WATER-DIESEL EMULSION: A REVIEW

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ABSTRACT

Due to its impact on human health and the nature surrounding us, diesel engine emissions have been significantly reduced over the last two decades. This reduction has been enforced by the legislating organizations around the world that gradually have made the manufacturers transform their engines to today's complex high-tech products. One of the most challenging area to meet the legislations is the emissions of the diesel engines which are the products of the combustion of diesel fuel. More restrictions have been imposed by some governments to reduce these emissions to a level such that will not cause any harmful impacts for the environment after releasing them to the atmosphere. This paper examines the effects of combusting a mixture of diesel fuel, water, and surfactant which forms emulsion on the nitrogen oxides NOx, carbon monoxide CO, carbon dioxide CO_2, sulfur oxides SOx emissions and particulate matter (PM) from a compression ignition (CI) or diesel engine. Previous research has attributed the observed reduction of these emissions to a suppression of the flame temperature due to quenching effects from the water, thereby reducing thermal NO_x formation and other pollutants. The focus of this review paper will be on experiments were previously conducted using a diesel engine with pure diesel fuel and compare it to the emulsion of water-diesel. Furthermore, results from the testing diesel fuel that mixed with varied ratios of water balanced with a surfactant to stabilize the emulsion will be presented and discussed. Three different samples of water- diesel emulsion were used with 10 % water and 90 % diesel, 20 % water and 80% diesel, and 30 % water and 70 % diesel (by volume) respectively to conduct the experiments in the lab . The purpose was to see the impact of adding the water from 10 % up to 30 % (by volume) to the diesel fuel making the emulsified fuel to investigate the impacts on the emissions and the performance of the engine. The data shows a significant NOx emission reduction when using the emulsion water diesel fuel in the range from 20% to 30 % water (by volume) in diesel. These results are correlated with a thermodynamic first law analysis to estimate the adiabatic flame temperature of the standard fuel and fuel-water emulsion cases. Results indicate that thermal NO_x is indeed reduced by quenching and flame temperature suppression confirming reports in the literature. Recommendations are given for further studies, including improving the fuel—water emulsion and considerations for long-term testing.

KEYWORDS: *Diesel-water emulsion, Emissions, NO_x, Micro-explosion, Adiabatic flame temperature*

I. INTRODUCTION

In 1892, a German engineer named Rudolf Diesel patented a new kind of a combustion engine which is called now the diesel engines. The diesel engine's advantage over other internal combustion engine was, and still is, its efficiency. The engines spreading vary in different markets depending on the geographical position, fuel supply and sometimes tradition. It also varies in different market segments; diesel engines or what are called (Compression ignition engines) are more dominating in high mileage segments where the improved fuel economy surpasses their higher prices. The diesel engine is dominating in heavy applications such as busses, heavy duty trucks and its market share in the passenger car segment is steadily increasing, mainly due to increasing fuel prices and improved emission. In 2015, 53 % of the sold cars in the European Union were powered by diesel engines [1]. This paper will present some characteristics of the diesel engines, then will discuss the mechanisms of diesel combustion in IC engines and the formation of pollutants (i.e. NO_x, soot, and Particulate matter PM). Then, the preparation procedure and the effects of the water diesel emulsion will be explained and the phenomena of micro-explosion will be presented. The most important effects of the water diesel emulsion on the BSFC (Brake Specific Fuel Consumption) and the brake thermal efficiency will be discussed in which an optimum percentage of water (by volume) in diesel should be decided. Consequently, it was concluded that 20 % of water (by volume) gives the best results (i.e. reduces the BSFC and increases the brake thermal efficiency) [2, 4 – 6].

1.1. Physical Engine Characteristics

Before discussing the operation, design, and analysis of internal combustion engines (ICEs), it is worthwhile to review the specific engine components involved in and affecting the combustion process.

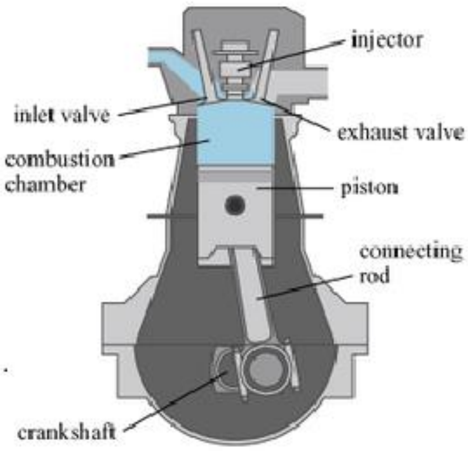

Figure 1 shows a cross-section of a compression engine (Diesel) engine.

