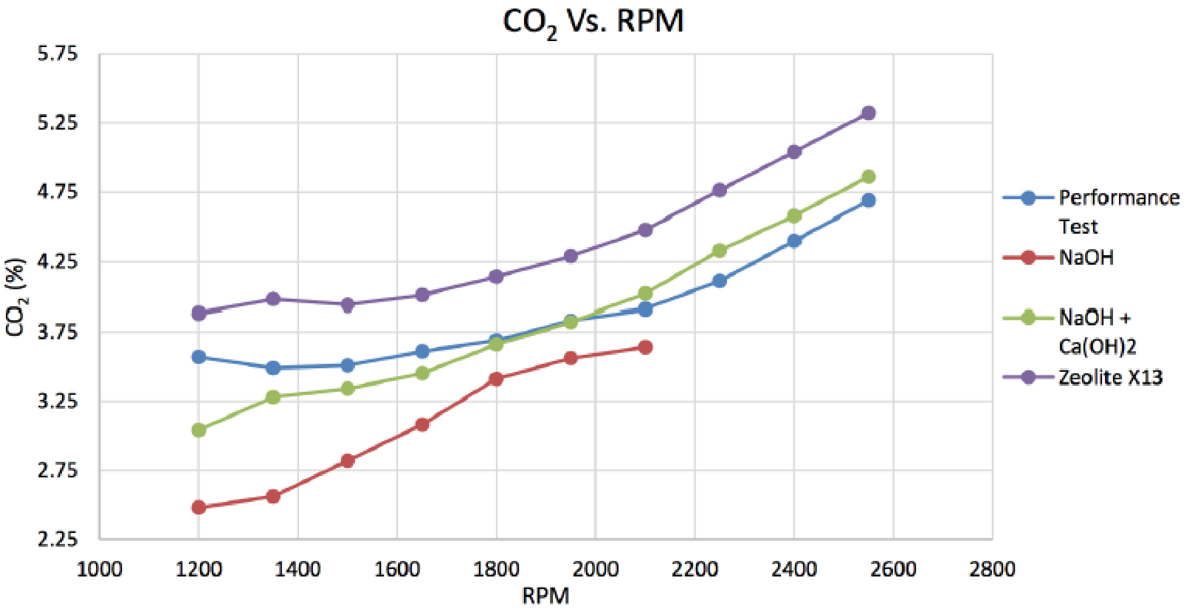


Figure 17. CO2 emissions Vs Speed for different absorption materials [15]

Above figure (17) shows the relation between the emissions of Carbon dioxide with varying speed while the load is constant and equal 1.5 Nm. As it can be seen that both Sodium hydroxide and the mixture of Sodium hydroxide and Calcium hydroxide emit carbon dioxide lower than the performance test. The emission of both of them increases gradually, the mixture intersects with the performance test at 1950 RPM, and then it emits carbon dioxide higher than the performance test. This could be the same reason as why the mixture produces more carbon dioxide than the performance test in the varying load with constant speed. For the sodium hydroxide, it emits lower amount of carbon dioxide than the performance test, in another word it is efficiently capture carbon dioxide. It is end at 2100 RPM this due to failure in the exhaust pipe happened while students conduct the experiment. On the other hand, Zeolite emits higher amount of carbon dioxide than the performance test. To conclude, Zeolite fails in capture Carbon dioxide.

2.4.5 Absorption-desorption capabilities of 2-amino-2-methyl-1-propanol (AMP), piperazine (PZ) and monoethanolamine (MEA) tri-solvent blends.

A study conducted by Chikezie Nwaoha and Chintana Saiwan along with other authors to achieve the task of enhancing the efficiency of CO2 capture a tri-solvent blend of AMP-PZ-MEA was tested experimentally and the results were studied and discussed thoroughly [14].

This study aimed at developing amine tri-solvent blend that will utilize the benefits of the individual amine solvents and to reduce the individual problems accompanying each. The blend of AMP-PZ-MEA was considered because of the high absorption capacity of AMP and the superior absorption rate of PZ compared to primary amines along with the good absorption rate of MEA as a primary amine. As a performance monitoring criteria, this research analyzed the absorption capacity (AC, mol CO_2/L amine solution), cyclic capacity, initial absorption rates, initial desorption rates, and heat duty (regeneration energy) of highly concentrated (6 kmol/m^3) AMP-PZ-MEA tri-solvent blends. The absorption capacity stated in this work is described as the equilibrium CO_2 loading multiplied by the amine concentration as seen in the below equation. This will better indicate the total moles of CO_2 absorbed by the amine solution, because the total concentration of the AMP-PZ-MEA blends and MEA is 6 kmol/m^3 and 5 kmol/m^3 respectively.

$$AC = \alpha CO_{2rich} * C_{amine}$$

Where αCO_{2rich} is the equilibrium CO_2 loading of the amine solution (mol CO_2/mol amine) and C_{amine} is the total concentration of the aqueous amine solution (kmol/m^3 or mol/L of solution).

Based on the findings of this study the tri-solvent blend of AMP-PZ-MEA introduced seems promising. At operating conditions of atmospheric pressure, 313K and 15.1% v/v CO_2, all the highly concentrated AMP-PZ-MEA tri-solvent blends possessed slightly higher equilibrium CO_2 loading (5.7-15.1%) compared to the conventional 5 kmol/m^3 MEA. Additionally, all the tri-solvent blends showed higher absorption capacities (29.1%-38.1% higher) than that of the standard 5 kmol/m^3 MEA. While there was no significant difference in the initial absorption rates of all studied amines, tri-solvent blends (after the first 60 minutes). But the cyclic capacities were raised (100-120%) by the AMP-PZ-MEA tri-solvent blends compared to the 5 Kmol/m^3. There is a trend in the results that was explained by an increase of easy to desorb bicarbonate concentration as the AMP/PZ molar ratio increased [14]. The initial desorption rates of the entire AMP-PZ-MEA tri-solvent blends were similar, thereby signifying slight significant difference in their initial desorption rates. However, their initial desorption rates were 93.5-125% higher than that of the single solvent 5 kmol/m^3 MEA and the heat duties of all the AMP-PZ-MEA blends witnessed a large (50-54.5%) reduction compared to that of the single solvent 5 kmol/m^3 MEA. This experiment demonstrated that the tri-solvent blends containing AMP-PZ-MEA are of high usefulness for CO_2 capture in post combustion processes. Another possible adjustment to the blend that might enhance the carbon dioxide capture characteristic is substituting the AMP with a tertiary amine that has a similar initial absorption rate, higher cyclic capacity and lower heat duty or substitute PZ with a polyamine with a superior CO_2 absorption-desorption capability. The significant 50% reduction in heat duty clarifies the possible usefulness of AMP-PZ-MEA tri-solvent blends in carbon dioxide capture applications.

The results of this study are demonstrated in the figures below:

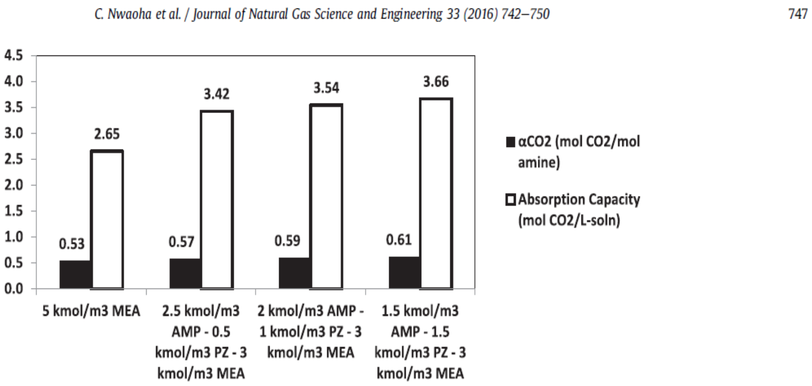


Figure 18. Absorption capacity of highly concentrated AMP-PZ-MEA tri-solvent blends compared to MEA at atmospheric pressure, 313K (absorption temperature) and 15% v/vCO2 [14]

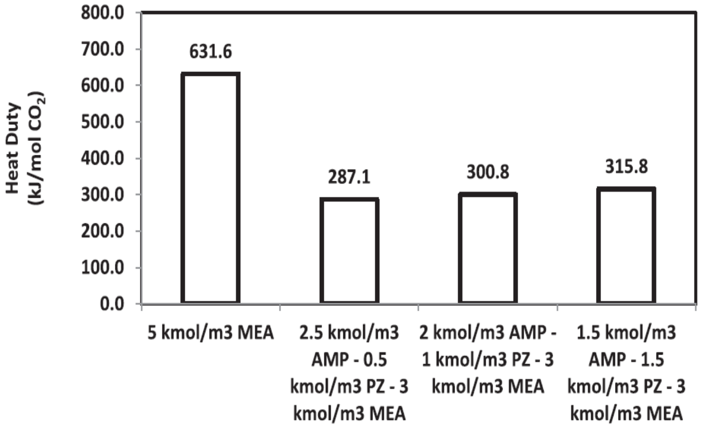


Figure 19. Heat duties of MEA and all the AMP-PZ-MEA blends using the correlation suggested by Sakwattanapong et al.(2005) [14]

2.4.6 Mixture of alumina, clay powder and an active component (Na_2CO_3)

A study done by “Srikanta Dinda” under the name of “Development of solid adsorbent for carbon dioxide capture from flue gas” focuses on the development of a low cost re-generable solid adsorbent for the capture of CO_2 from flue gas. The adsorption experiments were carried out in a fixed bed flow reactor. For each experiment about 10 g solid adsorbent was loaded into the reactor. Simulated flue gas (a mixture of N_2, CO_2 and water vapor) was used to the study of CO_2 adsorption. N_2 and CO_2 gas from two different cylinder stocks was passed separately through mass flow controllers at predetermined flow rates and are mixed together before passing through a water bubbler where the gas mixture was allowed to saturate with water vapor. Then the gas mixture (simulated flue gas) was passed through the adsorbent bed. The total flow rate of simulated flue gas was kept constant at 150 ± 2 cc/min for all the experiments. The reactor temperature was precisely controlled by using temperature controllers within ±1 °C. All the experiments were carried out at atmospheric pressure. The outlet concentration of CO_2 was measured by passing the reactor effluent through online CO_2 IR analyzer. The total system was tested for leak-proof condition and calibrated intermittently. [16].

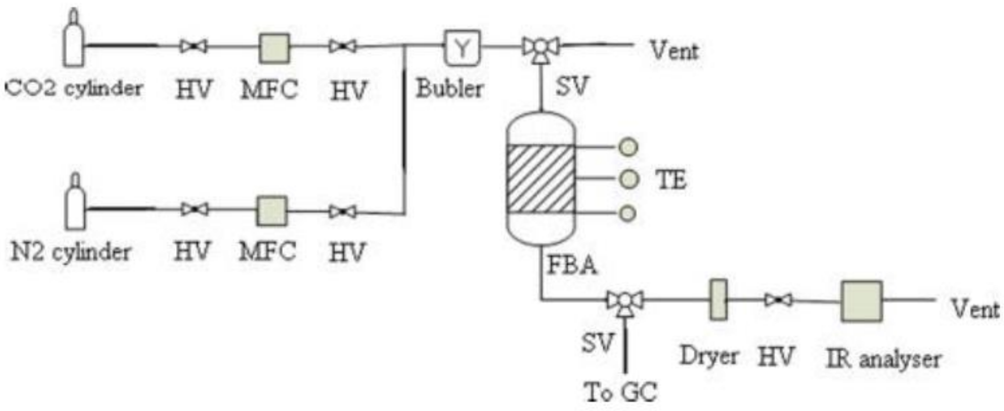


Figure 20. Schematic for test bed of Dinda's Experiment [16]

The adsorbent material used was a mixture of alumina, china clay powder and an active component of Na2CO3. It was observed that the surface area and pore-volume of the prepared adsorbents decreased with increasing Na2CO3 loading. The effect of various process parameters like adsorption temperature, CO2 level in the simulated flue gas, loading of active component at different concentrations on CO2 and CO2 concentration on the CO2 adsorption were discussed in this study. Simulated flue gas mixture containing 3–9 vol% CO2 in N2, saturated with water vapor was passed through the adsorbent bed. CO2 was chemically adsorbed by the supported Na2CO3 at 45–70 °C temperature and desorbed in the temperature range between 120 °C and 130 °C. The CO2 adsorption capacity of the adsorbents is expressed as the mmol of CO2 adsorbed per unit mass of adsorbent. In order to determine the effect of adding Na2CO3 on CO2 adsorption, five different loading were examined starting from 5 wt% to 25 wt% at 55 °C temperature results show that, CO2 adsorption increased with the increase of Na2CO3 loading up to 20 wt% and then drastically decreased at 25 wt% carbonate loading (SM-SC-25) due to the decrease of the surface area for adsorption CO2. Therefore, the maximum amount of Na2CO3 was 20 wt% (SM-SC-20). For the effect of temperature on CO2 adsorption, four tests were done at different temperatures ranging from 45 °C to 65 °C with three different concentrations of CO2.The results showed that as the adsorption temperature was increased from 45 °C to 55 °C, CO2 uptake also increased. However, increasing the temperature above 55 °C resulted in decreasing the CO2 uptake. This is due to the higher desorption rate of CO2. Moreover, results showed that there is a negligible effect of temperature with low concentration of CO2 due to the limitation of CO2 availability per site of adsorbent. For the effect on CO2 concentration on the CO2 adsorption, four tests were done with the concentration range 3-9 vol%. Results showed that as the CO2 concentration increased the adsorption increased, however above 9 vol% there was no significant change in the adsorption capacity due to the non-availability of free active sites. Also, an instrumental time lag of around 3 min after which CO2 response was observed. Thus, this study shows that using SM-SC-20 as a solid adsorbent with 20 wt% loading of Na2CO3 at a temperature of 55 °C with CO2 concentration of 9vol% results in CO2 adsorption capacity of 0.37–0.39 mmol/g. Also, the same adsorbent can be reuse for 3–4 times without significant decrease of adsorbent capacity.

2.5 Smoke Emissions and reduction methods

Black Smoke is the most common type of smoke emissions generated from diesel engine. It is simply an imbalance in the air to fuel ratio - too much fuel to not enough air. This means either too much fuel is being added to the mix or there's not enough oxygen being supplied to burn the fuel. The black smoke is full of particulates that are basically large diesel particles that normally would be burned as fuel. Any way you look at it, a diesel truck emitting black smoke is not going to be getting the optimal fuel mileage it should be getting.

Most common causes of black smoke are faulty injectors, a faulty injector pump, a bad air filter (causing not enough oxygen to be supplied), a bad EGR valve (causing the valves to clog) or even a bad turbocharger.

2.5.1 Previous study on smoke reduction

In this work, the effect of using a Whale filter on the overall vehicle exhaust emissions was evaluated [17]. A Whale filter is a South African patented diesel particulate filter designed to operate as a secondary diesel filter for the removal of particulate contaminants up to 0.5 microns in size in the fuel prior to injection. It is believed that removal of contaminants prior to injection may improve the fuel injection efficiency, thereby promoting efficient combustion, and thus resulting in reduced emissions and fuel consumption. Emissions tests were conducted on four different vehicle categories to validate this. All vehicles underwent pre-emissions testing prior to installation of the Whale filter. Each test was conducted for a period of approximately 20 minutes by varying the engine speed. The Applus + Autologic Vehicle Emissions Analyser was used to measure the emissions at each stage, and a similar procedure was followed to measure the emissions after installation of the Whale filter. The results showed a significant average reduction in carbon monoxide CO (35.3%), nitrogen oxides NOx (26.1%) and hydrocarbons HC (34.3%) emissions after the Whale filter was installed in the four vehicles.

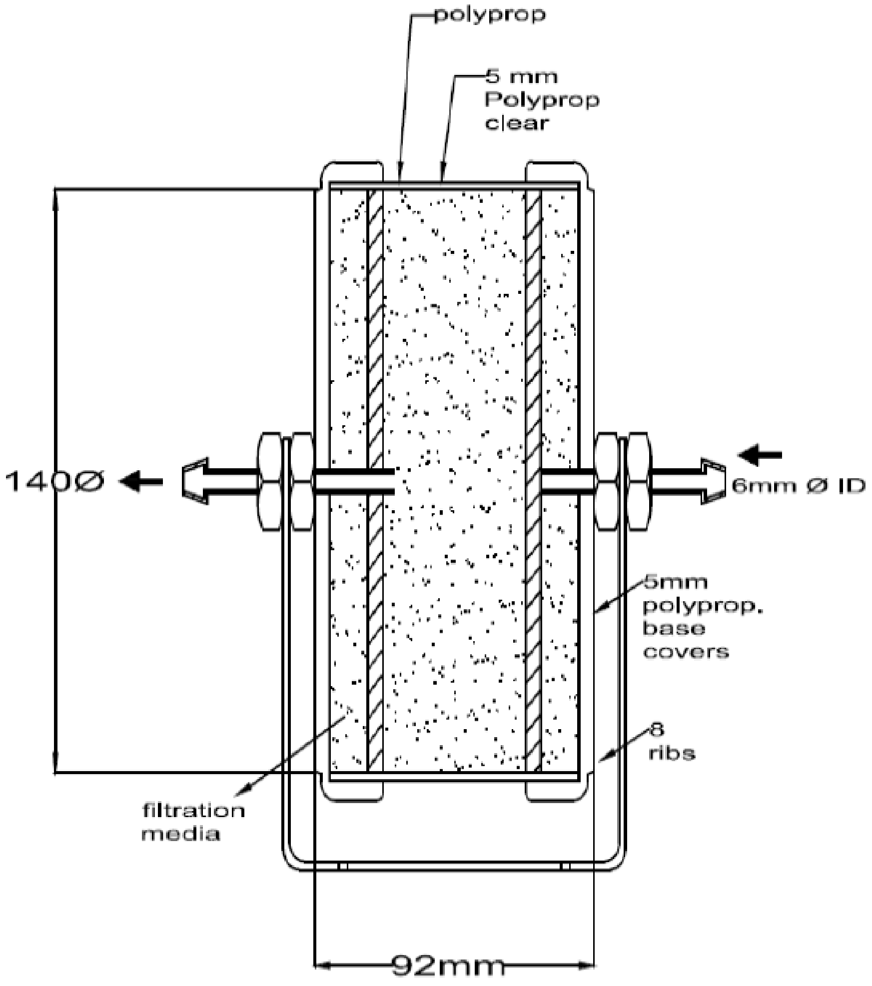


Figure 21. 2-D schematic for Whale Filter [17]

The Whale filter is a South African patented secondary diesel filter designed by Mr Hennie Joubert, the diesel filter is currently filed under patent number 2005/08375. The filter has a cylindrical shape of 140 mm in diameter and 92 mm width as shown in Figure 21.

The filter is made of transparent polypropylene plastic filter housing and polypropylene base covers with perforated mild steel backing plates on the suction and delivery sides. The fuel inlet and discharge nozzles are made from stainless steel 6 mm standard fitting compatible with any diesel engine. The porous filter medium is made of natural cotton fibres arranged in a specific pattern for uni-directional and uniform fuel flow throughout the filter. The contaminants are captured through the filter media by physical filtration process and accumulate from the inlet side to the suction side. The end life cycle of the filter can also be verified by visual inspection of the filter media through the transparent filter media housing. The filter has a larger active filtration area compared to conventional primary filters and it targets micro particles of 0.5 µm and smaller.

Four different vehicles categories were used for these tests and these include a 66 Seater bus from Vaal Maseru, a Toyota Hilux bakkie from Semwes, a BELL 315SJ and John Deere 7800 tractor from North River Carriers. All vehicles were subjected to pre-emissions testing prior to fitment of the filter. Each vehicle was started and allowed to idle for 5 minutes before a calibrated Autologic vehicle emission analyser probe was inserted into the exhaust pipe. The analyser samples the exhaust gases at a pre-defined time interval, the gases are diluted and analysed inside the analyser box. The analyser measures the emissions present in the exhausts gases and record the data into the analyser memory, the technical specifications of the emissions analyser used for this experiment is presented in Table 3. The engine speed was increased to 1200 rpm and kept constant for 5 minutes while the gas analyser was set to sample the gas every 5 seconds in order to obtain 60 data point over a 5 minutes interval. The same procedure was followed at 1500 rpm and 900 rpm. The gas analyser intake filter was replaced and a validation test was conducted. The data was downloaded to a computer and exported to Microsoft Excel spread sheet for evaluation.

The overall average reduction in CO (35.3%), NOx (26.1%) and HC (34.3%) is believed to be associated with the removal of fine particle contaminants in the diesel using the Whale filter. The Whale filter is capable of filtering particles of up to 0.5 μm; this was observed by a quick test conducted; whereby diesel fuel was contaminated with black toner dust of an average particle size of 0.5 μm. The diesel was filtered through a Whale filter in a single pass filtration resulting in a clear diesel filtrate. This test has shown the ability of whale filter to capture toner particles. Most vehicles are only fitted with primary diesel filters for the removal of particles contaminants prior to combustion. Dust particles less than 5 μm can enter the fuel system through the fuel cap when the vehicle is operated in dusty environment. Such particles are small enough to pass through an in-line primary diesel filter into the fuel injector system. A whale filter has been specially designed to work as a polishing filter for the primary fuel filter. The whale filter removes finer particles from the pre-filtered diesel fuel by physical filtration process through a filter media of helical platted cotton fibers with high packing density.

