# REAL-TIME WATER-IN-DIESEL EMULSION FUEL PRODUCTION SYSTEM FOR DIESEL ELECTRIC GENERATOR

AHMAD MUHSIN BIN ITHNIN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Malaysia-Japan International Institute of Technology
Universiti Teknologi Malaysia

AUGUST 2015

To my father, my mother, my wife and my relatives

## ACKNOWLEDGEMENT

All praise to Almighty Allah the Most Gracious and Most Merciful for the strength and blessing that is given to my life. First and foremost, my deepest gratitude goes to my main supervisor, Dr.Wira Jazair Yahya for his remarkable support and guidance during my entire study. I must also express my gratitude to the Malaysia- Japan International Institute of Technology (MJIIT) for the scholarship provided during my entire study period. A thousand thanks are also given to my research members and colleagues in Vehicle System Engineering (VSE) research laboratory especially Hassan, Azren, Aiman and Zahari for helping me during my research study. Lastly, I would like to express my sincere gratitude to my parents, Ithnin bin Mohamad and Che Norina binti Hasannalbashry for limitless love, support and pray that enables me to reach this level. Last but not least, to my lovely wife, Nurul Hazwani binti Mustaffa, special thanks for her pray, patience, love and understanding that encourages and strengthens my spirit to complete my study.

# ABSTRACT

This research focused on the design and development of a novel emulsion fuel making device that can eliminate emulsion fuel main weaknesses; stability issues and high dependency of surfactant. The device is called Real-Time Water-in-Diesel Emulsion Fuel Production System (RTES) and utilized for the diesel electric generator application. The concept of RTES device consists of fuel and water which being stored in different units. These two immiscible liquids are transferred and instantaneously being emulsified by a mixing system before the produced emulsion fuel is injected into the combustion chamber. The research started with engine performance and emission test using water-in-diesel emulsion as fuel under various water percentages (5, 10, 15 and 20 %). The water content that gives optimum impact of engine performance and emission was selected to be used in RTES. Next, emulsion fuel stability test was conducted where different mixing equipments and conditions were tested to mix water and diesel without the existence of surfactant. The findings are used as reference to generate the conceptual design in the design process of the RTES. RTES device was then developed and tested onto the 0.406 litre, single-cylinder, four-stroke, air-cooled diesel engine. The engine testing result showed that emulsion fuel without surfactant made by RTES does gives significant improvement to the engine with the 3.59 % increase in brake thermal efficiency (BTE) and 3.89% reduction in brake specific fuel consumption as compared to diesel fuel. In addition, Nitrogen Oxides (NOx) and Particulate Matter (PM) contents in the exhaust emission reduced significantly compared to neat diesel fuel with the average reduction of 31.66% and 16.33% respectively. Overall, RTES device proved that emulsion fuel can be used in the engine without the existence of surfactant while maintaining its benefits which are greener exhaust emission and fuel saving.