Compression ignition (CI) engines use fuels of lower volatility, with compression ratios from 11:1 to 22:1 and compression pressures between approximately 2700 and 4800 kPa [3].

As the name implies, the high compression pressures of the CI engine ignites the fuel/air mixture, so no ignition source (e.g., spark plug) is required. Advantages of the CI engines over the SI engines include the following:

1- Lower specific fuel consumption
2- Slightly higher thermal efficiency
3- Relatively cheaper fuel costs
4- Lower CO and hydrocarbon emissions at low and medium loads
5- Lower capital costs, and higher durability.

On the other hand, disadvantages include:

1- Higher noise of operation
2- Higher engine weight required to withstand the higher pressures
3- Excess oxygen in the exhaust preventing use of standard catalysts for air pollutant control.

1.2. Compression Ignition (CI) Combustion Processes

In the diesel engine, the fuel is injected directly into the cylinder during the last part of the compression stroke and the first part of the expansion stroke. The injected fuel mixes with the air in the cylinder and ignites due to the high temperature of the compressed gases in the cylinder. The ignition usually occurs during the initial part of the injection and the fuel that has been injected up to that point combusts rapidly. This part of the combustion is called the premixed combustion period and can be a significant fraction of the total combustion period, typically when the injection duration is short. The fuel that is injected after this point burns as it has evaporated and mixed with air to in combustible proportions after only a short reaction time compared to the initial ignition delay. This combustion period is therefore called diffusion combustion. The combustion process is both turbulent and in stationary but a time averaged, conceptual model for the diffusion combustion period has been proposed by El-Sinawi et al [3] and this provides a simplified way to describe the process. El-Sinawi's model is shown in a schematic in figure 2 together with a picture of a "real" combustion in an optical access engine.

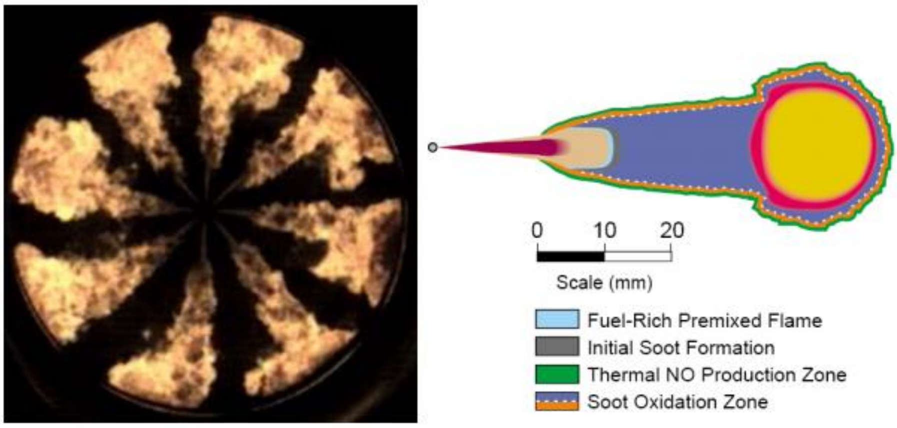

Figure 2 Diesel combustion process, [3], [4]

The disadvantage with diesel combustion, compared to e.g. Otto combustion (normally petrol also called Spark Ignited (SI) combustion), is that it is not homogenous throughout the cylinder, i.e. parts of the combustion takes place with a shortage of oxygen, so called rich conditions. Where there is rich combustion, soot is formed and although most of it is oxidized as the fuel is further mixed with the surrounding air, some of it will remain as the gases are expelled out of the cylinder and through the tailpipe. The regions were soot is formed according to El-Sinawi's model is the brown region shown in Figure 2. Soot is emitted from the engine in the form of particles on which water and hydrocarbons are condensated as the exhaust gases are cooled down. These particles are together with other solid and liquid material in the exhaust gases called Particulate Matter (PM). Particulate matter is a hazard for human's health and to the environment and is together with NOx the main emission from the diesel engine and thereby one of its greatest challenge. Figure 2 also shows a green region where most NO is formed in the flame front where the air/fuel mixture is approximately stoichiometric and the flame is as hottest region across the combustion chamber. NOx is also formed in SI engines but since these are operated without excess air, they can take care of the emissions relatively easy with a three-way catalytic converter [5, 6]. This is not possible in the diesel engine where overall air excess is necessary to achieve acceptable combustion efficiency and soot emissions. PM emissions have been shown to increase respiratorical symptoms, decrease lung function and increase use of asthmatic medicine. Increased health care and mortality has also been proved regarding cardiovascular and lung diseases. NOx has been shown to cause increased sensitivity to the respiratory passages [5, 7] and is also the cause of smog. By the influence of sunlight, NOx forms smog together with hydrocarbon emissions.