2.5.2. Removal of carbon dioxide by a spray dryer

With the global warming due to greenhouse effects becoming serious, many efforts are carried out to decrease the emissions of CO2 from the combustion of carbonaceous materials. In Taiwan, there are 19 large-scale municipal solid waste incinerators running and their total emission of CO2 is about 16 950 kton y^{-1}. Spray dryer is the most prevailing air pollution control devise for removing acid gas in waste incineration;

however, the performance of spray dryer on the removal of CO2 is seldom studied. This study employs a laboratory-scale spray dryer to investigate the removal efficiency of CO2 under different operating conditions. The evaluated parameters include different absorbents mixed with Ca(OH)2, operating temperature, the concentration of absorbent, and the inlet concentration of CO2. Experimental results show that the best removal efficiency of CO2 by a spray dryer is 48% as the absorbent is 10%NaOH + 5%Ca(OH)2 and the operating temperature is 150 °C. Comparing this result with previous study shows that the performance of spray dryer is better than traditional NaOH wet scrubber. For NaOH + Ca(OH)2 spray dryer, the removal efficiency of CO2 is decreased with the inlet concentration of CO2 increased and the optimum operating temperature is 150 °C. Except NaOH + Ca(OH)2, absorbents DEA + Ca(OH)2, TEA + Ca(OH)2, and single Ca(OH)2 are not effective in removing CO2 by a spray dryer [19].

CHAPTER 3: EXPERIMENTAL METHODS

In this section of the report, the experiments which have been done will be thoroughly elaborated and discussed. All of the experiment tools and apparatus will be mentioned in details stating its function and a self-explanatory picture. The test rig was designed and fabricated to match the size of a tail pipe of a common diesel engine. The idea is to come up with a device that can be easily mounted at the back of any automobile vehicle and fit properly.

In this experiment, a test rig which is a cylinder with a long dispenser will be installed at the exhaust port; which is a flexible metallic hose, of a single cylinder diesel engine in Qatar university’s heat engines laboratory. This test rig has been tested when it’s empty “reference”, with water and finally with NaOH solution. Each one of these three experiments have been tested for a constant load and variable speed at one time and for a constant speed and variable load at the second. The engine parameters were taken and tabulated as a function of torque and speed along with emissions using a gas analyzer and smoke meter.

3.1 Test rig

3.1.1 The engine and it’s components

The engine used in this experiment is a single cylinder compression ignition diesel engine figure (22). It is mounted on a fixed support and is attached to a dynamometer to vary the load on the engine. The engine has a volume of 230 CC, 3.5 kW of maximum power at 1800 RPM and 21 N.m of maximum torque at 1100 RPM figure (23)

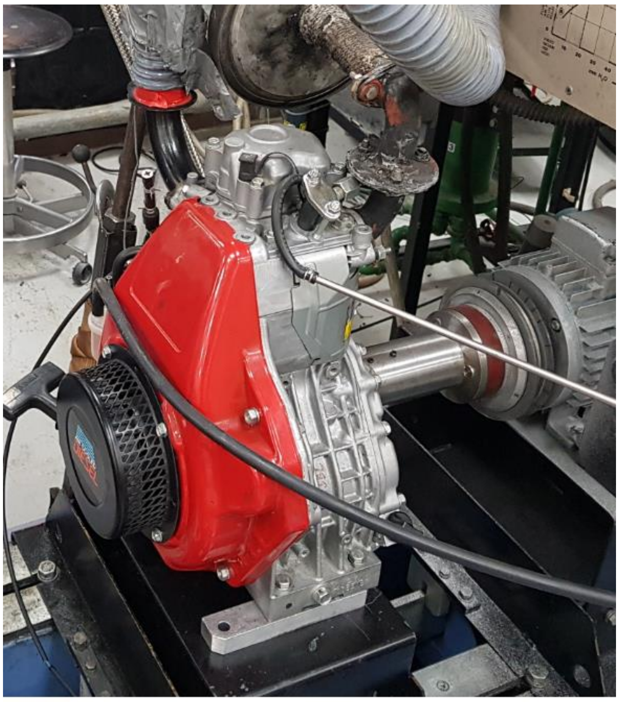
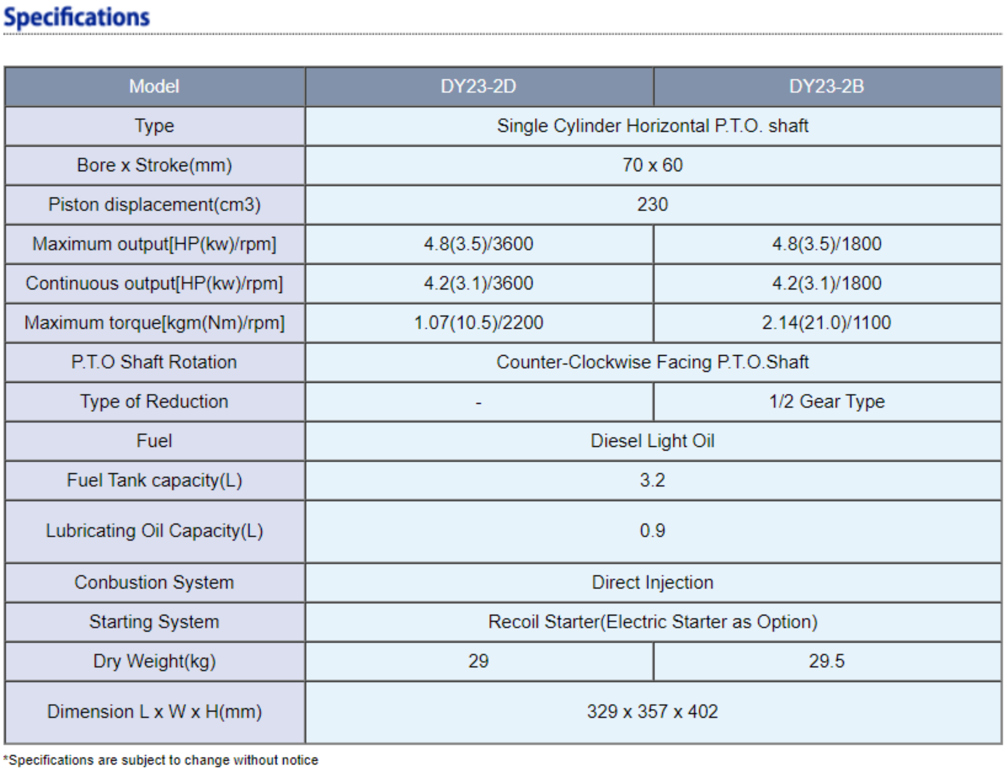


Figure 22. Engine's test bed “DY23-2B”



Specifications

Model	DY23-2D	DY23-2B
Type	Single Cylinder Horizontal P.T.O. shaft	
Bore x Stroke(mm)	70 x 60	
Piston displacement(cm3)	230	
Maximum output[HP(kw)/rpm]	4.8(3.5)/3600	4.8(3.5)/1800
Continuous output[HP(kw)/rpm]	4.2(3.1)/3600	4.2(3.1)/1800
Maximum torque[kgm(Nm)/rpm]	1.07(10.5)/2200	2.14(21.0)/1100
P.T.O Shaft Rotation	Counter-Clockwise Facing P.T.O.Shaft	
Type of Reduction	-	1/2 Gear Type
Fuel	Diesel Light Oil	
Fuel Tank capacity(L)	3.2	
Lubricating Oil Capacity(L)	0.9	
Conbustion System	Direct Injection	
Starting System	Recoil Starter(Electric Starter as Option)	
Dry Weight(kg)	29	29.5
Dimension L x W x H(mm)	329 x 357 x 402	

*Specifications are subject to change without notice

Figure 23. Engine's specifications

The engine’s shaft rotational speed is measured using a hand tachometer figure (24). The tachometer gives the speed in RPM which will be converted to RPS for calculations purpose. The engine has a manual pedal used to increase the amount of fuel entering the engine’s cylinder increasing its power which in other words is called the “throttle” figure (25). The dynamometer is connected to the engine’s protruded shaft by means of a rigid coupling figure (26). This dynamometer can vary the load on the shaft from 0 R to 5 R which can be converted to N.m using torque conversion tables.

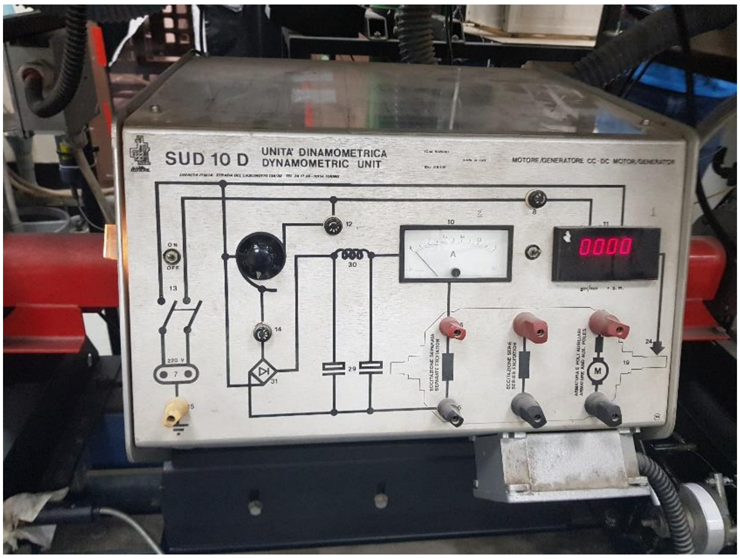


Figure 24. Dynamometer of the engine

Figure 25. Engine's throttle pedal

Figure 26. Tachometer

The volumetric fuel intake into the engine is calculated by measuring the time taken for 1 cubic centimeter to be consumed figure (27). Whereas the air intake is measured by a manometer device attached at the inlet port of the engine’s manifold, figure (28). Air volumetric mass has been calculated using the conversion chart “A” in figure (29). It basically tabulates the air’s cubic meters per hour as a function of the results which were indicted by the manometer in mm of H_2O.

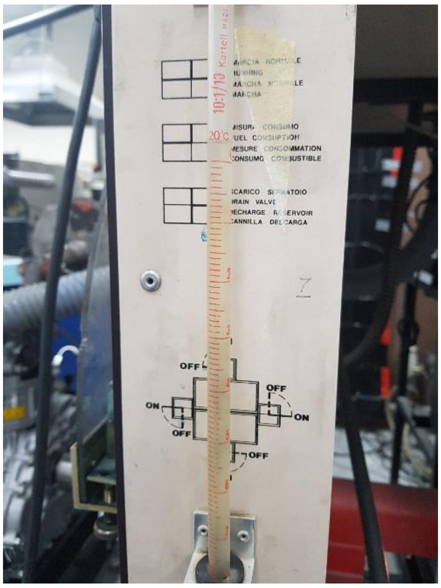


Figure 27. Fuel Guage

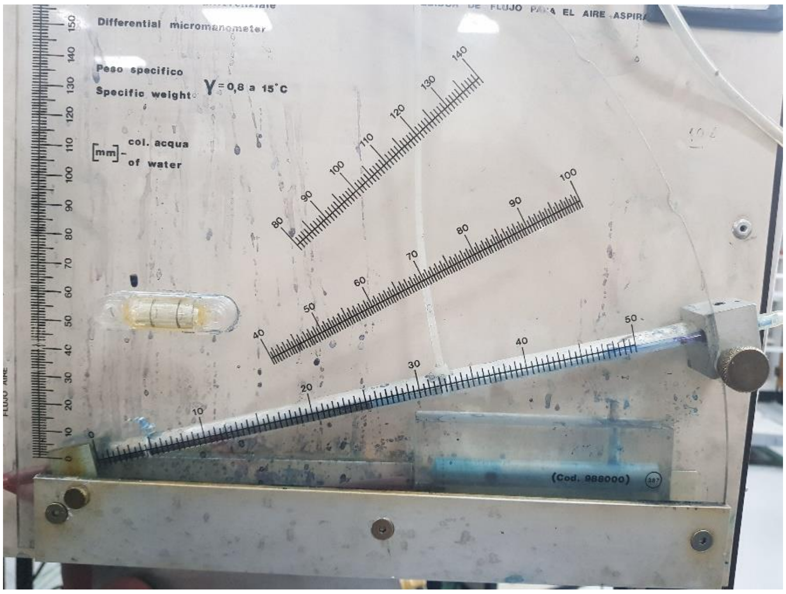


Figure 28. Manometer for indicating air flow into the engine in mmH2O

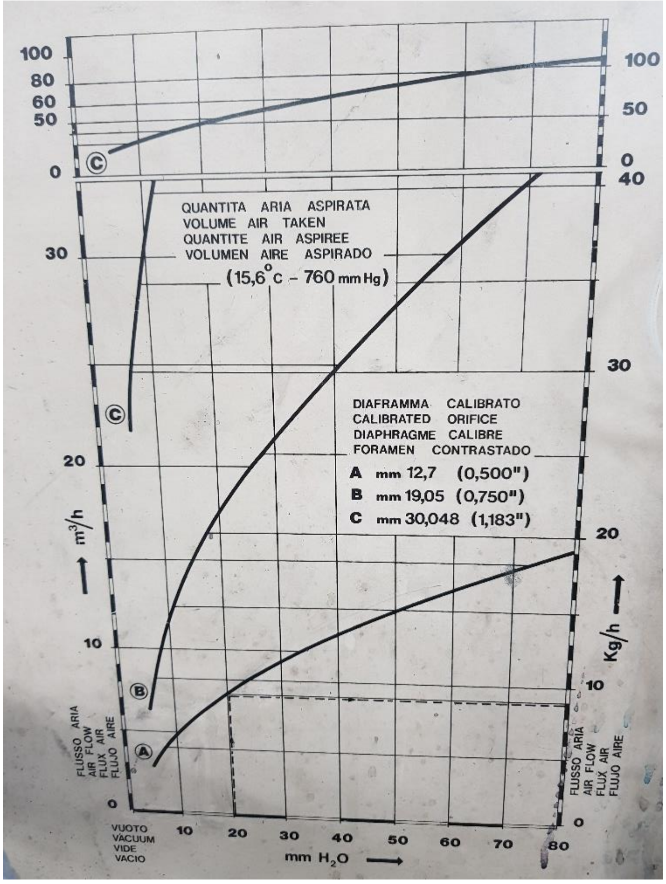


Figure 29. Air intake conversion chart

3.1.2 Emissions Reduction Tube

The reduction tube basically a cylinder with 1.25 meters in length and 4 inches in diameter figure (30). Inside of this cylinder is a dispenser that is 1 meter in length. The dispenser is a smaller pipe that has a diameter of 1 inch and contains 10 holes of 5 millimeters diameter along its whole length. This is to allow of more surface of contact between exhaust gasses and the liquid inside the cylinder thus enhancing the capturing due to proper mixing figure (31). This whole system was designed and fabricated as part of this study and the dimensions were chosen so that it can match the size of the already existing exhaust pipe dimensions.

Figure 30. Emissions reduction pipe

The material used to fabricate this test rig is stainless steel 316L. This type of metal was used to ensure that the alkaline solution NaOH does not react with the metal causing corrosion and erosion to the material. The cylinder has a capacity of 23 Liters but these 23 Liters will not be fully utilized with liquid since the dispenser will take some of that space and also the cooling coil which will be mentioned later in this chapter will take some of this space as well. These are the main disadvantages of this design. It should be mentioned that the dispenser is directed by 45 degrees elbow to the bottom of the 4 inches cylinder to maximize the area of contact.

Figure 31. Emissions reduction dispenser

3.1.3 Cooling system

Cooling system was added to the emissions reduction device in terms of a coil immersed into the liquid in order to reduce the amount of evaporation due to high exhaust temperature. The cooling system is composed of a cooling coil, a radiator, normal water with a pump and an AC/DC converter. The cooling coil is basically a copper tube with a diameter of 10 millimeters and a total length of 0.9 meters. The coil has a mean diameter of 3 inches and is helical in shape. There are 30 coils in the 0.9 meters of the tube. The volume of the cooling coil is about 1.5 Liters which will not take much of space from the cylinder. Normal water will be pumped into the cooling coil which is chilled by a radiator that has 2 big fans attached to it. The pump and the 2 fans are attached to the AC/DC converter since the electrical supply inside the lab is

AC type whereas the motor fans and pump are designed for DC type, figures (32,33,34)

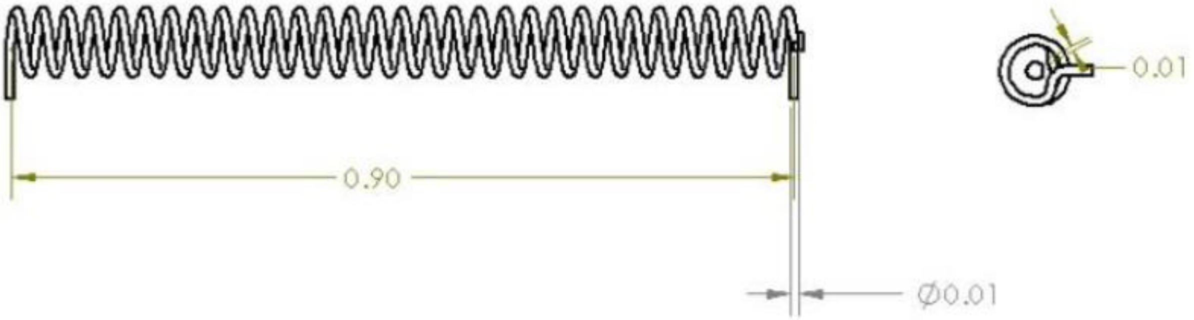


Figure 32. Cooling coil dimensions

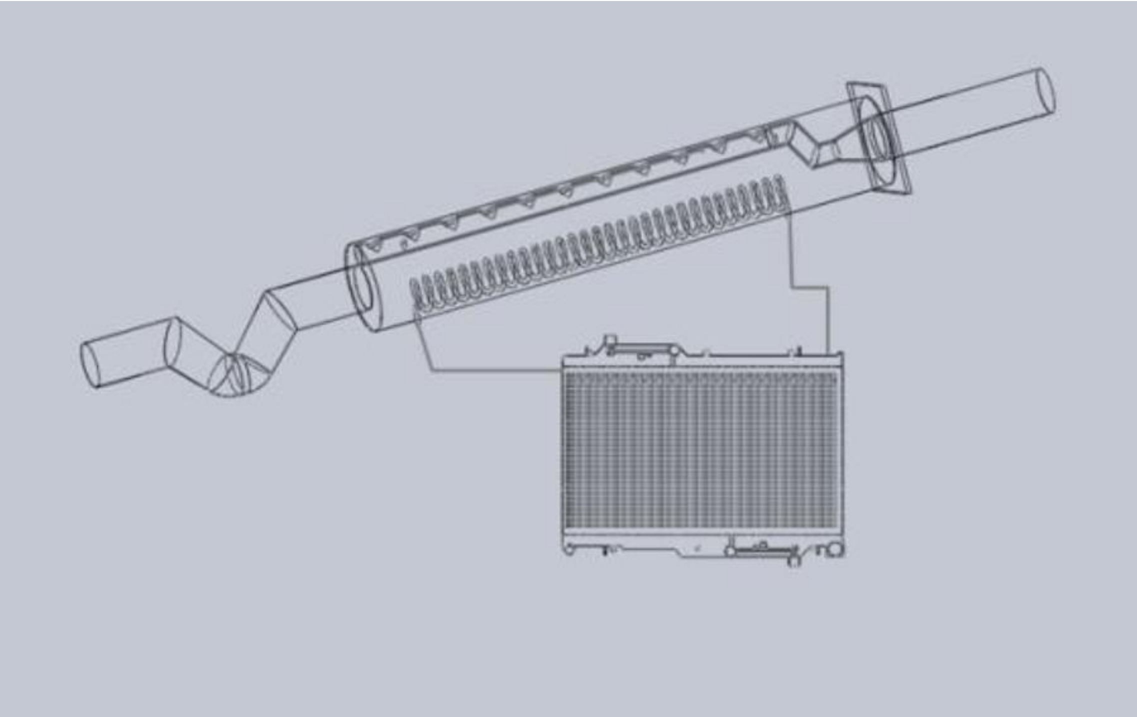


Figure 33. schematic for emissions reduction tube cooling system

The cooling coil has helped in keeping the water or NaOH solution at a constant temperature of about 35 degrees Celsius. This has resulted in less evaporation and thus allowing the liquid to settle for longer times inside the cylinder. The liquid wasn't affected much from the high temperature exhaust gasses that are existing the flexible exhaust metallic hose at around 120 degrees Celsius.