# ABSTRAK

Kajian ini tertumpu kepada mereka-bentuk dan membangunkan alat baru bagi menghasilkan bahan api emulsi yang dapat menyelesaikan masalah utama bahan api tersebut iaitu; isu kestabilan dan pergantungan yang tinggi kepada bahan penguat emulsi. Alat ini dinamakan 'Real-Time Water-in-Diesel Emulsion Fuel Production System' (RTES) dan ianya digunakan untuk penjana elektrik enjin disel. Konsep RTES adalah terdiri daripada bahan api dan air yang disimpan di dalam unit yang berbeza. Kedua-dua cecair yang secara fizikalnya tidak boleh bercampur, akan dipindahkan dan serta-merta diemulsikan oleh sistem pencampuran di dalam RTES sebelum disuntik ke dalam kebuk pembakaran enjin. Kajian ini dimulakan dengan menjalankan ujian prestasi enjin dan pelepasan ekzos dengan menggunakan bahan api emulsi yang mengandungi peratusan isipadu air berbeza (5, 10, 15 dan 20%). Peratusan isipadu air yang dapat memberikan kesan optimum terhadap prestasi enjin dan pelepasan ekzos dipilih untuk digunakan pada RTES. Seterusnya, ujian kestabilan bahan api emulsi tanpa menggunakan bahan penguat emulsi dijalankan dengan menggunakan alat dan keadaan pencampuran yang berbeza. Hasil daripada ujian tersebut digunakan sebagai rujukan untuk penghasilan konsep reka-bentuk RTES. Alat RTES dibangunkan dan kemudiannya diuji pada 0.406 liter, satu silinder, empat lejang, penyejukan udara disel enjin. Hasil ujian menunjukkan bahawa bahan api emulsi yang dihasilkan oleh RTES tanpa menggunakan bahan penguat emulsi memberikan perubahan yang ketara kepada enjin dengan peningkatan kecekapan haba (BTE) sebanyak 3.59% dan penjimatan bahan api sebanyak 3.89% berbanding bahan api disel. Nitrogen Oksida ($NO_x$) dan jirim zarahan (PM) dalam emisi ekzos berkurangan secara purata masing-masing sebanyak 31.66% dan 16.33%. Secara keseluruhan, alat RTES berjaya membuktikan bahawa bahan api emulsi boleh digunakan di dalam enjin tanpa bahan penguat emulsi di samping dapat mengekalkan manfaatnya iaitu pengurangan pelepasan ekzos dan penjimatan bahan api.

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $A_o$ | - | Orifice area |
| $C_D$ | - | Orifice discharge coefficient |
| g | - | Acceleration due to gravity |
| h | - | Height |
| $m$ | - | Mass |
| $m_a$ | - | Air mass flow rate |
| $m_f$ | - | Fuel mass flow rate |
| $N$ | - | Engine speed |
| $P$ | - | Pressure |
| $\dot{Q}$ | - | Heat release rate |
| $Q_{HV}$ | - | Calorific value |
| $R$ | - | Specific gas constant for air |
| $T$ | - | Torque |
| $T$ | - | Temperature |
| $V$ | - | Volume |
| $\dot{W}$ | - | Rate of work |
| $\gamma$ | - | Ratio of specific heat |
| $\rho_a$ | - | Density of air |
| $\rho_{man}$ | - | Density of manometer liquid fluid |
| $\Delta p$ | - | Pressure drop across the orifice plate |

# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| AFR | - | Air Fuel Ratio |
| ASA | - | Alkenyl succinic anhydride |
| BP | - | Brake Power |
| BSFC | - | Brake Specific Fuel Consumption |
| BTE | - | Brake thermal efficiency |
| C | - | Carbon |
| CA | - | Crank angle |
| CO | - | Carbon Monoxide |
| $CO_2$ | - | Carbon Dioxide |
| DC | - | Direct current |
| D2 | - | Malaysian Diesel Grade-2 |
| E | - | Emulsion fuel made by RTES without surfactant added |
| ES | - | Emulsion fuel made by RTES with surfactant added |
| E5 | - | 5 % water in emulsion fuel |
| E10 | - | 10 % water in emulsion fuel |
| E15 | - | 15 % water in emulsion fuel |
| E20 | - | 20 % water in emulsion fuel |
| HC | - | Hydrocarbon |
| MPRR | - | Maximum rate of heat release |
| MRHR | - | Maximum pressure rise rate |
| NOx | - | Nitrogen Oxides |
| OH | - | Hydroxyl |
| PM | - | Particulate Matter |
| RAM | - | Random-access memory |
| rpm | - | Revolution Per Minute |

| | | |
|---|---|---|
| RTES | - | Real-time emulsion fuel production system |
| SOC | - | Start of combustion |
| TDC | - | Top Dead Centre |
| W/D | - | Water-in-diesel emulsion fuel |

## LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Topic Background

The rise in sea level, shrinking snow cover and ice sheet, retreat of glaciers as well as the current extreme weather like severe droughts and flooding, are due to the effects of climate change. Over 90% of the causes of the climate change come from human activities [1] of which the biggest cause of this catastrophe is contributed from atmospheric emission, especially gasses and aerosols that are being stored in the atmosphere. These gasses are known as greenhouse gasses. The largest growth in their emission has come from fossil fuel combustion, representing 57% of the total greenhouse gasses, which is largely produced from the emissions from industry and transportation [2]. Industrial and transportation emissions are not only harmful to the environment, but are also hazardous to our health, especially nitrogen oxide (NOx) and particulate matter (PM) gas emissions. The effects of these hazardous emissions include serious damage to our health. Lung cancer, asthma, cardiovascular issues and other fatal illness that would cause premature death are among the effects of such harmful emissions. Due to the severe environmental issues that the world is facing recently, new emission regulations are constantly being introduced in order to mitigate this problem. The Kyoto Protocol, which was established in 1997, was the first step to set binding obligations on industrialized countries to reduce their emissions. In addition to environmental disputes, the issue of critical fossil fuel reserves is another concern. Some studies estimate that the worldwide fossil fuel reserves will only last for less than four decades [3]. Accordingly, these two serious issues have generated research interest worldwide in order to curb and find a solution to these problems. Currently, the more efficient utilization of energy and less polluting emissions are the prominent research areas that are progressively being studied [4]–[6].

The compression ignition engine, or so called diesel engine, is the favoured source of power for heavy industrial and transportation compared to the spark ignition engine, otherwise known as the gasoline engine, due to its high power output and fuel economy [7]. Nonetheless, diesel engines emit more hazardous emissions, especially NOx and PM. Due to the stringent emission regulations that have been implemented; many devices are being invented in order to reduce these exhaust gas emissions. Devices like NOx Absorber Catalysts (NAC) and Selective Catalytic Reduction (SCR) are able to reduce the formation of NOx to a large extent. Furthermore, Diesel Oxidation Catalysts (DOCs) and Diesel Particulate Filters (DPFs) are devices commonly used for the reduction of PM. DOC are an inexpensive, robust device that are suitable for non-road applications and are capable of reducing PM by 25% or more. As for DPFs, they are able to reduce the formation of PM by up to 90% and work effectively on engines that are able to sustain high exhaust temperature. However, the cost is three times more expensive than DOCs [8]. Nevertheless, the techniques that are used to reduce $NO_X$ lead to an increase in smoke and PM and vice versa [9]. In addition, they tend to increase the fuel consumption of the engine [10]. It is difficult to simultaneously reduce both NOx and PM, and, at the same time, maintain or improve the performance of the engine.

The introduction of water into the diesel engine is a promising method that can reduce the formation of NOx and PM emissions simultaneously [11], [12]. There are three common methods to introduce water into the engine: spraying water into the intake manifold, which is called intake manifold fumigation [13]–[15]; water injection into the combustion chamber or so called direct water injection [16], [17]; and water-in-diesel emulsion fuel (W/D). The intake manifold fumigation uses the combination of a valve and flow meter to control the water flow rate. It is claimed to reduce the NOx as a result of the presumable uniform water vapour in the cylinder at the time of combustion. The vaporization of the water process arises from the time the air and water are heated through the compression stroke [11]. As for the direct water injection method, the water is injected into the combustion chamber in a separate unit or injector. It can reduce NOx more than the fumigation method due to the water droplets being closer to the flame during the combustion. In addition, the presence of water in the fuel spray increases the penetration of the fuel (liquid and vapour) during the spray period [7]. However, both the intake manifold fumigation and direct water injection method lead to an increase in the formation of hydrocarbon (HC) and emission of carbon monoxide (CO) [18], [19]. Furthermore, as the water is introduced into the combustion chamber, it tends to be in direct contact with the fuel feed system and cylinder-piston group, thus resulting in oil contamination and increasing wear [18]. In addition, both methods require highly complex engine modification in order to integrate the water addition device to the engine. Thus, it requires high additional cost [20].