$$C_xH_y + a(O_2 + 3.76N_2) \rightarrow bCO_2 + cCO + dH_2O(g) + eH_2 + fO_2 + 3.76aN_2 . \quad [5, 6]$$

II. PREPARATION OF THE WATER-DIESEL FUEL EMULSION

Mixing water with diesel in the presence of surfactant (i.e. tween 20) which is essential to increase the stability of the mixture and prevent the water from being separated from the diesel. Furthermore, the surfactant will surround the dispersed water drops in micro size which is very desirable for better combustion.

The preparation process begins by adding the water to the diesel and then put the surfactant and blend the mixture by using mechanical blender for three to five minutes. The emulsion will form after that and the color of the emulsion will by white or milky as its shown in figure 3 [8].

The fuel / air equivalence ratio, ϕ, is defined as the ration of actual fuel/ air ratio to the stoichiometric fuel/ air ratio as the following equation

$$\phi = \frac{(F / A)_{actual}}{(F / A)_s}$$

For φ= 1, combustion is stoichiometric, for φ< 1, combustion is fuel-lean (excess air is used in combustion), and for φ> 1, combustion is fuel-rich (excess fuel is used in combustion. Diesel engines operate significantly fuel lean, with typical values of φ= 0.8. F/A is usually expressed on a mass basis as kg fuel per kg air, but a molar basis can also be used, kmole fuel per kmole air. The simplified combustion equation for a hydrocarbon fuel C_xH_y can be represented as the following chemical equation:

For practical applications combustion, air can be approximated as 21 % oxygen (O2) and 79 % Nitrogen (N_2). Thus, for each mole of O_2 in air, there are $\frac{0.79}{0.21}$ = 3.76 moles of N_2.

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a. 0 min left. b. 20 min left. c. 60 min left. d.1 day left.

Figure 3. Water – diesel emulsion samples

III. INFLUENCE OF WATER- DIESEL EMULSION ON DIESEL ENGINE

The presence of dispersed water drops with the diesel emulsion has a great impact on the combustion process inside the combustion chamber of the diesel engine. It was noticed the adiabatic flame temperature of the combustion chamber was decreased because the evaporation of water absorbs some heat which reduces the temperature [9]. This explains the reduction in the NOx in the emission because most of NOx is formed in the combustion chamber because of the high temperature or called the thermal NOx. The process is not fully understood yet because it happens very quickly and it's difficult to put a probe or a camera to see the phenomena. Another significant impact that is the increase the performance of the engine or the torque when we use the water- diesel emulsion [9, 10]. The reason behind that is that the water has the chemical build of (H_2O) and the oxygen of the water drops when mixed with the diesel and sprayed in the combustion chamber, it evaporates and converts to gas which burns with the diesel as extra oxygen (apart from the air oxygen). Consequently, this will enhance the combustion of the diesel because the extra portion of oxygen and increase the efficiency of the engine. The water-diesel emulsion has a better combustion criteria because the compression ignition engines depend on burning of the mixture of diesel and air in very high temperature and pressure under turbulence conditions to ensure a fully combustion for the fuel which enhances the distribution of the flame to cover all the space of the combustion chamber. Figure 4 [11] shows the differences of using diesel alone and the emulsion of water and diesel in the combustion period which comes after the compression stroke.

Micro-explosion is an important phenomena in the secondary atomization process of water-in-diesel emulsion fuels. Generally, this phenomenon is affected by volatility of base fuel, type of emulsion, water content, diameter of the dispersed liquid, location of the dispersed liquid, and ambient conditions like pressure and temperature. Although many studies have been conducted both experimentally and numerically to understand the phenomenon of micro-explosion, yet the study of its effects inside the combustion chamber are quite few.