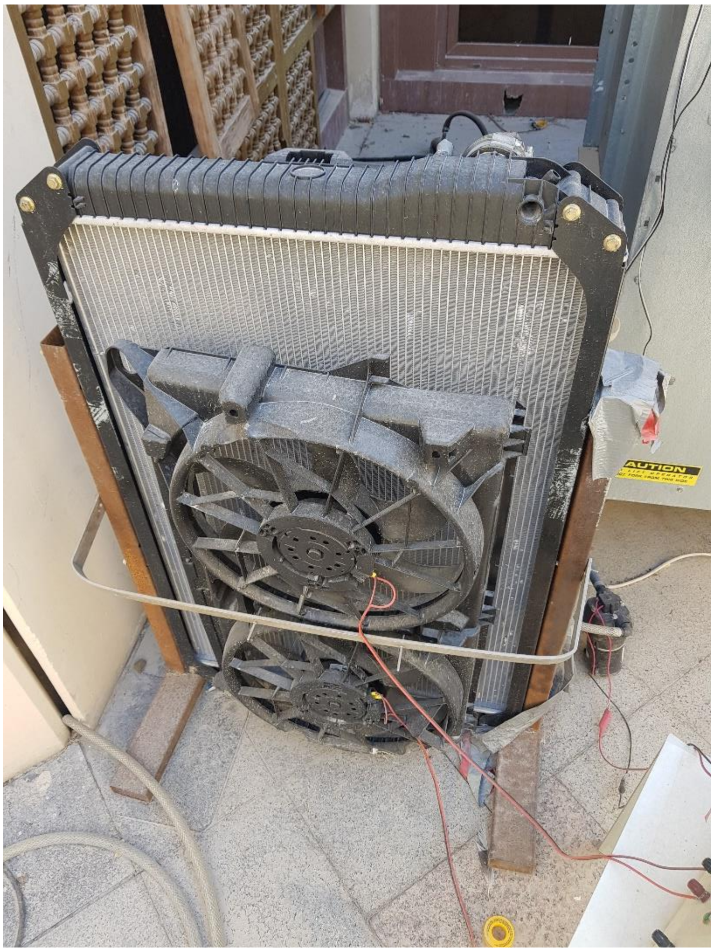


Figure 34. Cooling system radiator

Figure 35. Test rig assembly

Figure (35) shows the complete assembly of the emissions reduction tube with its cooling device and outlet chimney to the atmosphere.

3.1.4 The sodium hydroxide solution (NaOH)

Sodium hydroxide (NaOH) comes in a form of powder or small pellets and is converted to an alkaline solution by dissolving in water in a certain percentage. Every 1 kg of NaOH pellets dissolves completely in 1 liter of water making a 100% saturated

NaOH solution figure (36). In our experiment, only 0.5 kg was allowed to dissolve in 1 liter of water making a 50% saturated NaOH solution. This is to avoid the crystallization of NaOH with CO2 from the engine's emissions thus blocking the holes of the dispenser as was seen in previous researches in the literature. The NaOH preparation is hazardous since the reaction with water is exothermic thus releasing heat. So, an ice bath was used to cool down the reaction. NaOH pellets were added carefully to the water pan that was immersed into the ice bath and stirred carefully to avoid precipitation figure (37).

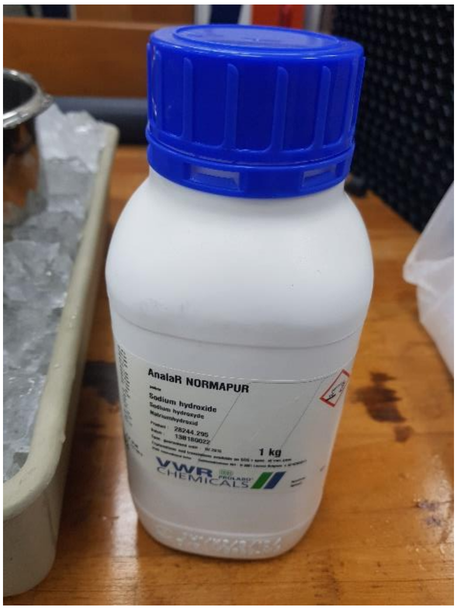


Figure 36. 1 kg bottle of NaOH pellets

Figure 37. Preparation pan with ice bath for NaOH solution

NaOH solution that was used in the experiment is only 50% saturated, this is due to the following:

- The fully or 100% saturated could cause crystallization and this blockage in the dispenser of the device (from literature)
- It requires lots of quantities of NaOH (more cost)
- The 50% saturated NaOH solution contains more molecular spaces for other gas emissions to settle in unlike the 100% saturated one which contains very less gaps.
- The 100% saturated solution behaves almost similarly to the 50% saturated solution in CO2 capturing (figure 13)

3.2 Measuring devices

3.2.1 Gas Analyzer (ENERAC 700)

A gas analyzer is a device which has multiple sensors calibrated to measure the amount of emissions from automobile engines. The gas analyzer plays a great role in this experiment because it shall give an indication about the effects of adding water or NaOH into the exhaust compared to the actual emissions from the engine, figure (38). Carbon dioxide in particular will be the main focus in the NaOH solution experiment. The emissions which this report will target are HC in ppm, CO2 in volume %, CO in ppm and NOx in ppm as well as the smoke released during combustion but was measured using a different device which will be mentioned in the next section.

Figure 38. Gas analyzer "ENERAC700"

The Model 700 emissions analyzer remove, clean, finally dry the taken sample. Once the probe is inserted in the exhaust pipe of the engine, a pump will suck a sample which is then cleaned and dried before entering the system. ENERAC Model 700 Emissions system has large number of sensors that best serve the objective of this project. The following are the integrated sensors which will be utilized during the experiment to measure the targeted emissions:

A. Carbon monoxide sensor

B. Nitric oxide sensor

C. Nitrogen dioxide sensor

D. Sulfur dioxide sensor

E. Oxygen sensor

Calibration of the system is recommended annually. Through which the device is sent to the factory for complete calibration depending on the sensor calibration span. Calibration for the same system was done on the 6th of January, 2018 in order to ensure accurate data and calibration certificate is attached as Appendix A

3.2.2 Smoke-o-meter

Smoke is a form of unburned light hydrocarbons which are called soot. The smoke is one of the hazardous emissions from diesel engines and thus was important to study. Smoke is measured by a device that takes part of the exhaust gases and allow it to pass through a clear lens, the amount of soot accumulated on the lens will give an indication of how much this soot covered the clean lens, figure (40). The unit of measure is called opacity which shows in percentage how dirty the lens is for each run or test.

Figure 39. Smoke-o-meter's display screen

Figure 40. Smoke-o-meter device "ECO SMOKE 100"

3.2.3 Thermocouple

A thermocouple was utilized to measure various temperatures at various points on the test rig. Temperatures were taken at the intake manifold, exhaust manifold, inlet and outlet of the cylinder capturing device.

Figure 41. Thermocouple

CHAPTER 4: RESULTS AND DISCUSSION

In this section of the report, the results obtained from the various experiments will be discussed thoroughly. The experiment has been done to examine the emissions reduction effectiveness of adding water or NaOH solution into a fabricated cylindrical pipe in the exhaust of a single cylinder diesel engine. It is divided into three segments; the first segment, in which it has been called the reference case, will show the various emissions and engine parameters for a constant engine crank rotational speed at 1800 RPM with varying the torque from 0.9 NM to 5.1 with a 0.6 increment, and another test with constant load of 1.5 NM but this time varying the speed from 1400 to 2600 with a 200 RPM increment. This experiment has been called the reference point because the exhaust is open to atmosphere for comparison reasons. For the second and third segments, the exact same thing was done except that water and NaOH solutions were added respectively into the fabricated cylindrical device which is installed on the outlet of the exhaust hose of the engine. The same emissions and engine parameters were taken and calculated in order to compare them with the reference point.

4.1 Engine Performance

In this part of the results section, the engine parameters like volumetric efficiency, break specific fuel consumption, thermal efficiency and air to fuel ratio will be tabulated as a function of various torque values keeping speed at a constant rate. Moreover, the same will be done for various speed values keeping the torque at a constant rate. This has been done for the three experiments, i.e. without any liquid (Ref), with water (W) and with sodium hydroxide (NaOH) solution.

4.1.1 Volumetric efficiency

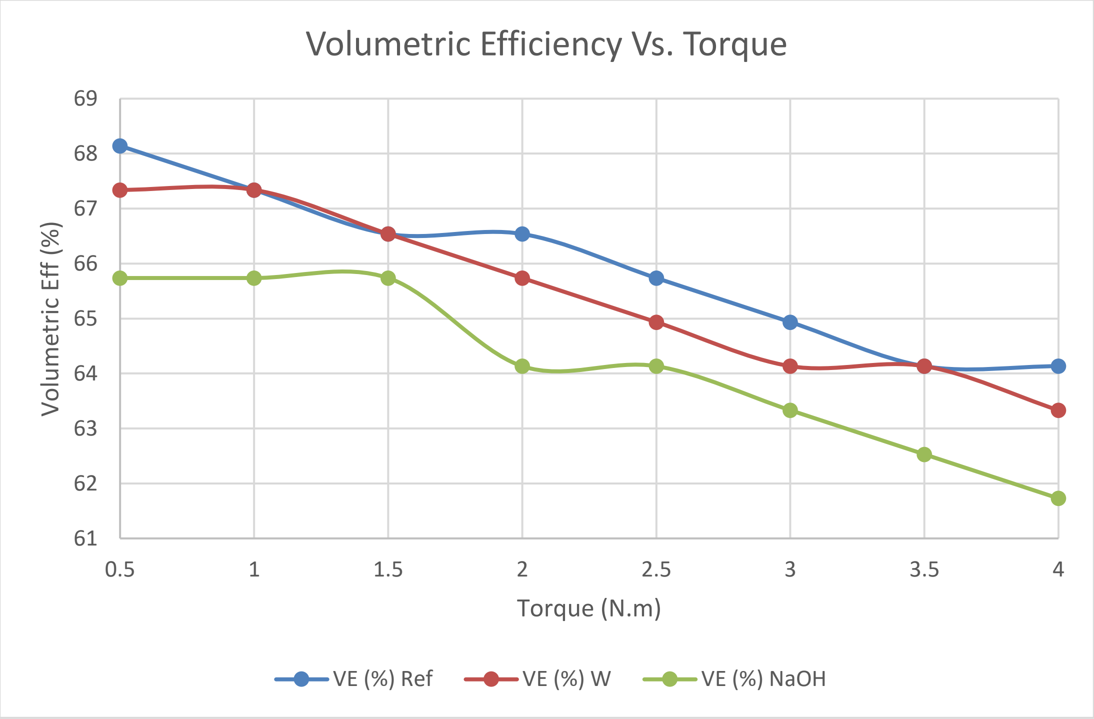


Figure 42. Volumetric efficiency vs. torque

figure (42) shows the relation between the volumetric efficiency which is one of the crucial engine parameters that directly contributes to the power and various torque values for the three experiments. It basically means how well the engine can breathe, i.e. the percentage in which the engine got air by how much the engine can theoretically take. The volumetric efficiency didn’t change much for water experiment but decreased around 2% from 68 to 66 % for NaOH solution experiment. It will be explained later why it is still acceptable to lose this much of volumetric efficiency when the results of emissions reduction are shown.

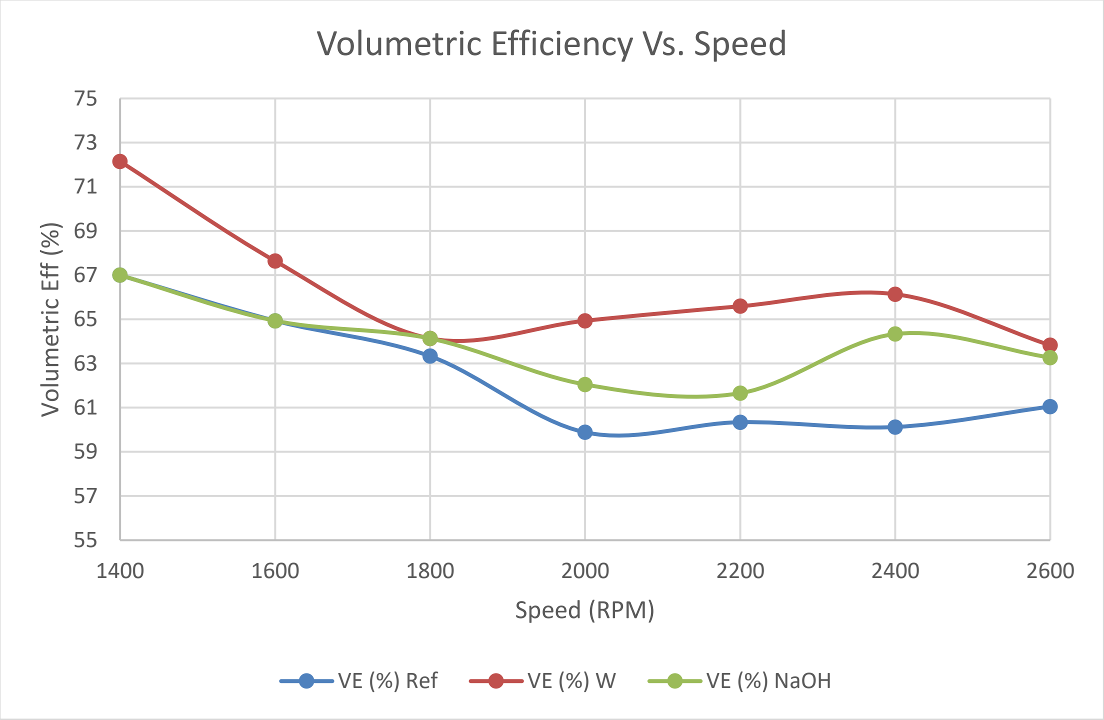


Figure 43. Volumetric effeciency vs. speed

Figure (43) shows the same relation as figure (42) but this time with varying the engine’s speed. The engine experienced a decrease in volumetric efficiency for higher RPMs. This means that the amount of air being taken by the engine is not big enough to compensate the quick increase in the speed. The engine doesn’t have enough time to let air into the cylinder, this could be due to the engine being a single cylinder. Anyways, the water experiment shows higher average values of volumetric efficiency with about 3% compared to the reference. The experiment with NaOH didn’t have much effect and was almost similar to the reference.

4.1.2 Break Specific Fuel Consumption

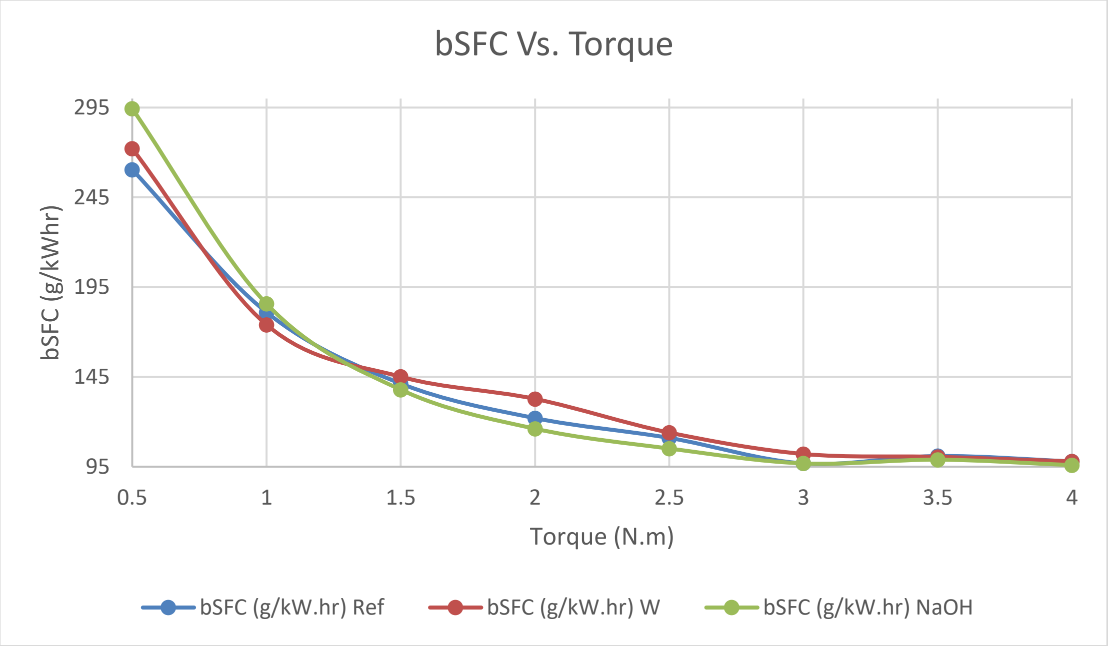


Figure 44. BSFC vs. torque

Figure (44) shows the relation between the break specific fuel consumption values for all three experiments and various torque values of the engine. The patterns are almost similar but with a slight increase of around 90 grams in the lower range values of torque, i.e. from 0.5 to 1.5. It can be noticed that with the increased torque, i.e. more load on the engine, the BSFC had an overall decrease from 1000 grams to 400 grams of fuel per kilowatt hours.

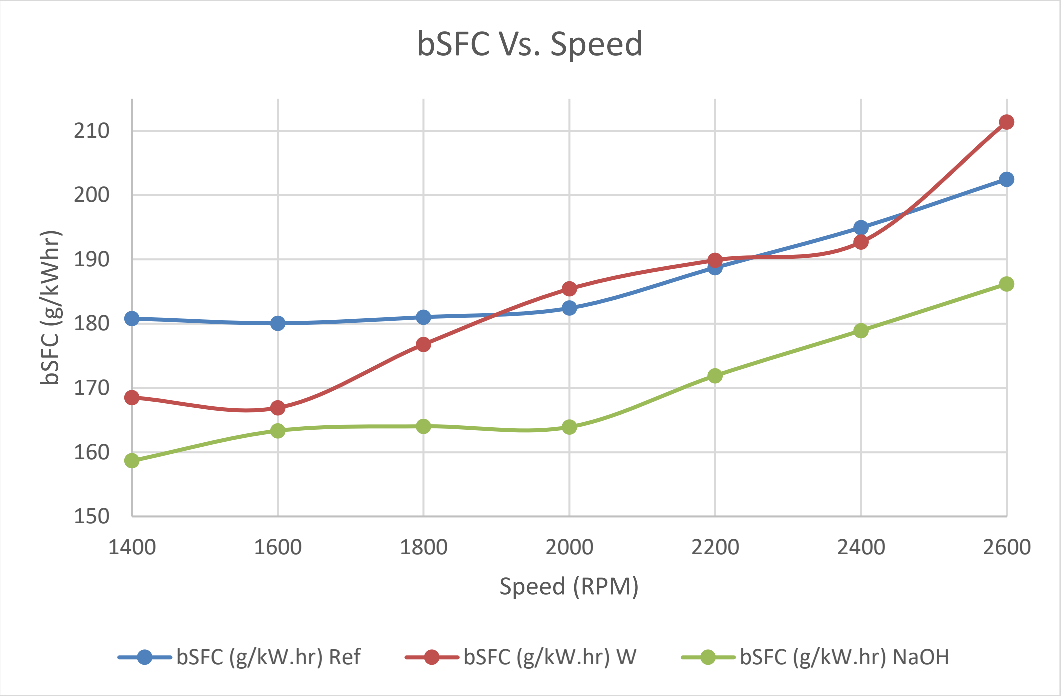


Figure 45. BSFC vs. speed

Figure (45) shows the same relation as figure (36) but with varying speed this time. The break specific fuel consumption had an overall increase for all three experiments with increasing speed. This is logically correct since the engine has to consume more fuel to produce high power values for the engine to move faster. The NaOH experiment had a decrease of 50 grams of fuel per kilowatt hours compared with the reference. The water experiment however didn’t have much difference compared to the reference. It kept fluctuating but with neglectable average.

4.1.3 Thermal Efficiency

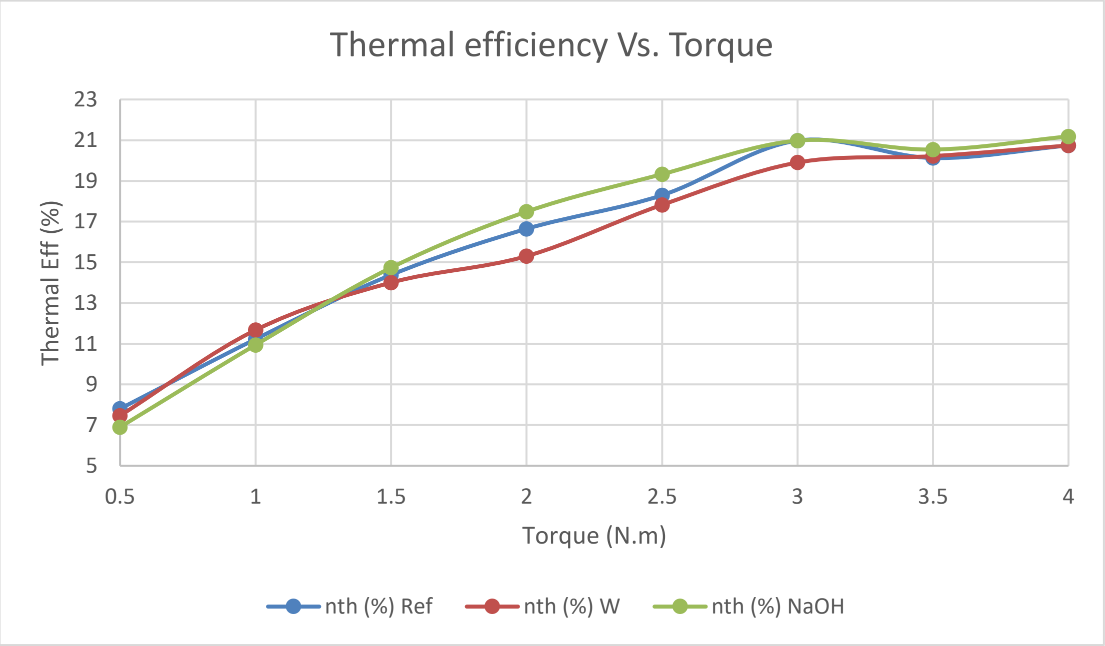


Figure 46. Thermal efficiency vs. torque

Figure (46) shows a relation between the thermal efficiency of the engine and the corresponding torques values for all experiments. On average, all three experiments had the same increased factor of thermal efficiency. NaOH solution experiment shares the same peak value with reference experiment of 21% at the same torque value. The reason behind this increase in thermal efficiency is because the fuel is being well mixed and almost completely burnt inside the cylinder.