Water-in- diesel(W/D) emulsion fuel is the only method in the water addition group that can reduce NOx and PM emission simultaneously while at the same time improving the combustion efficiency [9], [12], [21], [22]. Moreover, the usage of W/D emulsion fuel does not require any modification of the engine [22]. W/D emulsion fuel is the potential alternative fuel that could fulfil the world’s needs: more efficient energy usage and less polluting emission. The term emulsion is defined as a mixture of two or more immiscible liquids, which are unblended in nature; one is present as a dispersed droplet throughout the other liquid, which is present in a continuous phase. The dispersed droplet is called the internal phase, and the other liquid is the external phase [8], [23]. The emulsion is formed with the help of mechanical agitation together with the chemical additives so called surfactant to keep the immiscible liquids being tied together forming one solution. Generally, emulsions are divided into two types: oil-in-water emulsion (O/W) and water-in-oil emulsion (W/O). The O/W emulsion is where the oil is located in the internal phase presented as a dispersed droplet and the water is presented as a continuous phase, whereas for the W/O emulsion, it is the opposite [22]. Figure 1.1 shows the different of the physical structure of both types of emulsions. The O/W emulsion is not suitable to be an alternative fuel. This is due to the large amount of water that might come into direct contact with the cylinder-piston group and fuel feed system, which will result in failure of the fuel combustion [24]. The W/O emulsion fuel is the most suitable and widely used as the alternative fuel for fuelling compression ignition engines by researchers and experts. In addition, the type of oil stated earlier refers to the diesel fuel. The water-in-diesel (W/D) emulsion fuel type is preferable to be the alternative fuel compared to the water-in-gasoline emulsion fuel. This is due to the high combustion and the high pressure in the compression ignition engine, which is particularly suitable for the concept [25].

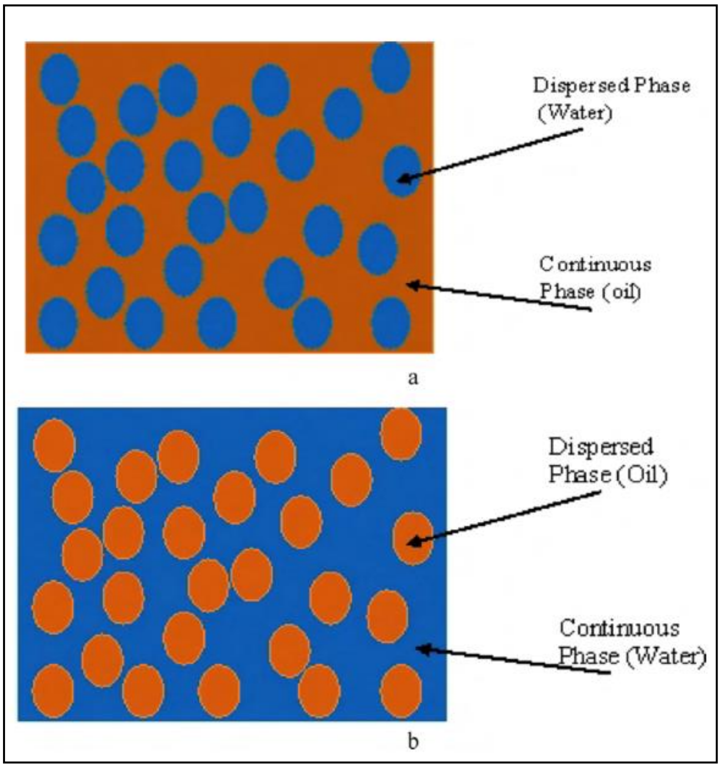


**Figure 1.1** Physical structures of two-phase emulsions: a) Water-in-oil emulsion b) Oil-in-water emulsion [22]

## 1.2 Research Question

W/D emulsion fuel has major weakness which is stability issue that brings a huge barrier to commercialize this alternative fuel. The immiscible liquids that previously being tied together forming one solution will separate after exceeding its stability period. Figure 1.2 shows W/D emulsion fuel is fully separated after one day where the diesel fuel floats on top of the water layer. The stability of the emulsion is very important in order to ensure this alternative fuel can run accordingly in the engine. If the emulsion is destabilized during the engine running time, the probability of the engine failure to operate is high. Plus, it may damage the parts inside the engine. Normally, water-in-diesel emulsion fuel can maintain its stability for up to 3 months [18] but it will depend on various factors, such as the type and percentage of surfactant, the temperature, viscosity, specific gravity and water content [8].