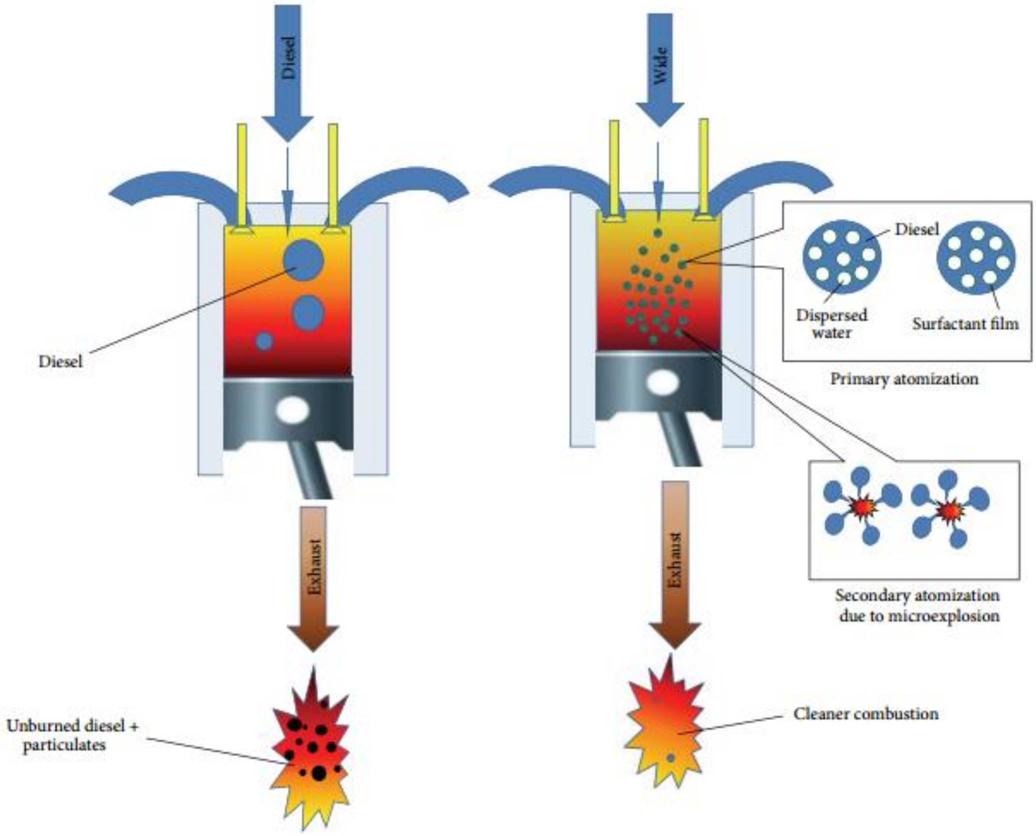

Figure 4. Combustion of diesel alone (Left) and the emulsion of water- diesel (right) [11]

It is believed that fuel injection and the passage of emulsified fuel through the narrow exit of the injection nozzle affect the dispersed liquid behavior of the fuel. It is therefore very important to study the micro-explosion phenomenon inside a combustion chamber and its effect on the combustion process like the secondary atomization, spray penetration, evaporation, and mixture ignition. Combustion process is generally characterized by factors such as injection characteristics, spray penetration, evaporation, chemical and physical atomization and mixture ignition, engine cylinder pressure and temperature, and heat release characteristics. As far as the fuel-injection characteristics is concerned, it is observed that the injection pressure profile extension over a longer period leads to retarded injection timing and 22–26% increase in injection duration [12]

IV. THERMAL EFFICIENCY AND WATER-DIESEL EMULSION

The literature and previous research in the topic of water-diesel emulsion shows that there was an increase in the brake power of the diesel engine by using the water- diesel emulsion. Ghojel [4, 7] mentioned that the rate of heat release found to increase with percentage of water addition in diesel. The reason seems to be the fact that the mixture is better prepared due to prolonged ignition delay. In addition Experimental investigations showed that strong micro-explosions of a group of droplets can occur in the specific regions of the luminous flame near the spray tip. Micro-explosions of the emulsion fuel seem to enhance the mixing of fuel with surrounding air for faster and more efficient combustion also resulting in a higher heat release rate. The cylinder pressure is increasing with the percentage of water in the emulsion, producing a better engine output, reducing BSFC (Brake Specific Fuel Consumption) for these emulsion rates. Abu Zaid [6] reported that the average increase in brake thermal efficiency for 20% water emulsion is approximately 3.5% over the use of diesel for the engine speed range studied. Figure 5 shows the reduction of the BSFC (Brake Specific Fuel Consumption) and the increasing of the brake thermal efficiency with different fractions of water (10%, 20% and 30 % by volume) in diesel.