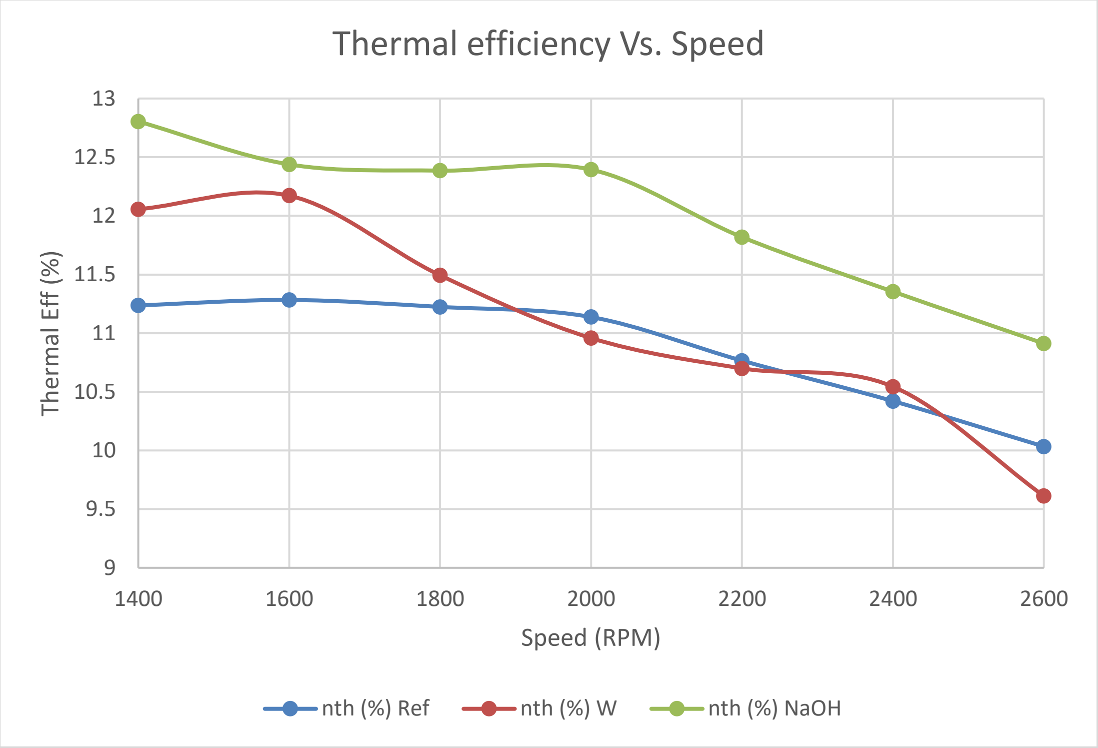


Figure 47. Thermal efficiency vs. speed

Figure (47) shows thermal efficiency for various speed values this time. The higher the RPM the lower the thermal efficiency of the engine for all experiments due to fuel not having enough time to properly mix and burn, thus not being fully consumed by the engine and converted to power. Having said that, the thermal efficiency for the NaOH solution experiment was higher than the reference. On average, there is an increase of 1% thermal efficiency or sometimes being called fuel conversion efficiency. For water experiment it didn’t show much deviation from the reference.

4.1.4 Air to Fuel Ratio

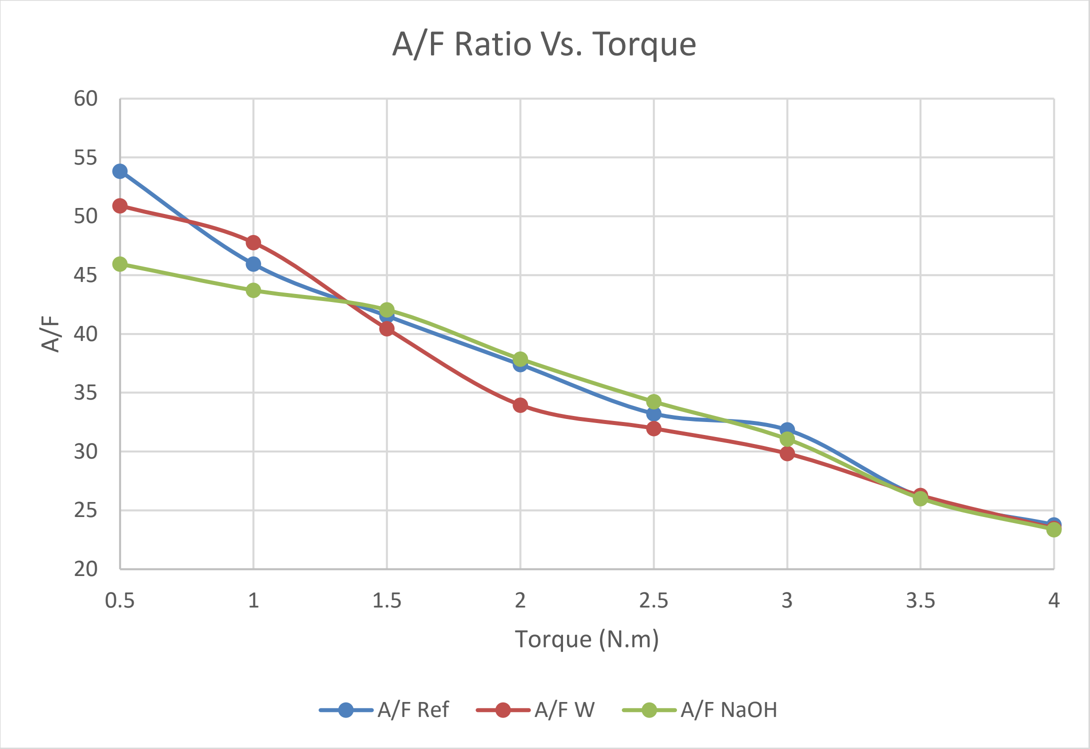


Figure 48. A/F ratio vs. torque

Figure (48) depicts that torque and air to fuel ratio are reversely proportional to each other’s. This happened for all experiments with a similar factor of decreasing. At lower values of torque, the NaOH solution experiment had lower values of A/F ratio of about 10 than the reference. The decrease in A/F ratio means that for higher torque values, the amount of air decreases as well. Although the fuel consumption decreases from figure (44) which should result in higher A/F ratios, the percentage of air decreases at a faster rate than fuel which results in an overall decrease in the air to fuel ratio.

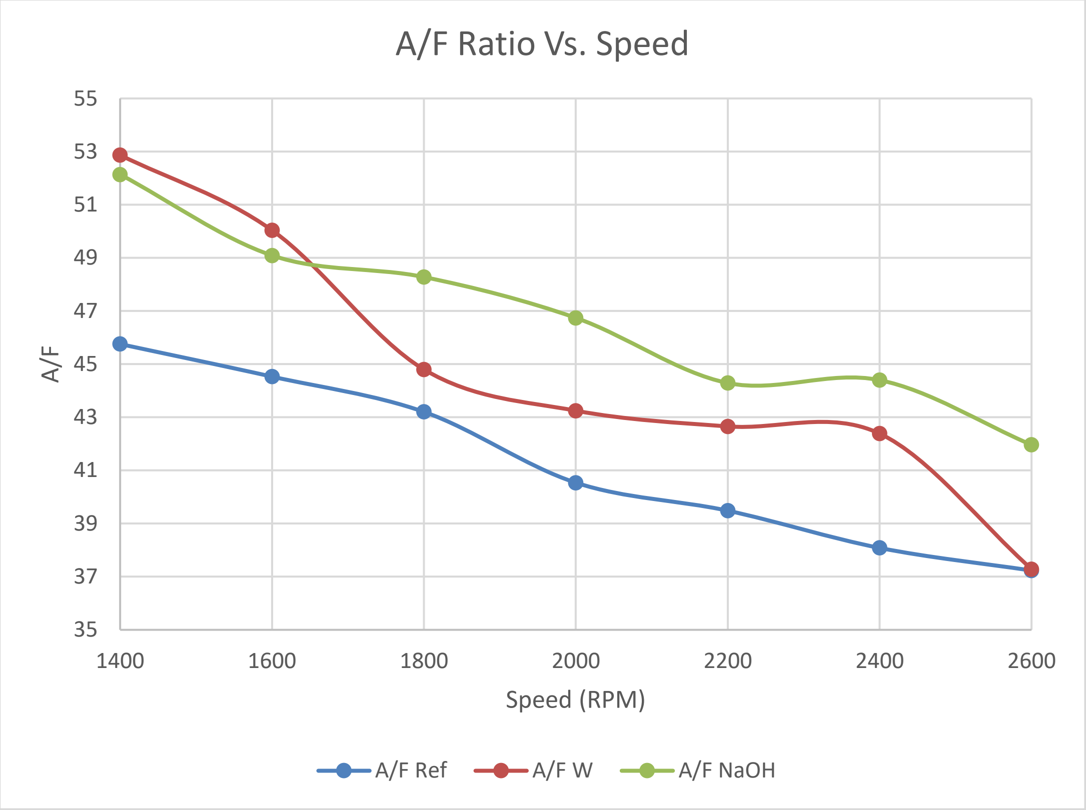


Figure 49. A/F ratio vs. speed

Figure (49) shows the relation between A/F ratio and engine's speed. The higher the speed the lower the air to fuel ratio for all three experiments. This is because the amount of air decreases for higher RPM as in figure (43) and amount of fuel increases for higher RPM as in figure (45). Both NaOH solution and water experiments gave better A/F ratios than the reference experiment. A/F ratio for NaOH solution experiment had the same factor of increasing of about 5 for all RPM values.

From the experiments above, it is clearly shown and proven that engine parameters were not affected much if not at all when adding the emissions reduction tube which is containing the absorption mediums. This indicates that the addition of an extra piece of device at the exhaust will not cause a serious or noticeable change in the behavior of the engine. Also, it will not impact the power created by the engine hence keeping the engine smooth and healthy and above all of that, preserving an environment friendly machine.

4.2 Engine Emissions

In this part of the results section, the engine exhaust emissions namely: hydrocarbons (HC), carbon dioxide (CO2), carbon monoxide (CO), nitrogen oxides (NOx) and smoke (Opacity) will be tabulated as a function of various torque values keeping speed at a constant rate. Also, the same will be done for various speed values keeping the torque at a constant rate. This has been done for the three experiments, i.e. without any liquid (Ref), with water (W) and with sodium hydroxide (NaOH) solution.

4.2.1 Hydrocarbons (HC)

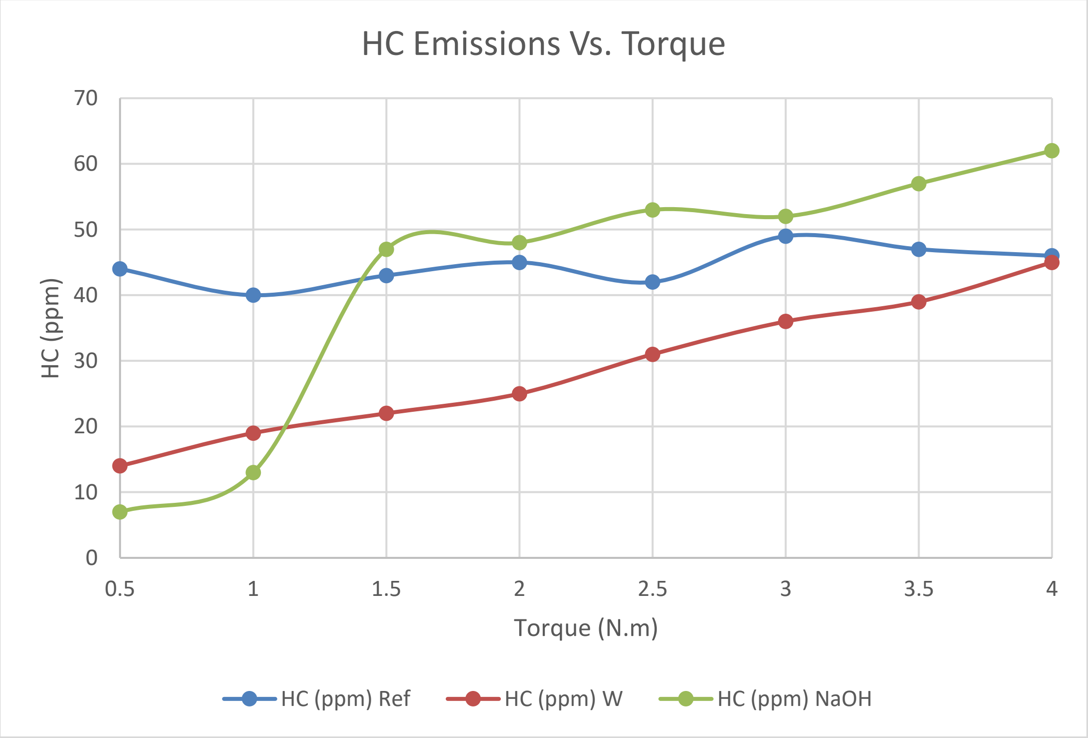


Figure 50. HC vs. torque

The hydrocarbon emmisions are very common when it comes to diesel engines. These are the side effects of uncomplete combustion which could happen due to many factors like not proper mixing of air and fuel inside the cylinder or no enough time for fuel mixture to burn. Figure (50) shows that for constant speed the HC emissions increase for both NaOH solution and water experiments with increasing load on the engine. However, for the reference it did not increase that much. Having said that, both NaOH solution and water had lower values of HC emissions than the reference. HC emissions deceased by 75% at lower torque values compared with reference case. NaOH experiment didn’t have much effect for higher loads, but water experiment gave much lower emissions than the others. This is because HC atoms have despersed into the water and settled in leaving only small amount to exit the vehicles exhaust. It is as if the HC dissolved into water.

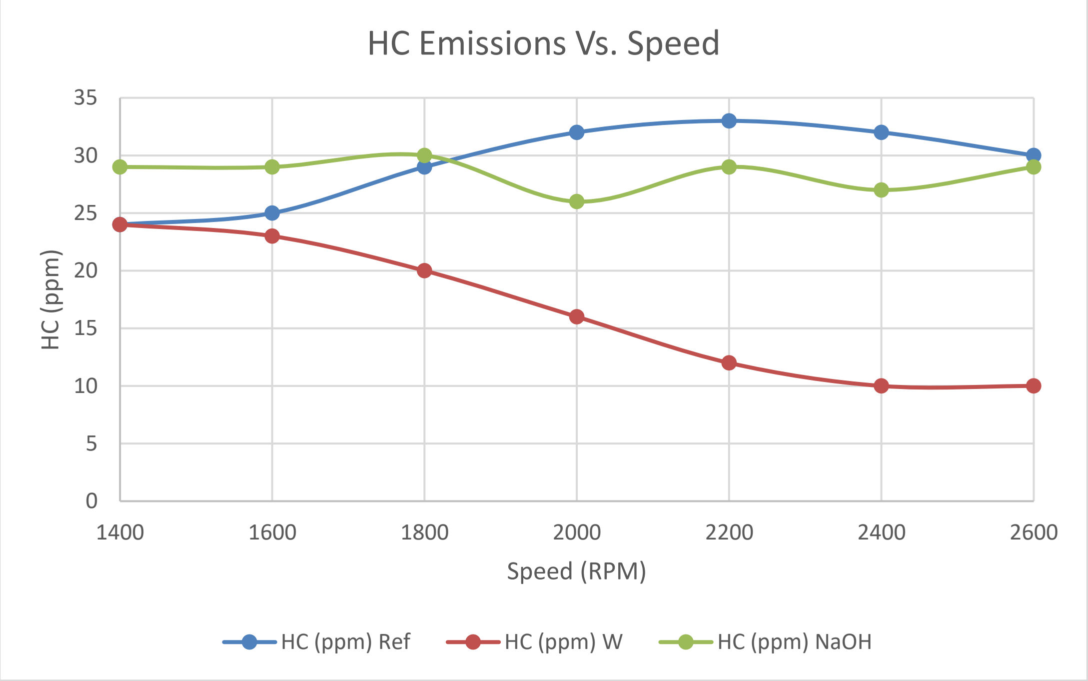


Figure 51. HC vs. speed

For constant load and varying speed tests, the above figure (51) clearly shows that the overall HC emissions for all three experiments are lower than those in the constant speed varying load tests. This is because with higher loads the fuel entering the cylinder increases replacing the air and thus making the mixture richer which results in uncomplete combustion. Figure (51) also shows that reference and NaOH experiments have similar HC emissions, however, this is not the case for water. The HC emissions decreased around 15 PPM on average compared with the reference. This is because water molecules contain gaps that HC can easily fit in or in other words dissolve into water unlike the NaOH solution which is 50% saturated in water.

4.2.2 Carbon Dioxide (CO2)

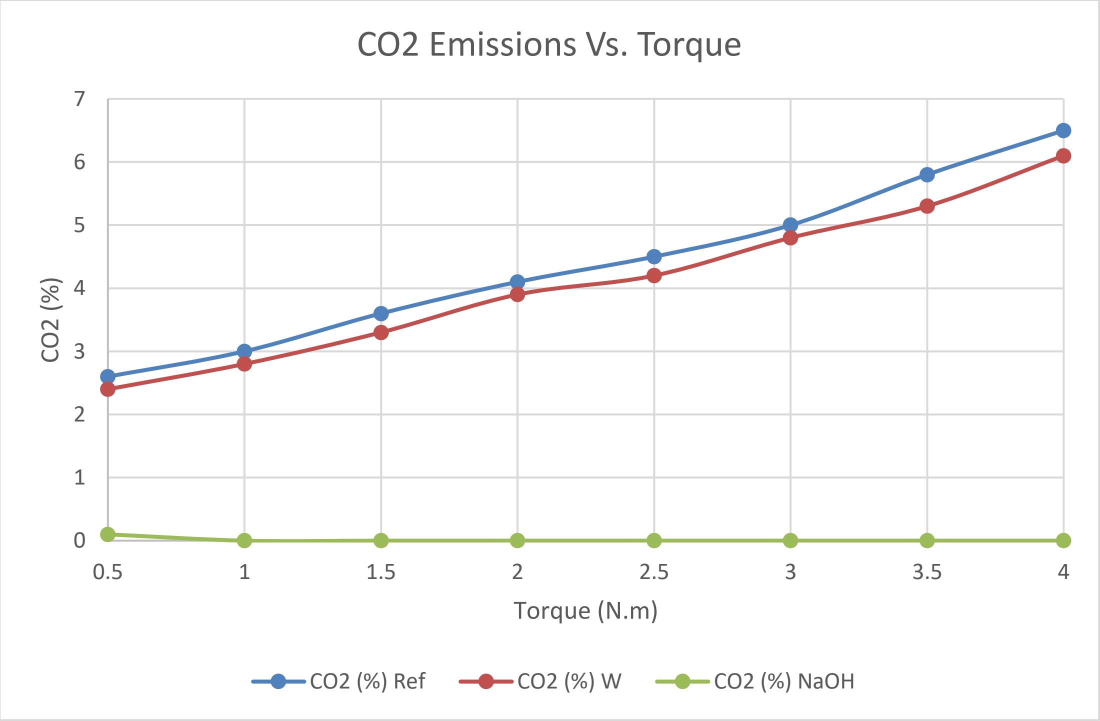


Figure 52. CO2 vs. torque

Carbon dioxide emissions are not that crucial when it comes to diesel engines as it is not produced in high quantities like gasoline engines. This is because most gasoline engines contain a catalytic converter which converts the CO into CO2. Also, diesel engines have higher thermal fuel conversion efficiencies. Anyways, it was worth testing whether or not the CO2 emissions will be affected by adding water or NaOH into the exhaust system. Figure (52) shows that both the reference and water experiments have similar values of CO2 emissions with slightly less for water. However, these emissions came down to almost nothing when tested with NaOH solution. From literature review, it was proven in many researches that NaOH solution is very effective for reducing the CO2 emissions [7]. Carbon dioxide reacts with sodium hydroxide producing sodium carbonate Na_2CO_3 and water.