**Figure 1.2** The separation of W/D emulsion fuel after exceeding its stability period

The destabilization process of W/D emulsion fuel will occur after it goes through several phenomena: flocculation, coalescence and sedimentation or creaming. The flocculation process is where the droplets in the internal phase attract each other. As for the coalescence process, the combination of those droplets and become bigger droplet size. The sedimentation/creaming process is where the result of the different densities of two phases can be observed. The internal phase either precipitates at the bottom or rises to the surface of the external. For the case of the W/D emulsion fuel, the internal phase, which is the water, will sink to the bottom [26]. Figure 1.3 shows the schematic of mechanism of the three aforementioned processes. In a specific view [27], the W/D emulsion fuel starts to destabilize when the repulsive force of the dispersed droplets become weaker; the dispersed droplets, which are located in the internal phase tend to gather towards each other and those droplets are separated by the thin film. This process is called the flocculation process. The thin film thickness will reduce due to the attraction of the Van der Waals forces.

Then, if the thin film thickness is reduced to a critical value, it will break leading to newly formed droplets to move to each other forming a larger droplet (coalescence). Consequently, those droplets (water droplets) will settle at the bottom due to the difference in density (sedimentation). All of these processes will continually destabilize the emulsion until the water and the diesel fuel are fully separated. In addition, the W/D emulsion fuel separation can be initiated by these following cases: low speed environment (the phases after long period will be separated by gravity effect), increase in temperature (lower viscosity), external electric field, high shear stress in the emulsion, the addition of a chemical that influences the emulsifier or liquids, and the addition of a diluting liquid [26].