It is shown that adding up to 20 % of water by volume to the diesel has the best results that decreased BSFC and increased the brake thermal efficiency for the whole load conditions. However, adding 30 % of water into the diesel has increased the BSFC and decreased the thermal efficiency.

V. Energy Management and the Water- Diesel Emulsion

The water- diesel emulsion is still a new topic to investigate in as more concerns and restrictions have been imposed on the engines industry especially the diesel type. This needs more study and experiments in the lab and on road conditions to know in details what the best optimization of water percentage and surfactant type. Using alternative fuel is a must as the world is consuming much more fossil fuel nowadays. Another reason is the environmental concerns as pollution and climate changes are threating the ecosystem of the earth. More population need to use more transportation and more energy are required to meet their demands so we need to think about the next generation energy resources. Although the technology of water- diesel emulsion is not commercialized yet, it has the potential to fulfill and satisfy the energy demands of different important sectors i.e. transportation, electricity generation etc) using the combined fuel resources and reduce the pollutions. Another significant aspect of the emulsion fuels is that it does not need any modification or adjustment for the current technology of diesel engine. It offers a feasible feature that we can start using it in public transportation vehicles and then to personal cars. However, there are some difficulties that need more research such as the separation of water and diesel and the cold conditions of starting the diesel engines. Also the corrosion that might be caused because of using water with the diesel.

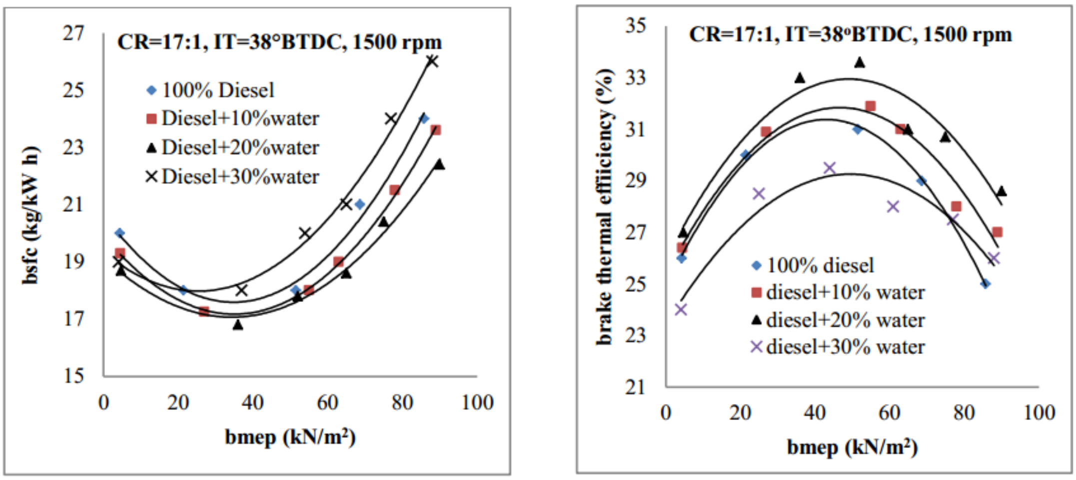

Figure 5. Effect of water-diesel emulsion in BSFC (Left) and brake thermal efficiency (Right) [4, 7]

VI. Conclusion

There was a common agreement by most of the researchers on the report of the effect of water content on the simultaneous reduction of both NOx and particulate matter (PM) using the water –diesel emulsion fuel instead of diesel alone in the compression ignition engines. The inconsistency was on the percentage amount reduction compared to pure diesel. Up to 37% reduction NOx and 90% reduction in particulate matter were reported by different researchers as mentioned in section 3 of this paper. In section 4 of this paper, it was clear that 20 % of water (by volume) in the emulsified diesel fuel was the optimum fraction of water which reduces the BSFC (Brake Specific Fuel Consumption) and increase the brake thermal efficiency.

The reasons behind the increase in the efficiency of the engine can be summarized as the followings:

1- Water-diesel emulsion fuel has water in it which means H_2O. This emulsified fuel already have some oxygen in it which will evaporate and (covert to vapor phase) when the emulsified fuel is injected in the combustion chamber and form oxygen gas. Furthermore, oxygen gas will increase the efficiency of the combustion of the emulsified fuel due to the complete combustion or semi complete combustion that takes place in the combustion chamber.