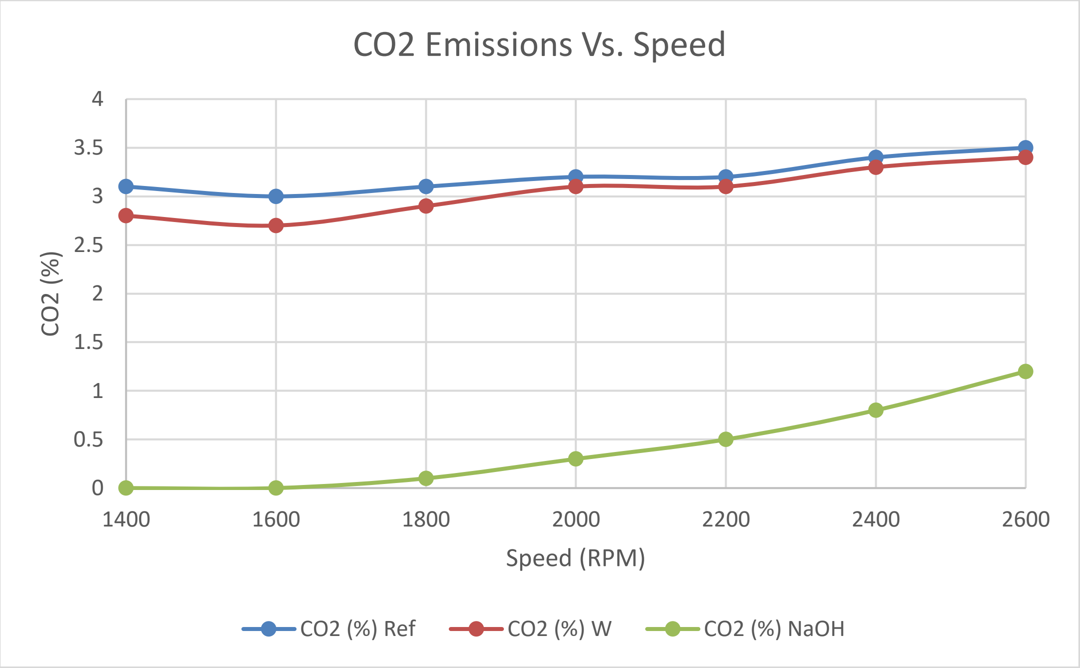


Figure 53. CO2 vs. speed

CO2 emissions for constant load variable speed are also similar for both reference and water experiments, but in overall, they are lower than the emissions produced in the constant speed variable torque tests. This is because CO2 is mainly produced due to high temperatures inside the engine which is caused by too rich fuel mixtures. The CO2 emissions as can be seen in the figure (53) also decreases by 85% for NaOH when compared to reference case which is quite the same result as the previous experiment with constant speed.

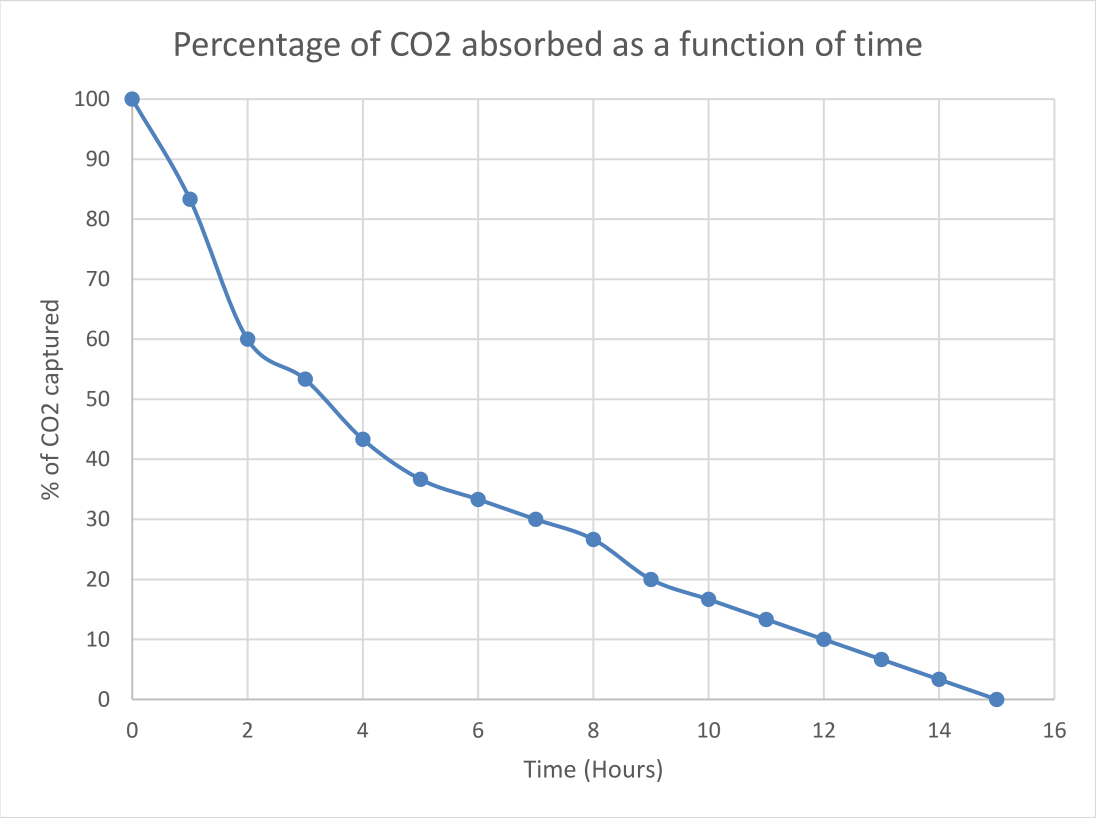


Figure 54. CO2 absorption efficiency curve

Engine was allowed to run until the NaOH solution can not react with CO2 any more. In other words, the CO2 emissions were taken every hour until the percentage of CO2 reaches that of the reference value without adding anything. As can been seen in figure (54), the capturing efficiency dropped down from 100% to 60% for the first 2 hours. Then it dropped from 60% to 30% for the next 6 hours. Finally, it took another 7 hours for the NaOH to be fully saturated with CO2 and can’t do any more absorption.

At this stage, the solution needs to be refilled.

This experiment's main point is to show how much time can the NaOH solution capture CO2 before it gets exhausted and reach a 0% efficiency.

4.2.3 Carbon Monoxide (CO)

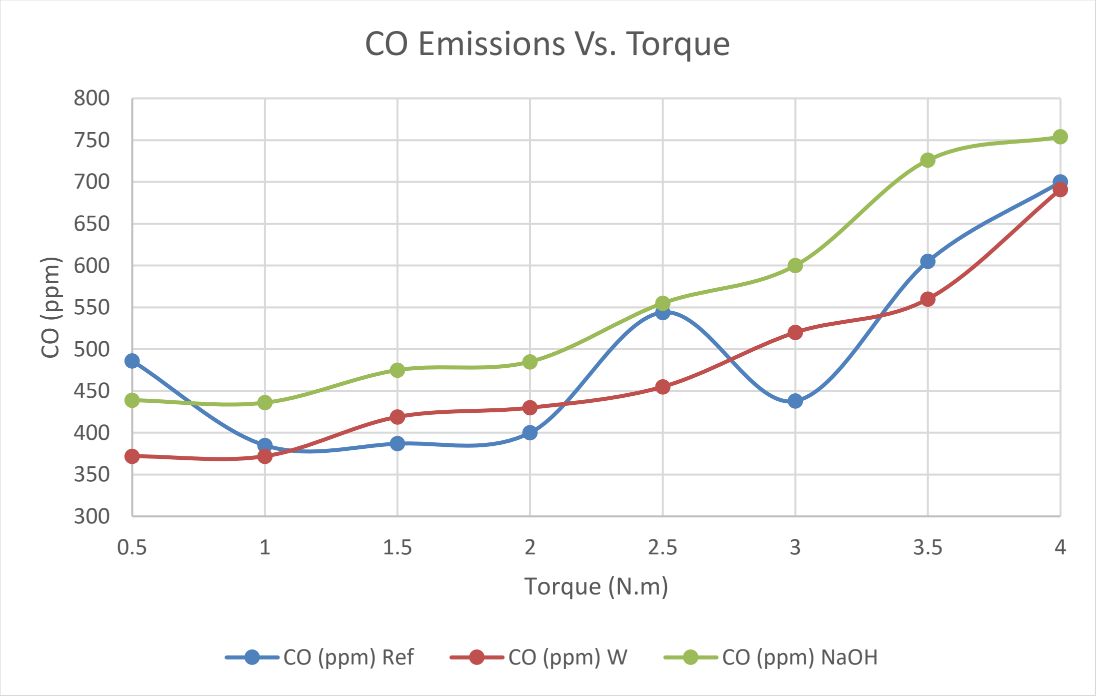


Figure 55. CO vs. torque

The CO emissions are cause by incomplete oxidation of fuel to CO2. CO emissions increase with richer fuel mixture. This means that the mixture is too rich to burn or no enough air is available to burn with fuel properly. All three experiments as shown in figure (55) have the same pattern of increased CO production with increasing load on the engine because more fuel is getting into the engine causing lower air intake causing lower air to fuel rations resulting in incomplete combustion which results in CO and CO2 production. NaOH solution gave worst results than the reference and water tests.

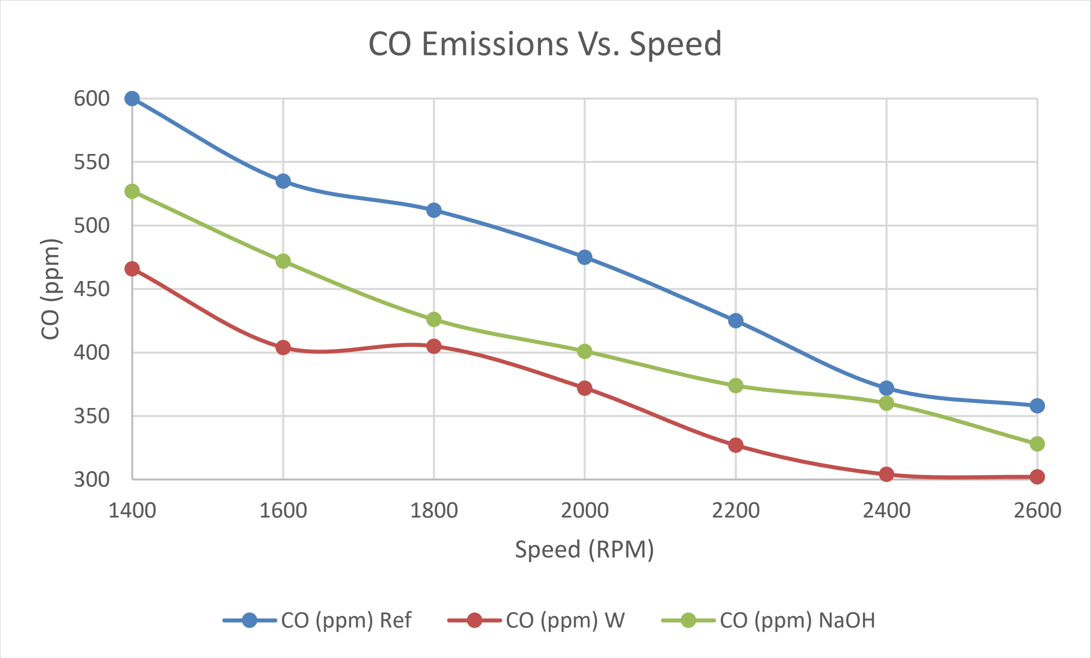


Figure 56. CO vs. speed

The CO emissions decrease for all three experiments as a result of increased engine's RPM which results in more air intake and thus slightly leaner mixtures. Leaner mixtures tend to have lower CO emissions because of more air is allowed to mix with fuel resulting in complete combustion. Also, the higher the engine speed the more the turbulence which result in better mixing of fuel and air. Water and NaOH showed lower results than that of the reference as shown in figure (56).

4.2.4 Nitrogen oxides (NOx)

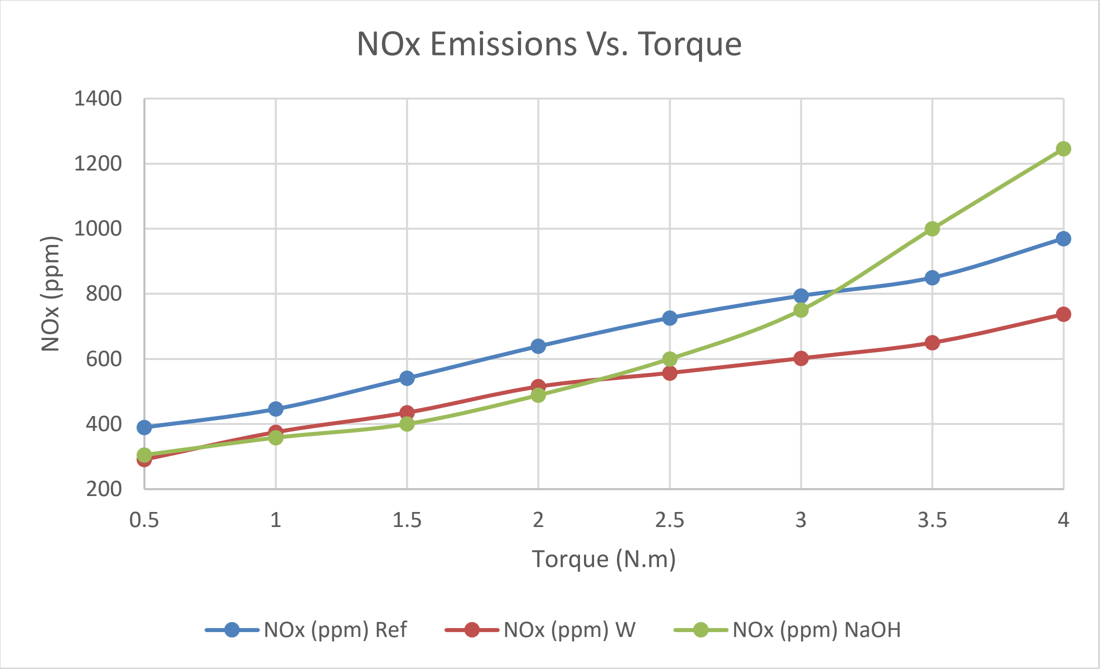


Figure 57. NOx vs. torque

Figure (57) shows the relation between NOx emissions and torque for constant speed. The NOx emissions tend to increase with increasing load on the engine. This is due to higher cylinder temperature which is caused by richer mixtures inside the engine's combustion chamber. Too lean mixture also tends to produce NOx because of the lower flame speeds which is giving more time for NOx to form. NOx is produced mainly due to high-temperature thermal fixation of molecular O2 & N2 existing in the combustion air and also the reaction of atmospheric oxygen with nitrogen-containing compounds in fuel molecules. Water and NaOH solution tend to reduce the NOx emissions by 50% on average.

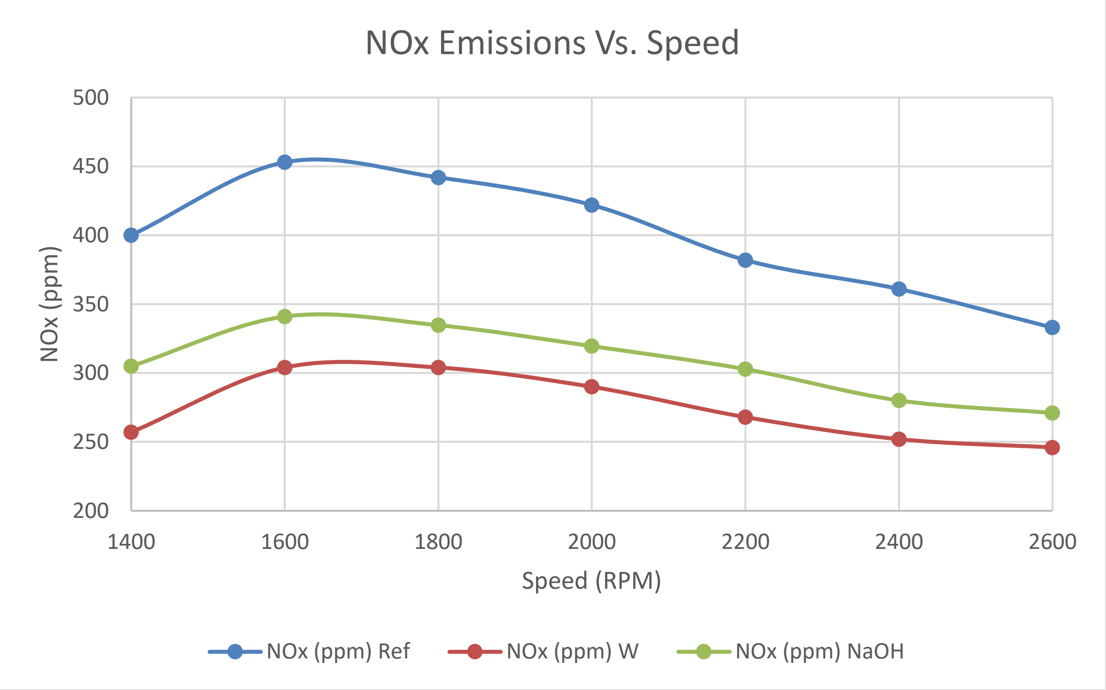


Figure 58. NOx vs. speed

NOx emissions tend to increase for lower RPMs but decrease for higher RPMS as can be depicted from figure (58). Both water and NaOH gave better results than the reference. NOx came down around 25% for NaOH solution and by 37% for water. The NOx emissions decreased for higher RPMs due to better mixing of fuel and air. NOx is dissolving more in water than NaOH because of the saturation limit. There are more spaces in water than in NaOH for NOx to dissolve in thus giving water lower NOx emissions.

4.2.5 Smoke (Opacity)

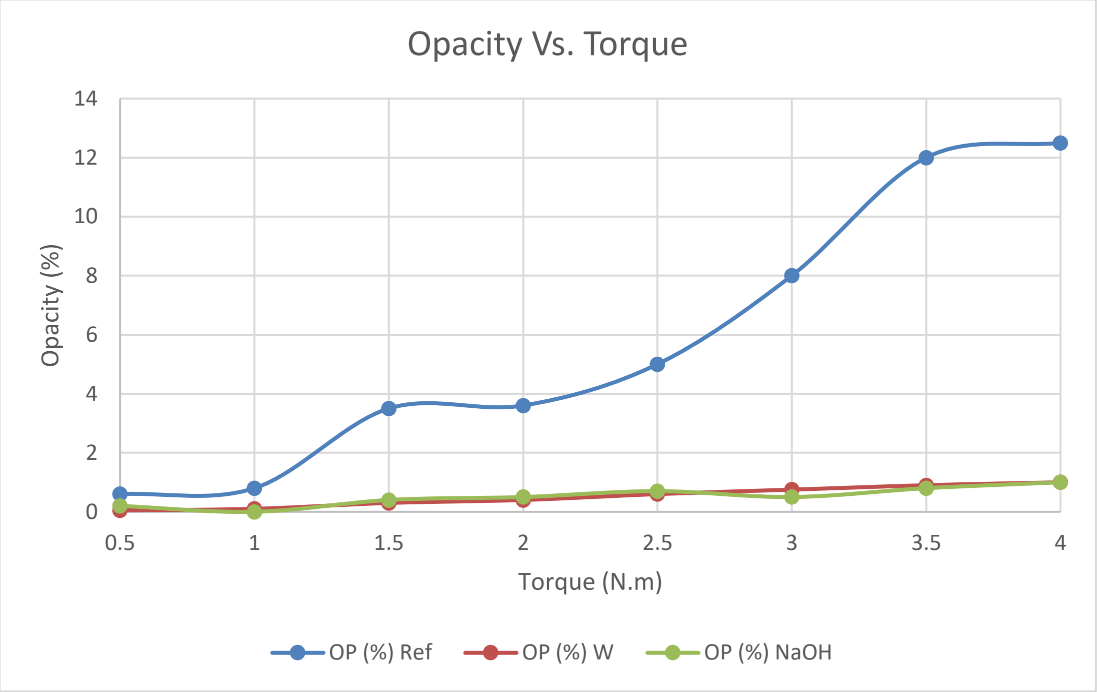


Figure 59. Smoke vs. torque

The smoke is the most pollutant of diesel engine’s emissions. Smoke is considered as the light hydrocarbons. Larger hydrocarbons thermal crack into smaller hydrocarbons under the effect of temperature which is raising due to lower air to fuel ratios or higher equivalence ratios. Smoke is measured by a device that takes part of the exhaust gases and allow it to pass through a clear lens, the amount of soot accumulated on the lens will give an indication of how much this soot covered the clean lens. The unit of measure is called opacity which shows in percentage how dirty the lens is for each run or test.

Reference experiment produced lots of smoke which increased with increasing the load on the engine. For water and NaOH experiments, the opacity decreased by 90% compared to the reference case for higher torque values. This is logically true since these light weight form of HCs dissolve easily in liquids.

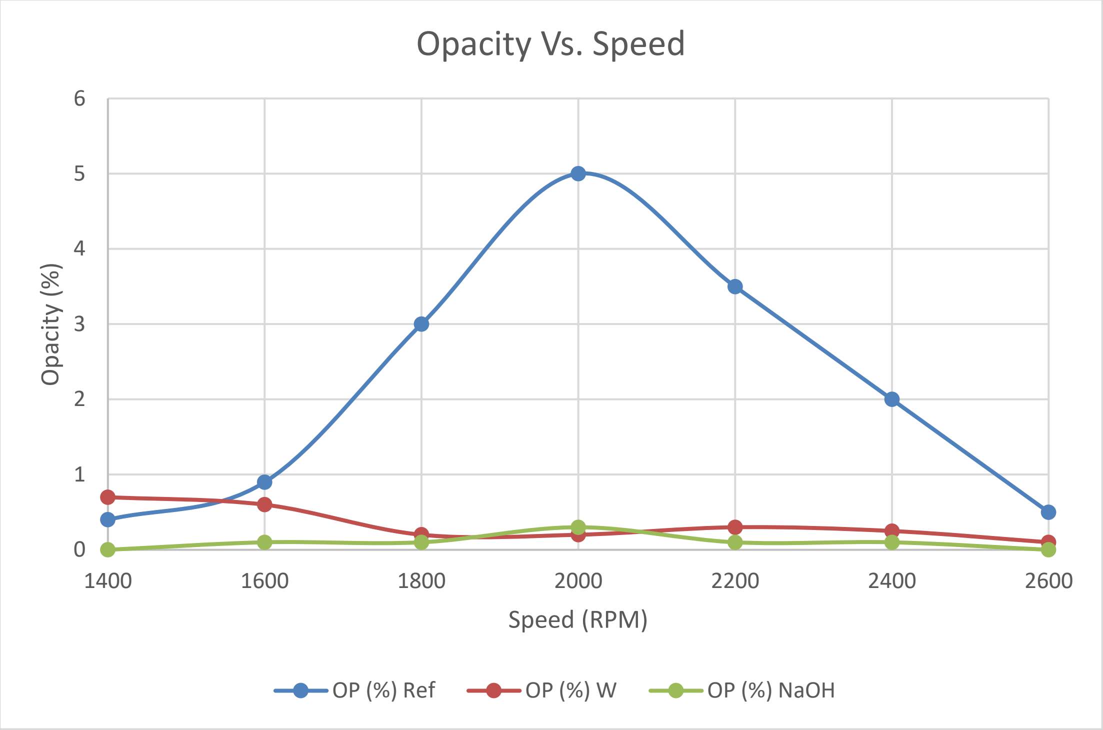


Figure 60. Smoke vs. speed

The opacity for constant load variable speed increased and then decreased when it comes for the reference experiment. Maximum opacity value of about 5% at 2000 RPM was obtained for the reference experiment. The reason behind this bell-shaped graph is that lower RPMs tend to have higher air to fuel ratios which means slightly leaner mixtures and thus less production of unburned HCs due to incomplete combustion. In other words, the combustion is kind of complete and negligible amount of unburned HC is released. At 2000 RPM, the amount of air is not enough for burning all fuel completely resulting in the release of unburned HCs and thus smoke. After 2000 RPM until 2600 RPM, the opacity decreases which means that the air drawn into the engine is enough to burn the fuel injected into the cylinder at constant load resulting in complete combustion and thus less unburned hydrocarbons. Water and NaOH again showed great effect on smoke even for variable speed and constant load experiment.

From above experiments concerning engine emissions, it was clearly proven how much the values can change when adding an absorption device with certain absorption liquids such as water or NaOH solution. Water reduces HC emissions efficiently and NaOH reduces CO2 efficiently. Both mediums have similar reduction effects for NOx and CO emissions. Smoke is reduced dramatically as well for both water and NaOH.

4.3 Temperature readings

4.3.1 Reference case

The outlet temperatures of exhaust gases were taken for both constant torque and constant speed as well. The thermocouple was installed at the very outlet tip of the exhaust pipe. It was logically noticed that with higher speed and torque the temperature of exhaust increase. The temperature readings are slightly more for constant speed variable load since increasing the load on the engine makes it burn more fuel and thus increasing the overall temperature inside the combustion chamber.

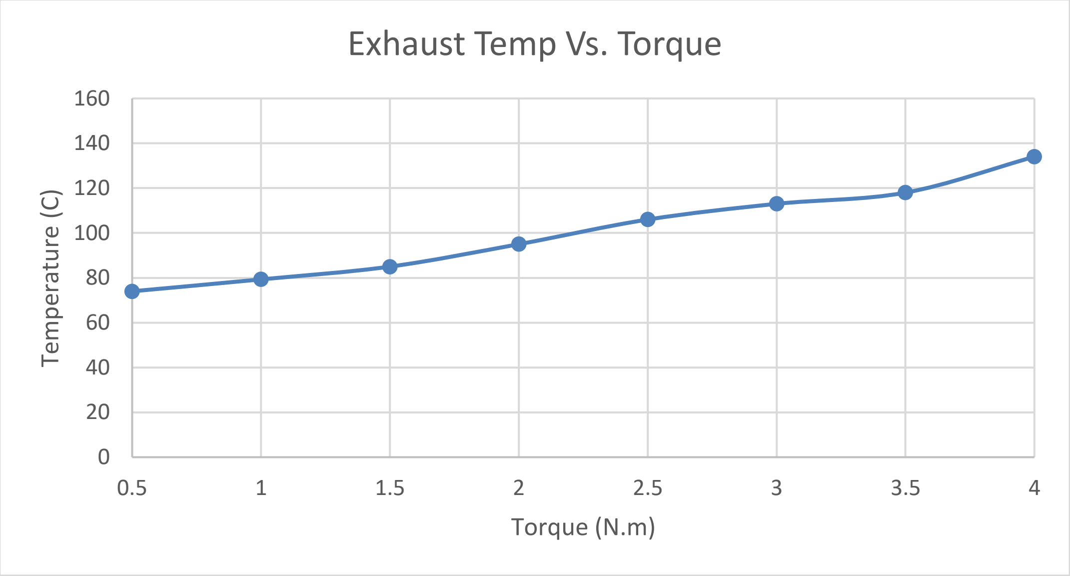


Figure 61 Exhaust Temp Vs. Torque

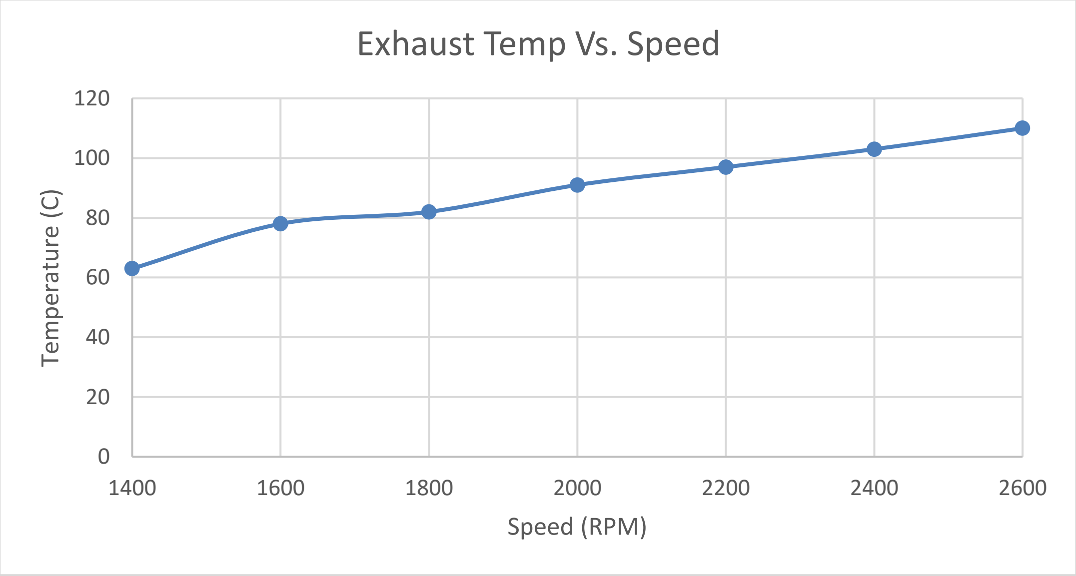


Figure 62 Exhaust Temp Vs. Speed

4.3.2 Water case

The temperatures of exhaust gases were taken for both constant torque and constant speed as well. The thermocouples were installed at the inlet and outlet of the exhaust reduction tube to give an insight about the temperature gradient of the absorption medium. It was noticed that the overall temperature of the absorption medium increase with both increasing speed and torque but more with increasing torque as explained in the previous page. Temperature gradient was kept to a maximum value of 4.5 degrees Celsius. This is due to the cooling coil which was continuously removing heat from the system at a constant rate.

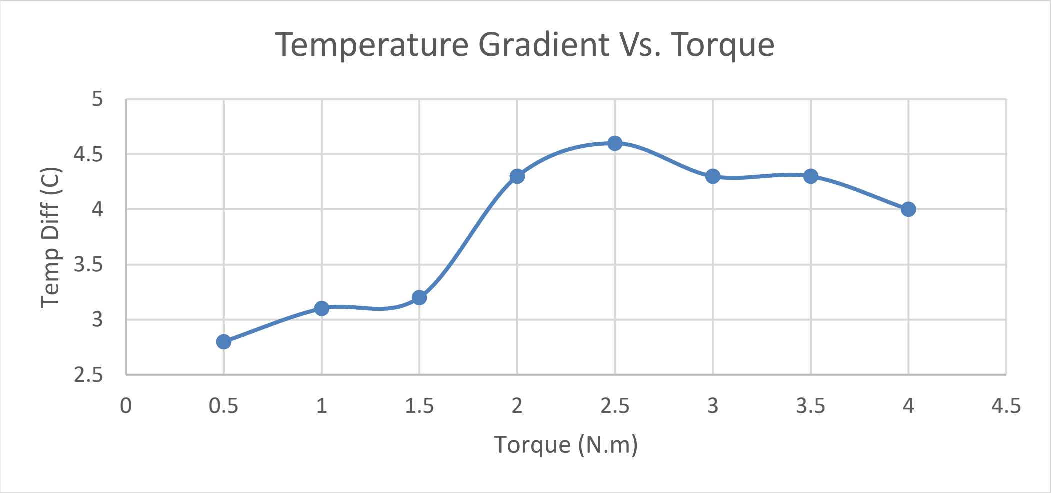


Figure 63 Temp Diff Vs. Torque (Water Case)

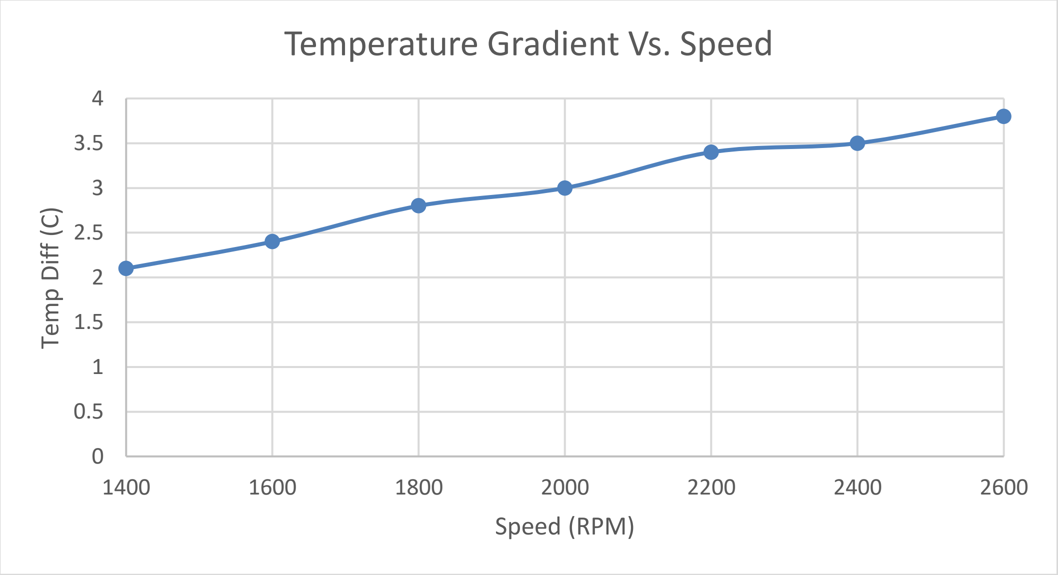


Figure 64 Temp Diff Vs. Speed (Water Case)

4.3.3 NaOH solution case

The temperatures of exhaust gases were taken for both constant torque and constant speed as well. The thermocouples were installed at the inlet and outlet of the exhaust reduction tube to give an insight about the temperature gradient of the absorption medium. It was noticed that the overall temperature of the absorption medium increase with both increasing speed and torque but more with increasing torque as explained in the previous page. Temperature gradient was kept to a maximum value of 5 degrees Celsius. This is due to the cooling coil which was continuously removing heat from the system at a constant rate.

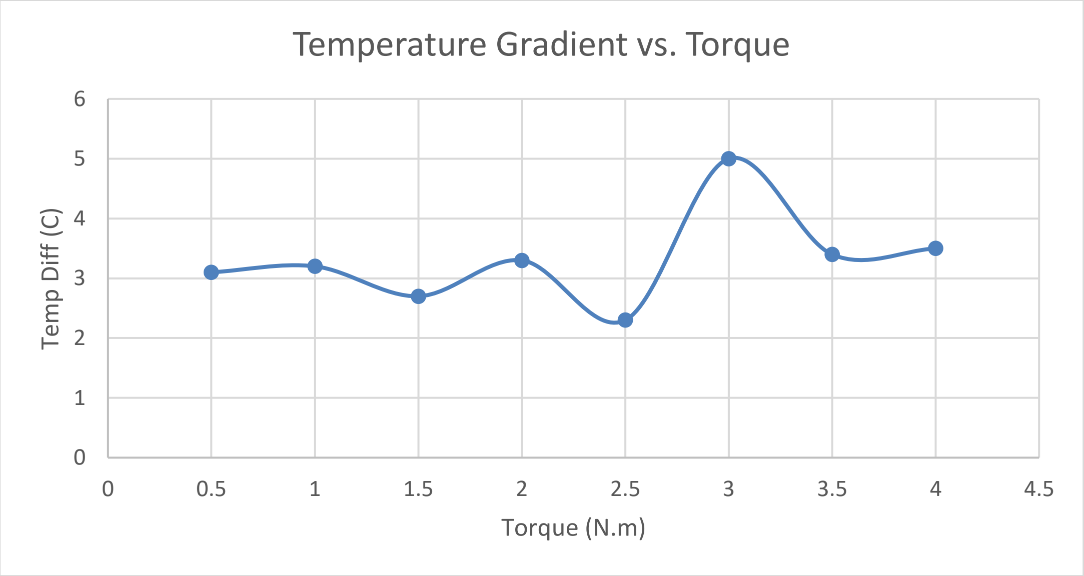


Figure 65 Temp Diff Vs. Torque (NaOH Case)

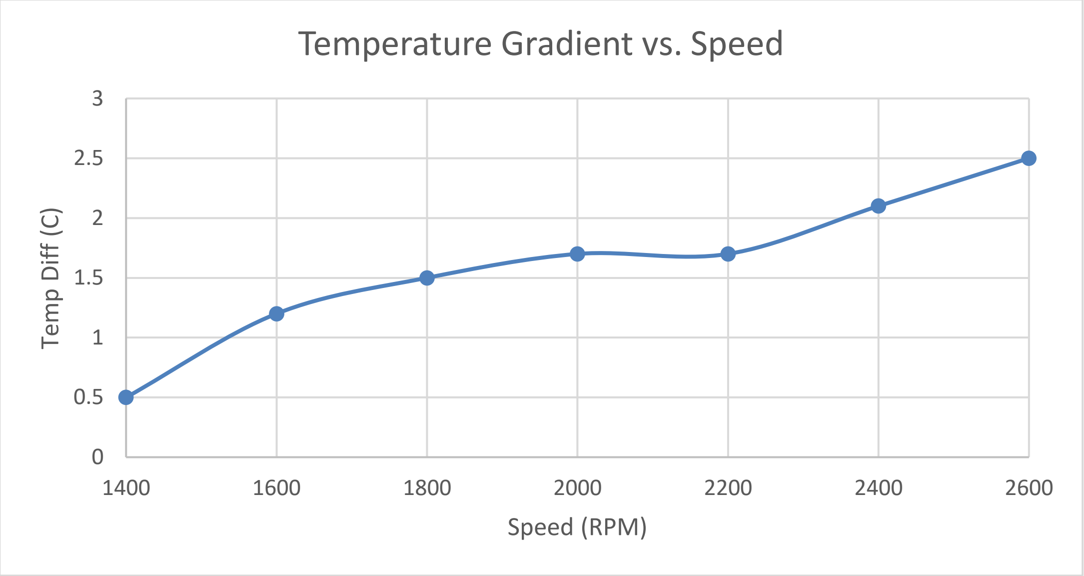


Figure 66 Temp Diff Vs. Speed (NaOH Case)

CHAPTER 5: CONCLUSIONS

Diesel engines contribute in the release of many harmful gasses to the environment due to the nature of diesel fuel that contains oil and lots of other forms of hydrocarbons. The combustion process itself can never reach an optimum percentage of completely oxidizing the fuel. This is because an ideal value of air to fuel can never be reached in real life applications. A complete combustion can’t be practically reached because of many reasons like ignition delay, compression ratio, inlet air density, valve timings, fuel injector’s efficiency, intake and exhaust manifold designs, flow restrictions and lots of other parameters.

In this report, the main concern was to test fluids like water and Sodium Hydroxide (NaOH) and study their effect on exhaust gasses of a single cylinder diesel engine of the type DY23-2B. A calibrated gas analyzer and smoke meter were utilized to compare the results of the emissions one time without anything added to the exhaust, second time with water added to the capturing device and third time with the alkaline solution NaOH. Hydrocarbons, Nitrogen oxides, carbon monoxide, carbon dioxide and smoke were taken for all three experiments two times, one time at a constant torque value of 1.5 NM varying speed from 1400 RPM to 2600 RPM and a second time at a constant speed value of 1800 RPM varying torque from 0.9 NM to 5.1 NM. If was found that for hydrocarbon emissions; at both constant load and constant speed, water experiment helped in reducing them. The reason lies behind the molecular gaps between molecules of water that exists more in water than in NaOH solution which is 50% saturated. For carbon dioxide emissions however, the reduction percentage reached around 90% when using NaOH solution rather than water at both constant speed and constant torque cases. Water did not show any reductions in CO2 levels and thus resulting in a phenomenon of HC-CO2 reduction trade off. Levels of carbon monoxide (CO) stayed almost the same when using water for the constant speed experiment but increased when using NaOH. This problem can be solved after adding a diesel oxidation catalyst (DOC) before the capturing device where almost all the CO can be oxidized to CO2, hence captured by NaOH. NOx emissions did not show much deviation from the reference for the constant speed experiment, but for constant load, the levels of NOx decreased by almost 40% for both water and NaOH mediums. So, using any of both would be fine leaving NOx as a non-decisive factor for choosing the most appropriate medium. Or in other words, it would stand in the side of whichever gets better results in all experiment in general. Last but not least is smoke, both experiments using water or NaOH solution have resulted in reduced amount of smoke. This is because smoke is a light form of HCs that; because if their light weight, dissolve easily in liquids [18]. In other words, the liquid absorbs or captures the smoke and not allow it to escape to the atmosphere. A reduction of 80% was noticed in for the constant load experiment and 85% for constant speed experiment.

Engine parameters like volumetric efficiency, thermal efficiency, air to fuel ratio and break specific fuel consumption were also taken for all experiments with the same variations of torque and speed. Volumetric efficiency for constant speed experiment didn’t change for water but decreased when using NaOH. This might be because of the higher density NaOH solution causing a little back pressure on the engine unlike the lower density water. Having said that, the decrease was about 2% which is negligible for the greater cause of reducing CO2 emissions. For constant load, varying the speed didn’t seem to have much effect on volumetric efficiency. The break specific fuel consumption didn’t show much variation for constant speed experiment for both water and NaOH. However, NaOH solution showed better results for constant load. The

BSFC decreased by 100 g/kWhr which again gives more points to the NaOH solution to be used as capturing material. No scientific reason was found to explain this phenomenon. Thermal efficiency showed better results when using NaOH with an increase of about 2% on average basis than the reference for the constant load experiment. Lastly, the air to fuel ratio was enhanced when using NaOH and water for the constant load experiment.

The solution of NaOH has been tested as a function of time in order to see how much can the NaOH solution capture CO2 until it finally becomes fully saturated. Taking into considerations that the solution was only 50% saturated, the solution lasted around 15 hours until it was exhausted. No blockage was noticed in the dispenser even after the solution being fully saturated.

As a final conclusion, using NaOH as capturing solution after the diesel oxidation catalyst will result in general in a reduction in CO, CO2, NOx and smoke emissions but with a slight negligible increase in the HC emissions. Also, using NaOH will result in a decrease in BSFC and an increase in thermal efficiency and air to fuel ration. However, the volumetric efficiency decreased but with a very negligible value for a greater cause of CO2 reduction.