2- The dispersed water droplet in the emulsion will increase the turbulence of the mixture inside the combustion chamber which means burning the fuel in the entire space of the chamber. Thus, the distribution of the burned gases will be identical on the cylinder which makes the engine works much smoothly.
3- The noise of diesel engine is high sometimes because the mentioned turbulence in the combustion chamber. Using water-diesel emulsion will decrease the noise because more energy are harvested to be converted into mechanical brake power instead of converting to acoustic waves (losses).

Micro-explosion is an important phenomena in the secondary atomization process of water-diesel emulsion fuels. Generally, this phenomenon is affected by volatility of base fuel, type of emulsion, water content, diameter of the dispersed liquid, location of the dispersed liquid, and ambient conditions like pressure and temperature. Although many studies have been conducted both experimentally and numerically to understand the phenomenon of micro-explosion, yet the study of its effects inside the combustion chamber are quite few.

VII. Future Work

A systematic approach of studying the optimization of water content in the emulsion for best engine performance and emission by both experimental and numerical investigations is necessary so that it can give the best recommendations for the commercialization of water- diesel emulsion as an alternative source of energy for the future diesel engines. Stabilization of the emulsified diesel is still a challenge and needs to be investigated to have the best surfactant materials.

References

[1] Kannan1 K & Udayakumar M, NOx and HC emission control using water emulsified diesel in single cylinder engine, Asian Research Publishing Network (ARPN), vol. 4, No. 8, 2016.
[2] Nadeem M, Rangkuti C, Anuar K, Haq M R U, Tan I B & Shah S S, Diesel engine performance and emission evaluation using emulsified fuels stabilized by conventional and gemini surfactants, Fuel, vol. 85, pp: 2111–2119, 2006.
[3] El-Sinawi A H, Water- surrogate fuel emulsion combustion effect on CO and NOx emissions, Int. J. of Thermal & Environmental Engineering, vol. 1, No. 2, pp: 99-108, 2010.
[4] Ghojel J, Honnery D & Al-Khaleefi K, Performance, emission and heat release characteristics of direct injection diesel engine operating on diesel oil emulsion. Applied Thermal Engineering, vol. 26, pp: 2132-2141, 2006.
[5] Armas O, Ballesteros R, Martos F J & Agudelo J R, Characterization of light duty diesel engine pollutant emissions using water-emulsified fuel, Fuel, vol. 84, pp: 1011-1018, 2005.
[6] Abu-Zaid M, Performance of single cylinder, direct injection diesel engine using water fuel emulsions, Energy Conversion and Management, vol. 45, pp: 697-705, 2004.
[7] Tran X T & Ghojel J I, Impact of introducing water into the combustion chamber of diesel engines on emissions-an overview, Proceedings of the 5th Aisa-Pasific Conference of Combustion, July 17-20, University of Adelaide, Adelaide, Australia, pp: 233-236, 2005.
[8] De Fries T H, Anthony J W, Kishan S, Ullman T L, Matthews R D & Lewis D J, The Texas diesel fuels project, Part 1: Development of txdot-specific test cycles with emphasis on a "route" technique for comparing fuel/water emulsions and conventional diesel fuels, SAE Paper No. 2004-01-0090, 2004.
[9] M T Chaichan, H. A.Kazem, T. A. Abid, The Environmental Impact of Transportation in Baghdad, Iraq, Environment, Development and Sustainability, 2016. DOI: 10.1007/s10668-016-9900-x.
[10] S H Khudhur, A. M. Salih, M. T.Chaichan, The Effect of Variable Valve Timing on SIE Performance and Emissions, International Journal of Scientific & Engineering Research, 6(8), 2015, 173-179.
[11] Mohammed Yahaya Khan, Z. A. Abdul Karim, Ftwi Yohaness Hagos, A. Rashid A. Aziz, and Isa M. Tan, " Current Trends in Water-in-Diesel Emulsion as a Fuel ", Hindawi Publishing Corporation, the Scientific World Journal Volume 2014, Article ID 527472, 15 pages.
[12] P. S. Kumar, B. Venkatesh, B. Rajeswari, Veeranjaneya L. Reddy and ShaValli P. S. Khan, Emission Control By Using Water Emulsified Diesel In Single Cylinder Diesel Engine, Int. J. Adv. Engg. Technol., 5(2) (2013).

ACKNOWLEDGMENT

The author would like to appreciate the Mechanical Engineering Department at Oakland University for the support and guidance.

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