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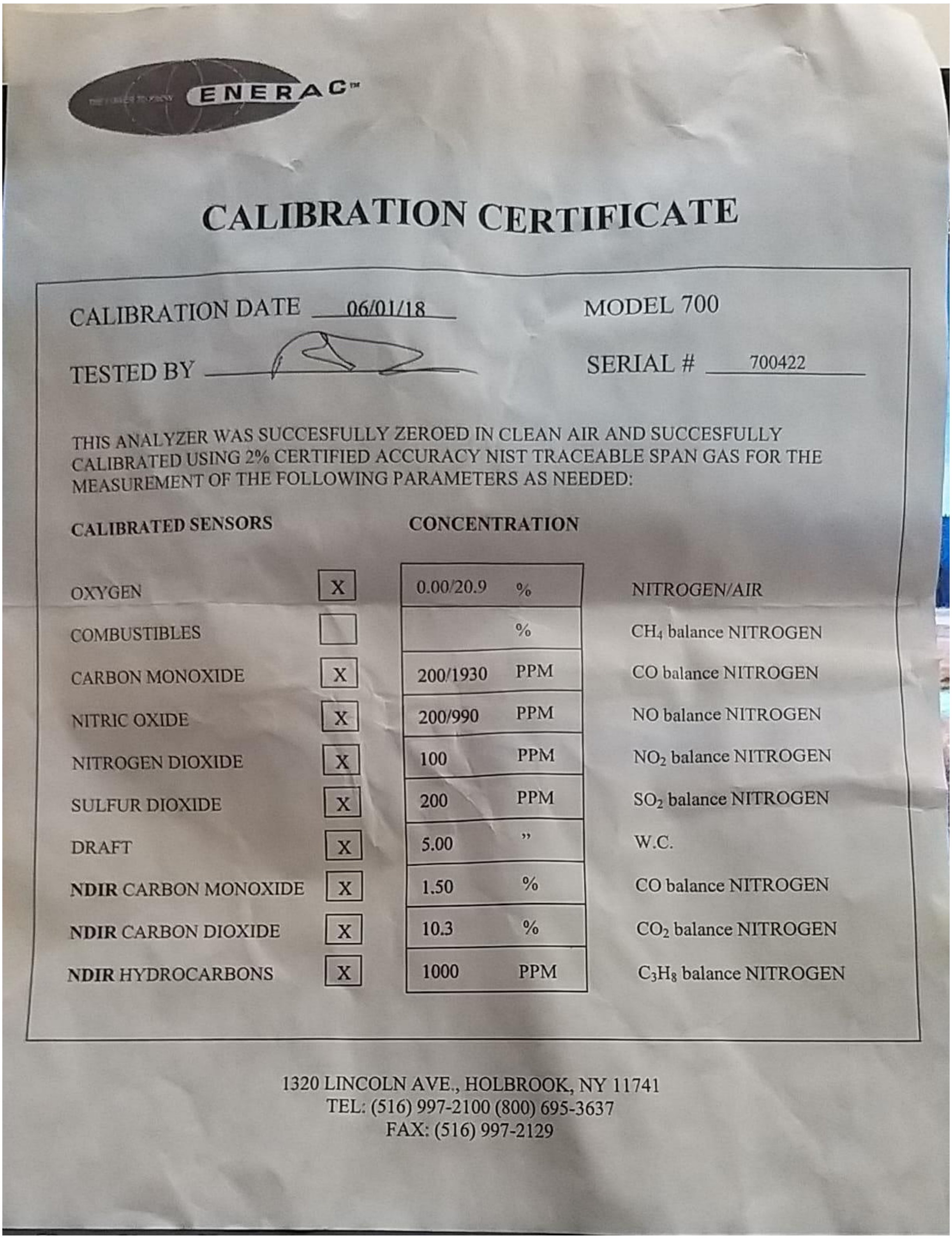
APPENDIX A: CALIBRATION CERTIFICATE



ENERAC™

CALIBRATION CERTIFICATE

CALIBRATION DATE 06/01/18

MODEL 700

TESTED BY

SERIAL # 700422

THIS ANALYZER WAS SUCCESFULLY ZEROED IN CLEAN AIR AND SUCCESFULLY CALIBRATED USING 2% CERTIFIED ACCURACY NIST TRACEABLE SPAN GAS FOR THE MEASUREMENT OF THE FOLLOWING PARAMETERS AS NEEDED:

CALIBRATED SENSORS		**CONCENTRATION**		
OXYGEN	☒	0.00/20.9	%	NITROGEN/AIR
COMBUSTIBLES	☐		%	CH_4 balance NITROGEN
CARBON MONOXIDE	☒	200/1930	PPM	CO balance NITROGEN
NITRIC OXIDE	☒	200/990	PPM	NO balance NITROGEN
NITROGEN DIOXIDE	☒	100	PPM	NO_2 balance NITROGEN
SULFUR DIOXIDE	☒	200	PPM	SO_2 balance NITROGEN
DRAFT	☒	5.00	”	W.C.
NDIR CARBON MONOXIDE	☒	1.50	%	CO balance NITROGEN
NDIR CARBON DIOXIDE	☒	10.3	%	CO_2 balance NITROGEN
NDIR HYDROCARBONS	☒	1000	PPM	C_3H_8 balance NITROGEN

1320 LINCOLN AVE., HOLBROOK, NY 11741
TEL: (516) 997-2100 (800) 695-3637
FAX: (516) 997-2129

Figure67 . Calibration Certificate for ENERPAC700 Gas Analyzer

APPENDIX B: NAOH SDS

Safety Data Sheet

according to 29CFR1910/1200 and GHS Rev. 3

Effective date : 12.14.2014 Page 1 of 7

Sodium Hydroxide, 0.5M

SECTION 1 : Identification of the substance/mixture and of the supplier

Product name : **Sodium Hydroxide, 0.5M**

Manufacturer/Supplier Trade name:

Manufacturer/Supplier Article number: **S25881**

Recommended uses of the product and uses restrictions on use:

Manufacturer Details:

AquaPhoenix Scientific
9 Barnhart Drive, Hanover, PA 17331

Supplier Details:

Fisher Science Education
15 Jet View Drive, Rochester, NY 14624

Emergency telephone number:

Fisher Science Education Emergency Telephone No.: 800-535-5053

SECTION 2 : Hazards identification

Classification of the substance or mixture:

Corrosive
Serious eye damage, category 1
Corrosive to metals, category 1
Skin corrosion, category 1B

Skin Corr. 1B
Eye corr. 1
Metal Corr. 1

Signal word :Danger

Hazard statements:
May be corrosive to metals
Causes severe skin burns and eye damage
Causes serious eye damage
Precautionary statements:
If medical advice is needed, have product container or label at hand
Keep out of reach of children
Read label before use
Keep only in original container
Do not breathe dust/fume/gas/mist/vapours/spray
Wash … thoroughly after handling
Wear protective gloves/protective clothing/eye protection/face protection
Absorb spillage to prevent material damage
IF ON SKIN (or hair): Remove/Take off immediately all contaminated clothing. Rinse skin with water/shower
IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses if present and easy to do. Continue rinsing
IF SWALLOWED: Rinse mouth. Do NOT induce vomiting
Wash contaminated clothing before reuse
IF INHALED: Remove victim to fresh air and keep at rest in a position comfortable for breathing

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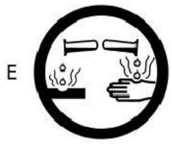
Immediately call a POISON CENTER or doctor/physician
Store in a corrosive resistant/... container with a resistant inner liner
Store locked up
Dispose of contents/container to ...

Other Non-GHS Classification:

WHMIS



NFPA/HMIS

NFPA SCALE (0-4)

Health	3
Flammability	0
Physical Hazard	0
Personal Protection	X

HMIS RATINGS (0-4)

SECTION 3 : Composition/information on ingredients

Ingredients:		
CAS 1310-73-2	Sodium Hydroxide	2 %
CAS 7732-18-5	Deionized Water	98 %
		Percentages are by weight

SECTION 4 : First aid measures

Description of first aid measures

After inhalation: Move exposed individual to fresh air. Loosen clothing as necessary and position individual in a comfortable position.Seek medical advice if discomfort or irritation persists.If breathing difficult, give oxygen.

After skin contact: Take off contaminated clothing and shoes immediately.Wash affected area with soap and water.Seek medical attention if irritation, discomfort persist.

After eye contact: Protect unexposed eye. Rinse/flush exposed eye(s) gently using water for 15-20 minutes. Remove contact lens(es) if able to do so during rinsing. Immediately get medical assistance.

After swallowing: Rinse mouth thoroughly. Do not induce vomiting. Have exposed individual drink sips of water. Seek medical attention if irritation, discomfort or vomiting persists.

Most important symptoms and effects, both acute and delayed:

Irritation, Nausea,Headache, Shortness of breath.;

Indication of any immediate medical attention and special treatment needed:

If seeking medical attention, provide SDS document to physician.

SECTION 5 : Firefighting measures

Extinguishing media

Suitable extinguishing agents: If in laboratory setting, follow laboratory fire suppression procedures. Use appropriate fire suppression agents for adjacent combustible materials or sources of ignition

For safety reasons unsuitable extinguishing agents:

Special hazards arising from the substance or mixture:

Combustion products may include carbon oxides or other toxic vapors.Thermal decomposition can lead to release of irritating gases and vapors.Sodium oxides.

Advice for firefighters:

Protective equipment: Use NIOSH-approved respiratory protection/breathing apparatus.

Additional information (precautions): Move product containers away from fire or keep cool with water spray as a protective measure, where feasible.

SECTION 6 : Accidental release measures

Personal precautions, protective equipment and emergency procedures:

Wear protective equipment. Transfer to a disposal or recovery container.Use respiratory protective device against the effects of fumes/dust/aerosol. Keep unprotected persons away. Ensure adequate ventilation.Keep away from ignition sources. Protect from heat.

Environmental precautions:

Prevent from reaching drains, sewer or waterway. Collect contaminated soil for characterization per Section 13

Methods and material for containment and cleaning up:

If in a laboratory setting, follow Chemical Hygiene Plan procedures.Place into properly labeled containers for recovery or disposal. If necessary, use trained response staff/contractor.Collect liquid and dilute with water. Neutralize with dilute acid solutions. Decant water to drain with excess water. Absorb with suitable material. Dispose of remaining solid as normal refuse. Always obey local regulations.

Reference to other sections:

SECTION 7 : Handling and storage

Precautions for safe handling:

Absorb spillage to prevent material damage due to corrosiveness to metal. Avoid contact with eyes, skin, and clothing. Wash hands after handling. Do not mix with acids.Follow good hygiene procedures when handling chemical materials. Use only in well ventilated areas.

Conditions for safe storage, including any incompatibilities:

Protect from freezing and physical damage.Provide ventilation for containers. Avoid storage near extreme heat, ignition sources or open flame. Store away from foodstuffs. Store away from oxidizing agents.Store in cool, dry conditions in well sealed containers. Store with Corrosives.

SECTION 8 : Exposure controls/personal protection

Control Parameters:	1310-73-2, Sodium Hydroxide, OSHA PEL TWA 2 mg/m3 1310-73-2, Sodium Hydroxide, ACGIH TLV TWA 2 mg/m3
Appropriate Engineering controls:	Emergency eye wash fountains and safety showers should be available in the immediate vicinity of use/handling.Provide exhaust ventilation or other engineering controls to keep the airborne concentrations of vapor or dusts (total/respirable) below the applicable workplace exposure limits (Occupational Exposure Limits-OELs) indicated above.
Respiratory protection:	Not required under normal conditions of use. Use suitable respiratory protective device when high concentrations are present. Use suitable respiratory protective device when aerosol or mist is formed. For spills, respiratory protection may be advisable.
Protection of skin:	The glove material has to be impermeable and resistant to the product/ the substance/ the preparation being used/handled.Selection of the glove material on consideration of the penetration times, rates of diffusion and the degradation.
Eye protection:	Safety glasses with side shields or goggles.
General hygienic measures:	The usual precautionary measures are to be adhered to when handling chemicals. Keep away from food, beverages and feed sources. Immediately remove all soiled and contaminated clothing. Wash hands before breaks and at the end of work. Do not inhale gases/fumes/dust/mist/vapor/aerosols. Avoid contact with the eyes and skin.

SECTION 9 : Physical and chemical properties

Appearance (physical state,color):	Clear, colorless liquid	**Explosion limit lower**: **Explosion limit upper**:	Non Explosive Non Explosive
Odor:	Odorless	**Vapor pressure**:	14mmHg @ 20C
Odor threshold:	Not Determined	**Vapor density**:	>1
pH-value:	Alkaline	**Relative density**:	Approx 1
Melting/Freezing point:	Approx 0°C	**Solubilities**:	Soluble in Water
Boiling point/Boiling range:	Approx 100°C	**Partition coefficient (n-octanol/water)**:	Not Determined
Flash point (closed cup):	Not Determined	**Auto/Self-ignition temperature**:	Not Determined
Evaporation rate:	Not Determined	**Decomposition temperature**:	Not Determined
Flammability (solid,gaseous):	Not Determined	**Viscosity**:	a. Kinematic:Not Determined b. Dynamic: Not Determined
Density: Not Determined			

SECTION 10 : Stability and reactivity

Reactivity:
Chemical stability: No decomposition if used and stored according to specifications.
Possible hazardous reactions:
Conditions to avoid: Incompatible materials, excess heat

Incompatible materials:acids, Organic materials, Chlorinated solvents, Aluminum, Phosphorus, Tin/tin oxides, Zinc
Hazardous decomposition products:sodium oxides, hydrogen. Carbon oxides (CO, CO2).

SECTION 11 : Toxicological information

Acute Toxicity: No additional information.	
Chronic Toxicity: No additional information.	
Corrosion Irritation: No additional information.	
Sensitization:	No additional information.
Single Target Organ (STOT):	No additional information.
Numerical Measures:	No additional information.
Carcinogenicity:	No additional information.
Mutagenicity:	No additional information.
Reproductive Toxicity:	No additional information.

SECTION 12 : Ecological information

Ecotoxicity Persistence and degradability: Readily degradable in the environment.
Bioaccumulative potential: Not Bioaccumulative.
Mobility in soil:
Other adverse effects:

SECTION 13 : Disposal considerations

Waste disposal recommendations:

Product/containers must not be disposed together with household garbage. Do not allow product to reach sewage system or open water.It is the responsibility of the waste generator to properly characterize all waste materials according to applicable regulatory entities (US 40CFR262.11). Consult federal state/ provincial and local regulations regarding the proper disposal of waste material that may incorporate some amount of this product.Neutralize with dilute acid solutions.

SECTION 14 : Transport information

UN-Number

1824

UN proper shipping name

Sodium hydroxide solution

Transport hazard class(es)

Class:
8 Corrosive substances

Packing group:II
Environmental hazard:
Transport in bulk:

Special precautions for user:

SECTION 15 : Regulatory information

United States (USA)

SARA Section 311/312 (Specific toxic chemical listings):

None of the ingredients is listed

SARA Section 313 (Specific toxic chemical listings):

None of the ingredients is listed

RCRA (hazardous waste code):

None of the ingredients is listed

TSCA (Toxic Substances Control Act):

All ingredients are listed.

CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act):

1310-73-2 Sodium Hydroxide 1000 lb

Proposition 65 (California):

Chemicals known to cause cancer:

None of the ingredients is listed

Chemicals known to cause reproductive toxicity for females:

None of the ingredients is listed

Chemicals known to cause reproductive toxicity for males:

None of the ingredients is listed

Chemicals known to cause developmental toxicity:

None of the ingredients is listed

Canada

Canadian Domestic Substances List (DSL):

All ingredients are listed.

Canadian NPRI Ingredient Disclosure list (limit 0.1%):

None of the ingredients is listed

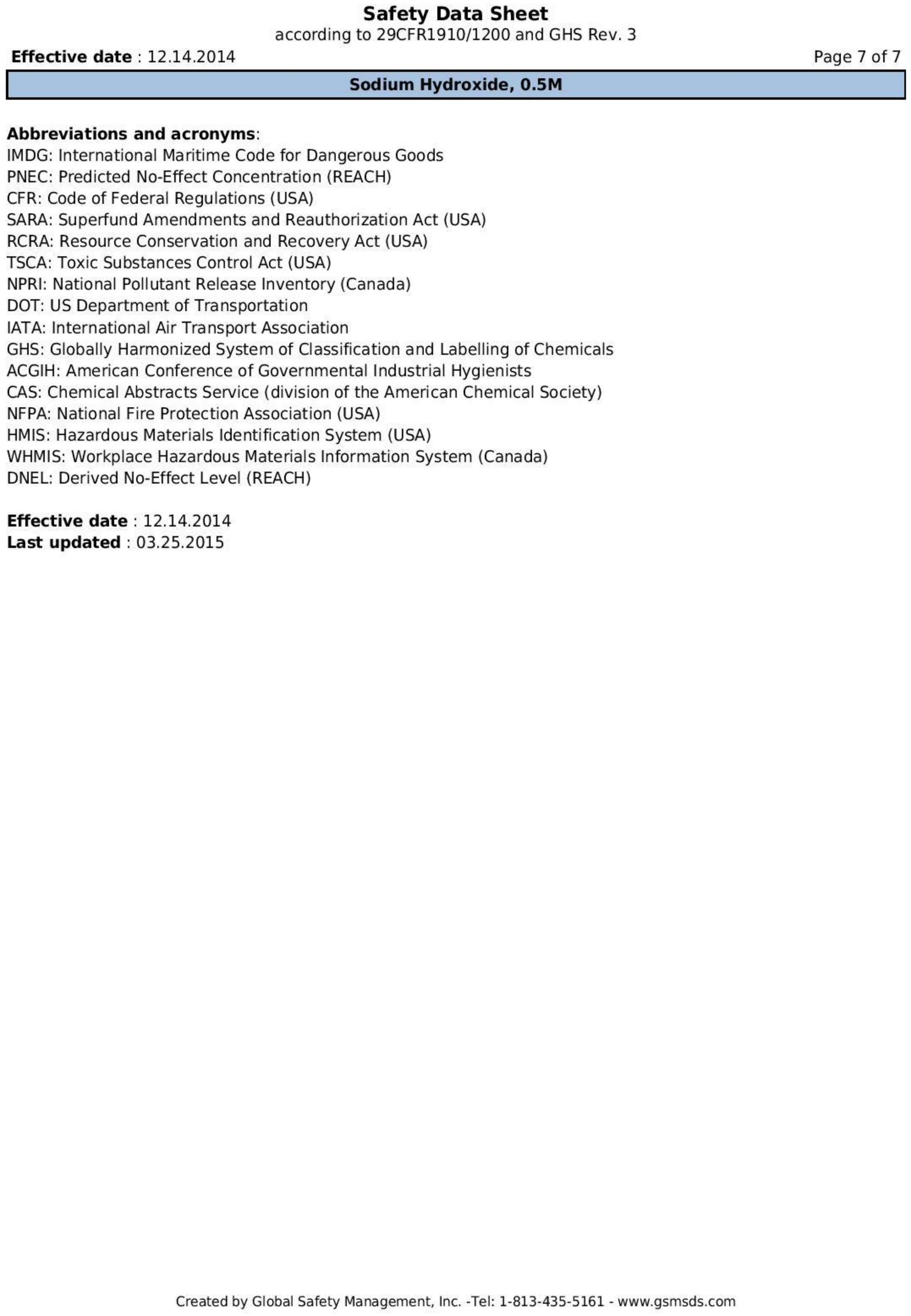
Canadian NPRI Ingredient Disclosure list (limit 1%):

1310-73-2 Sodium Hydroxide

SECTION 16 : Other information

This product has been classified in accordance with hazard criteria of the Controlled Products Regulations and the SDS contains all the information required by the Controlled Products Regulations.Note:. The responsibility to provide a safe workplace remains with the user.The user should consider the health hazards and safety information contained herein as a guide and should take those precautions required in an individual operation to instruct employees and develop work practice procedures for a safe work environment.The information contained herein is, to the best of our knowledge and belief, accurate.However, since the conditions of handling and use are beyond our control, we make no guarantee of results, and assume no liability for damages incurred by the use of this material.It is the responsibility of the user to comply with all applicable laws and regulations applicable to this material.

GHS Full Text Phrases:



Safety Data Sheet
according to 29CFR1910/1200 and GHS Rev. 3

Effective date : 12.14.2014 Page 7 of 7

Sodium Hydroxide, 0.5M

Abbreviations and acronyms:
IMDG: International Maritime Code for Dangerous Goods
PNEC: Predicted No-Effect Concentration (REACH)
CFR: Code of Federal Regulations (USA)
SARA: Superfund Amendments and Reauthorization Act (USA)
RCRA: Resource Conservation and Recovery Act (USA)
TSCA: Toxic Substances Control Act (USA)
NPRI: National Pollutant Release Inventory (Canada)
DOT: US Department of Transportation
IATA: International Air Transport Association
GHS: Globally Harmonized System of Classification and Labelling of Chemicals
ACGIH: American Conference of Governmental Industrial Hygienists
CAS: Chemical Abstracts Service (division of the American Chemical Society)
NFPA: National Fire Protection Association (USA)
HMIS: Hazardous Materials Identification System (USA)
WHMIS: Workplace Hazardous Materials Information System (Canada)
DNEL: Derived No-Effect Level (REACH)

Effective date : 12.14.2014
Last updated : 03.25.2015

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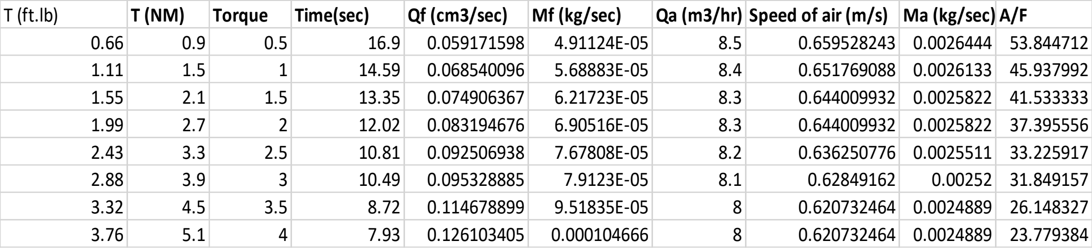
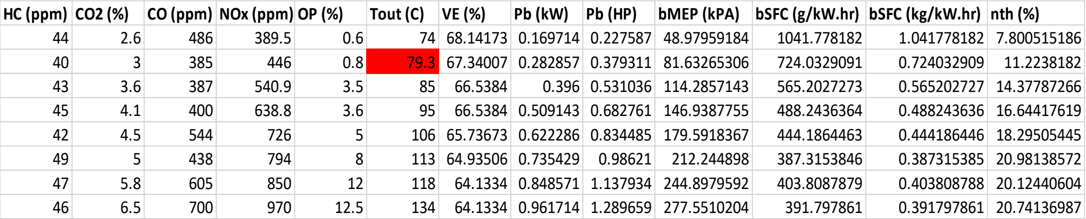
Figure68 . SDS for NaOH

APPENDIX C: EXPERIMENTS EXCEL TABLES

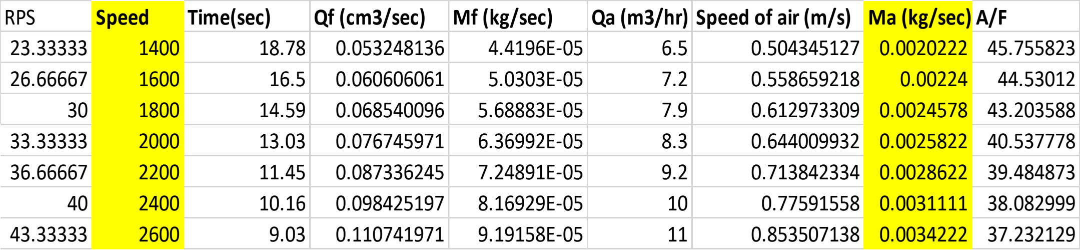


T (ft.lb)	T (NM)	Torque	Time(sec)	Qf (cm3/sec)	Mf (kg/sec)	Qa (m3/hr)	Speed of air (m/s)	Ma (kg/sec)	A/F
0.66	0.9	0.5	16.9	0.059171598	4.91124E-05	8.5	0.659528243	0.0026444	53.844712
1.11	1.5	1	14.59	0.068540096	5.68883E-05	8.4	0.651769088	0.0026133	45.937992
1.55	2.1	1.5	13.35	0.074906367	6.21723E-05	8.3	0.644009932	0.0025822	41.533333
1.99	2.7	2	12.02	0.083194676	6.90516E-05	8.3	0.644009932	0.0025822	37.395556
2.43	3.3	2.5	10.81	0.092506938	7.67808E-05	8.2	0.636250776	0.0025511	33.225917
2.88	3.9	3	10.49	0.095328885	7.9123E-05	8.1	0.62849162	0.00252	31.849157
3.32	4.5	3.5	8.72	0.114678899	9.51835E-05	8	0.620732464	0.0024889	26.148327
3.76	5.1	4	7.93	0.126103405	0.000104666	8	0.620732464	0.0024889	23.779384

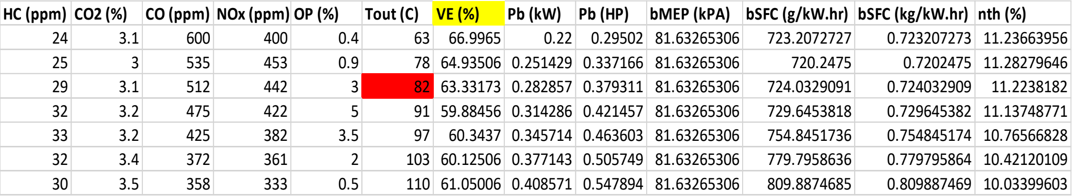


HC (ppm)	CO2 (%)	CO (ppm)	NOx (ppm)	OP (%)	Tout (C)	VE (%)	Pb (kW)	Pb (HP)	bMEP (kPA)	bSFC (g/kW.hr)	bSFC (kg/kW.hr)	nth (%)
44	2.6	486	389.5	0.6	74	68.14173	0.169714	0.227587	48.97959184	1041.778182	1.041778182	7.800515186
40	3	385	446	0.8	79.3	67.34007	0.282857	0.379311	81.63265306	724.0329091	0.724032909	11.2238182
43	3.6	387	540.9	3.5	85	66.5384	0.396	0.531036	114.2857143	565.2027273	0.565202727	14.37787266
45	4.1	400	638.8	3.6	95	66.5384	0.509143	0.682761	146.9387755	488.2436364	0.488243636	16.64417619
42	4.5	544	726	5	106	65.73673	0.622286	0.834485	179.5918367	444.1864463	0.444186446	18.29505445
49	5	438	794	8	113	64.93506	0.735429	0.98621	212.244898	387.3153846	0.387315385	20.98138572
47	5.8	605	850	12	118	64.1334	0.848571	1.137934	244.8979592	403.8087879	0.403808788	20.12440604
46	6.5	700	970	12.5	134	64.1334	0.961714	1.289659	277.5510204	391.797861	0.391797861	20.74136987

Figure 69. Reference experiment for constant speed



RPS	Speed	Time(sec)	Qf (cm3/sec)	Mf (kg/sec)	Qa (m3/hr)	Speed of air (m/s)	Ma (kg/sec)	A/F
23.33333	1400	18.78	0.053248136	4.4196E-05	6.5	0.504345127	0.0020222	45.755823
26.66667	1600	16.5	0.060606061	5.0303E-05	7.2	0.558659218	0.00224	44.53012
30	1800	14.59	0.068540096	5.68883E-05	7.9	0.612973309	0.0024578	43.203588
33.33333	2000	13.03	0.076745971	6.36992E-05	8.3	0.644009932	0.0025822	40.537778
36.66667	2200	11.45	0.087336245	7.24891E-05	9.2	0.713842334	0.0028622	39.484873
40	2400	10.16	0.098425197	8.16929E-05	10	0.77591558	0.0031111	38.082999
43.33333	2600	9.03	0.110741971	9.19158E-05	11	0.853507138	0.0034222	37.232129



HC (ppm)	CO2 (%)	CO (ppm)	NOx (ppm)	OP (%)	Tout (C)	VE (%)	Pb (kW)	Pb (HP)	bMEP (kPA)	bSFC (g/kW.hr)	bSFC (kg/kW.hr)	nth (%)
24	3.1	600	400	0.4	63	66.9965	0.22	0.29502	81.63265306	723.2072727	0.723207273	11.23663956
25	3	535	453	0.9	78	64.93506	0.251429	0.337166	81.63265306	720.2475	0.7202475	11.28279646
29	3.1	512	442	3	82	63.33173	0.282857	0.379311	81.63265306	724.0329091	0.724032909	11.2238182
32	3.2	475	422	5	91	59.88456	0.314286	0.421457	81.63265306	729.6453818	0.729645382	11.13748771
33	3.2	425	382	3.5	97	60.3437	0.345714	0.463603	81.63265306	754.8451736	0.754845174	10.76566828
32	3.4	372	361	2	103	60.12506	0.377143	0.505749	81.63265306	779.7958636	0.779795864	10.42120109
30	3.5	358	333	0.5	110	61.05006	0.408571	0.547894	81.63265306	809.8874685	0.809887469	10.03399603

Figure 70. Reference experiment for constant torque

T (NM)	Torque	Time(sec)	Qf (cm3/sec)	Mf (kg/sec)	Qa (m3/hr)	Speed of air (m/s)	Ma (kg/sec)	A/F
0.9	0.5	16.17	0.061842919	5.13296E-05	8.4	0.651769088	0.0026133	50.912771
1.5	1	15.17	0.065919578	5.47132E-05	8.4	0.651769088	0.0026133	47.764177
2.1	1.5	13	0.076923077	6.38462E-05	8.3	0.644009932	0.0025822	40.444444
2.7	2	11.05	0.090497738	7.51131E-05	8.2	0.636250776	0.0025511	33.963588
3.3	2.5	10.53	0.094966762	7.88224E-05	8.1	0.62849162	0.00252	31.970602
3.9	3	9.95	0.100502513	8.34171E-05	8	0.620732464	0.0024889	29.83668
4.5	3.5	8.76	0.114155251	9.47489E-05	8	0.620732464	0.0024889	26.268273
5.1	4	7.93	0.126103405	0.000104666	7.9	0.612973309	0.0024578	23.482142

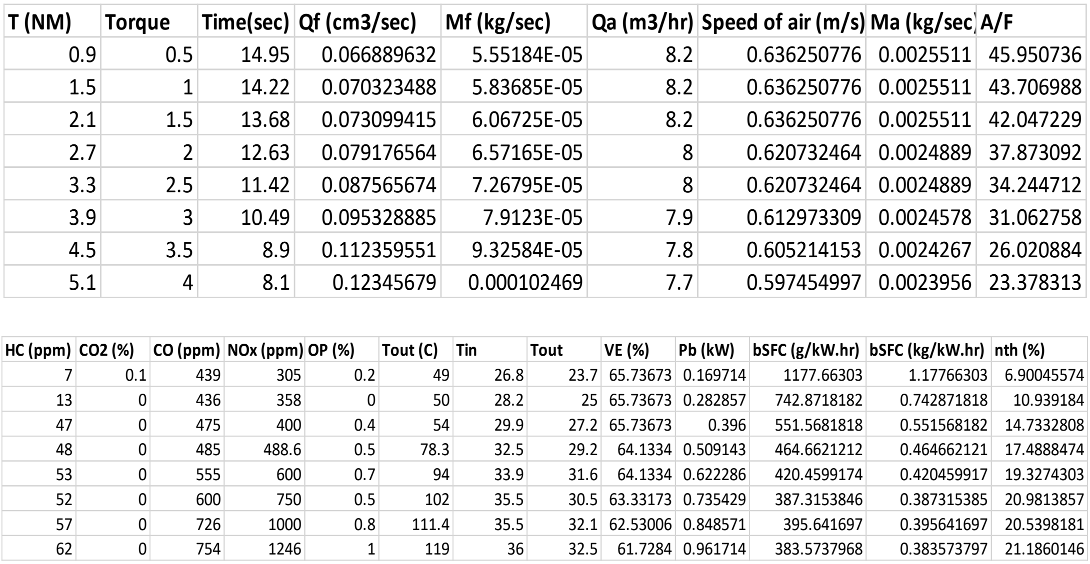
HC (ppm)	CO2 (%)	CO (ppm)	NOx (ppm)	OP (%)	Tout (C)	Tin	Tout	VE (%)	Pb (kW)	bSFC (g/kW.hr)	bSFC (kg/kW.hr)	nth (%)
14	2.4	372	291	0.05	67	31.6	28.8	67.34007	0.169714286	1088.809697	1.088809697	7.46356986
19	2.8	372	375	0.1	73	32.5	29.4	67.34007	0.282857143	696.3498182	0.696349818	11.6700015
22	3.3	419	435	0.3	85	33.2	30	66.5384	0.396	580.42	0.58042	14.0009247
25	3.9	430	515	0.4	96	34.5	30.2	65.73673	0.509142857	531.1027273	0.531102727	15.3010106
31	4.2	455	557	0.6	108.6	35.2	30.6	64.93506	0.622285714	455.9973554	0.455997355	17.821177
36	4.8	520	602	0.75	122.3	35.4	31.1	64.1334	0.735428571	408.3354545	0.408335455	19.9013144
39	5.3	560	650	0.9	128	35.4	31.1	64.1334	0.848571429	401.9650303	0.40196503	20.2167198
45	6.1	691	737	1	137.7	35	31	63.33173	0.961714286	391.797861	0.391797861	20.7413699

Figure 71. Water experiment for constant speed

RPS	Speed	Time(sec)	Qf (cm3/sec)	Mf (kg/sec)	Qa (m3/hr)	Speed of air (m/s)	Ma (kg/sec)	A/F
23.33333	1400	20.15	0.049627792	4.11911E-05	7	0.543140906	0.0021778	52.870147
26.66667	1600	17.8	0.056179775	4.66292E-05	7.5	0.581936685	0.0023333	50.040161
30	1800	14.94	0.066934404	5.55556E-05	8	0.620732464	0.0024889	44.8
33.33333	2000	12.82	0.07800312	6.47426E-05	9	0.698324022	0.0028	43.248193
36.66667	2200	11.38	0.087873462	7.2935E-05	10	0.77591558	0.0031111	42.655957
40	2400	10.28	0.097276265	8.07393E-05	11	0.853507138	0.0034222	42.386078
43.33333	2600	8.65	0.115606936	9.59538E-05	11.5	0.892302917	0.0035778	37.286479

HC (ppm)	CO2 (%)	CO (ppm)	NOx (ppm)	OP (%)	Tout (C)	Tin	Tout	VE (%)	Pb (kW)	bSFC (g/kW.hr)	bSFC (kg/kW.hr)	nth (%)
24	2.8	466	257	0.7	37	32	29.9	72.15007	0.22	674.0361818	0.674036182	12.0563518
23	2.7	404	304	0.6	69	31.7	29.3	67.64069	0.251428571	667.6453636	0.667645364	12.1717441
20	2.9	405	304	0.2	82	32.1	29.3	64.1334	0.282857143	707.0712727	0.707071273	11.4930668
16	3.1	372	290	0.2	94	32.1	29.1	64.93506	0.314285714	741.5970545	0.741597055	10.9579887
12	3.1	327	268	0.3	105	31.7	29.6	65.59097	0.345714286	759.4884298	0.75948843	10.699852
10	3.3	304	252	0.25	115	32	29.1	66.13757	0.377142857	770.6933182	0.770693318	10.5442861
9	3.4	302	246	0.1	124	32.8	29	63.82506	0.408571429	845.467049	0.845467049	9.61174592

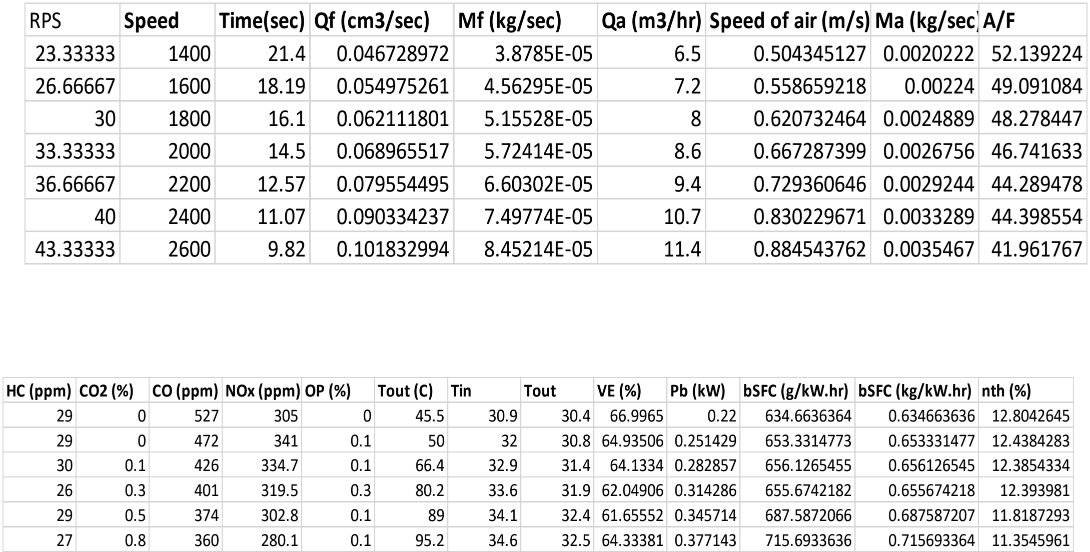
Figure 72. Water experiment for constant torque



T (NM)	Torque	Time(sec)	Qf (cm3/sec)	Mf (kg/sec)	Qa (m3/hr)	Speed of air (m/s)	Ma (kg/sec	A/F
0.9	0.5	14.95	0.066889632	5.55184E-05	8.2	0.636250776	0.0025511	45.950736
1.5	1	14.22	0.070323488	5.83685E-05	8.2	0.636250776	0.0025511	43.706988
2.1	1.5	13.68	0.073099415	6.06725E-05	8.2	0.636250776	0.0025511	42.047229
2.7	2	12.63	0.079176564	6.57165E-05	8	0.620732464	0.0024889	37.873092
3.3	2.5	11.42	0.087565674	7.26795E-05	8	0.620732464	0.0024889	34.244712
3.9	3	10.49	0.095328885	7.9123E-05	7.9	0.612973309	0.0024578	31.062758
4.5	3.5	8.9	0.112359551	9.32584E-05	7.8	0.605214153	0.0024267	26.020884
5.1	4	8.1	0.12345679	0.000102469	7.7	0.597454997	0.0023956	23.378313

HC (ppm)	CO2 (%)	CO (ppm)	NOx (ppm)	OP (%)	Tout (C)	Tin	Tout	VE (%)	Pb (kW)	bSFC (g/kW.hr)	bSFC (kg/kW.hr)	nth (%)
7	0.1	439	305	0.2	49	26.8	23.7	65.73673	0.169714	1177.66303	1.17766303	6.90045574
13	0	436	358	0	50	28.2	25	65.73673	0.282857	742.8718182	0.742871818	10.939184
47	0	475	400	0.4	54	29.9	27.2	65.73673	0.396	551.5681818	0.551568182	14.7332808
48	0	485	488.6	0.5	78.3	32.5	29.2	64.1334	0.509143	464.6621212	0.464662121	17.4888474
53	0	555	600	0.7	94	33.9	31.6	64.1334	0.622286	420.4599174	0.420459917	19.3274303
52	0	600	750	0.5	102	35.5	30.5	63.33173	0.735429	387.3153846	0.387315385	20.9813857
57	0	726	1000	0.8	111.4	35.5	32.1	62.53006	0.848571	395.641697	0.395641697	20.5398181
62	0	754	1246	1	119	36	32.5	61.7284	0.961714	383.5737968	0.383573797	21.1860146

Figure 73. NaOH experiment for constant speed



RPS	Speed	Time(sec)	Qf (cm3/sec)	Mf (kg/sec)	Qa (m3/hr)	Speed of air (m/s)	Ma (kg/sec	A/F
23.33333	1400	21.4	0.046728972	3.8785E-05	6.5	0.504345127	0.0020222	52.139224
26.66667	1600	18.19	0.054975261	4.56295E-05	7.2	0.558659218	0.00224	49.091084
30	1800	16.1	0.062111801	5.15528E-05	8	0.620732464	0.0024889	48.278447
33.33333	2000	14.5	0.068965517	5.72414E-05	8.6	0.667287399	0.0026756	46.741633
36.66667	2200	12.57	0.079554495	6.60302E-05	9.4	0.729360646	0.0029244	44.289478
40	2400	11.07	0.090334237	7.49774E-05	10.7	0.830229671	0.0033289	44.398554
43.33333	2600	9.82	0.101832994	8.45214E-05	11.4	0.884543762	0.0035467	41.961767

HC (ppm)	CO2 (%)	CO (ppm)	NOx (ppm)	OP (%)	Tout (C)	Tin	Tout	VE (%)	Pb (kW)	bSFC (g/kW.hr)	bSFC (kg/kW.hr)	nth (%)
29	0	527	305	0	45.5	30.9	30.4	66.9965	0.22	634.6636364	0.634663636	12.8042645
29	0	472	341	0.1	50	32	30.8	64.93506	0.251429	653.3314773	0.653331477	12.4384283
30	0.1	426	334.7	0.1	66.4	32.9	31.4	64.1334	0.282857	656.1265455	0.656126545	12.3854334
26	0.3	401	319.5	0.3	80.2	33.6	31.9	62.04906	0.314286	655.6742182	0.655674218	12.393981
29	0.5	374	302.8	0.1	89	34.1	32.4	61.65552	0.345714	687.5872066	0.687587207	11.8187293
27	0.8	360	280.1	0.1	95.2	34.6	32.5	64.33381	0.377143	715.6933636	0.715693364	11.3545961
29	1.2	328	271	0	101.3	35.2	32.7	63.27006	0.408571	744.734014	0.744734014	10.9118318

Figure 74. NaOH experiment for constant torque