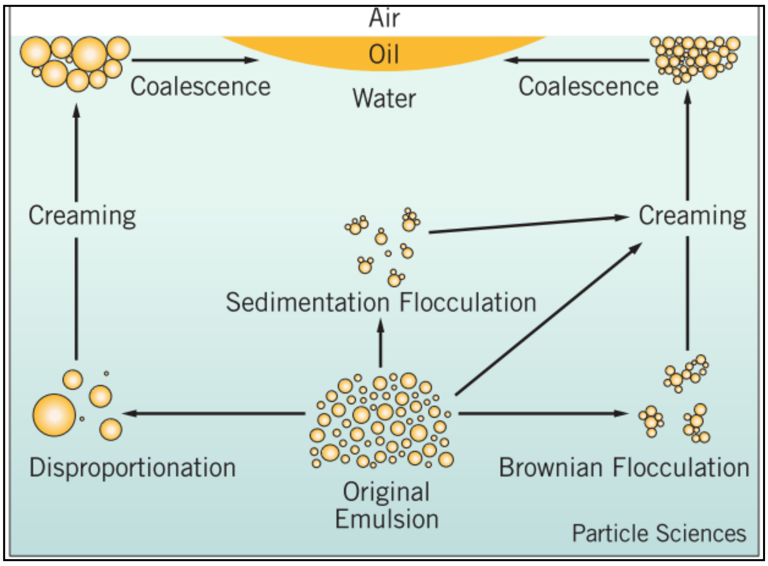


**Figure 1.3** Mechanism leading to sedimentation of an oil-in-water emulsion [28]

The presence of a surfactant, sometimes called an emulsifier, is crucial in forming a stable emulsion. The surfactant works as a surface active agent that is a typical chemical additive to attract both the immiscible liquids in forming one stable solution [26]. The surfactant functions by reducing the surface tension of the water by adsorbing at the liquid-gas interface and also reduce the interfacial tension between oil and water by adsorbing at the liquid-liquid inter phase [23]. An alternate perspective is that the surfactant possesses an equal ratio of polar and non-polar portions. As the surfactant blends into the mixture of water and oil, the polar groups of the surfactant orient toward the water and the non-polar group toward the oil, thus lowering the interfacial tension between the two liquids [29]. There are numerous types of surfactant on the market, which are categorized based on their Hydrophilic-Lipophilic Balance (HLB). A low HLB is generally suitable for forming W/O emulsion and vice versa [8], [22]. As for the selection of surfactant for forming W/D emulsion fuel, the surfactant should be free from sulphur and nitrogen and burn easily without soot [25]. In addition, it should not have any impact on the physiochemical properties of the fuel. The surfactants that are most used by researchers and experts are Sorbitanmonooleate, which is called Span 80; Polyoxyethylenenonylphenyl ether, so called Span 80 and Tween 80; Octylphenoxy poly ethoxy ethanol or called Triton X-100; and Dai-Ichi Kogyo Seiyaku (Solgen and Noigen TDS-30)[22].Other than that, glycerine is also can be used as a surfactant since it has the potential to reduce the interfacial tension between the immiscible liquids. However it is the weakest in terms of strength as compared to the other surfactants. That is why none of the studies / researchers reported to use it alone to form emulsion fuel. It is made from the by-product of the biodiesel production. Based on the stability testing, it only can hold the stability period within few minutes [30]. However, it is the cheapest in terms of price as compared to others. Most of researches conducted regarding the emulsion are heading towards on finding the best surfactant that can maintain its stability for very long time. In facts some researchers have already succeeded in forming a thermodynamically stable emulsion (micro-emulsion). However, another issue has come to the fore, which is the price. These alternative fuels are much more expensive compared to neat diesel fuel since they require a high amount of surfactant and other chemical additives, plus they need tedious processes to be completed. One particular company, for example, commercializes the emulsion fuel that contains about 5% water; 12.6% organic oxygenated additives, which consist of glycerine and polyethoxy-ester; and NP-9 surfactant. Almost 13 % of chemical additives required to form the stabilized emulsion fuel. Hence, the advantage of using the W/D emulsion fuel does not compensate for the additional price.

## 1.3 Research Objectives

There is a novel concept which could eliminate the high dependency of the surfactant as well as the concerns towards the stability issues of the emulsion. The said concept is about producing the emulsion fuel in real-time, and directly and continuously supplied into the engine. The proposed name for the concept is real-time emulsion fuel production system (RTES). The concept of RTES is consisting of the fuel and the water which is stored in different unit. The two immiscible liquids will be transferred quantitatively and instantaneously being emulsified by a mixing system before it injected into the combustion chamber. This system is attached close to the engine fuel delivery system so that the new developed emulsion fuel made from that system is transfers instantaneously into the combustion chamber, thus the need to have emulsion with having long stability period is not necessary anymore. By implementing this concept, the presence of surfactant could be eliminated or the used of surfactant can be very minimal, plus the material that have the surfactant potential such as glycerine can be utilized only on its own. There is one patented invention [31] which nearly same with the concept of RTES, utilizes for burner and also diesel engine. However, no technical data or report revealed through the use of that invention on the engine/ burner (The technical details explaining the said invention is discussed in chapter 2).

Therefore, this project aims to design and develop the real-time emulsion fuel production system (RTES) specifically for the application of the diesel electric generator. The diesel electric generator is mostly running on constant speed and load. Thus it is suitable to be applied with the RTES concept. There are four objectives in the project:

1. To investigate the engine performance and emission of a single cylinder diesel electric generator fuelled with surfactant added emulsion fuel under various water percentages.
2. To investigate the stability behaviour of emulsion fuel (without surfactant) under various mixing condition and types of mixer
3. To design and develop a working prototypes based on the RTES concept
4. To evaluate the physical properties of emulsion fuel and the engine performance and exhaust emission running with the RTES prototypes

## 1.4 Research Scope

Before proceeding with the main objective of the project, which is to design and develop the RTES, there are two additional objectives that need to be completed (first and second objective). The purpose of the first objective is to find the best water percentage in the emulsion fuel that can provide optimum engine performance and greener exhaust emission under various engine load conditions. This is because water content inside the emulsion fuel plays a major role in the effectiveness of the emulsion fuel [32]. The optimal water percentage in the emulsion fuel from this experiment will be used in the RTES prototype when running it on the engine. The measurements considered for the engine performance test include brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), in-cylinder pressure, maximum rate of heat release (MRHR) and maximum pressure rise rate (MPRR). As for the exhaust emissions, nitrogen oxides ($NO_X$), particulate matter (PM), carbon monoxide (CO), carbon dioxide ($CO_2$) and oxygen ($O_2$) are measured. As for the second objective, different mixing condition/ mixer were tested to mix water and diesel without the existence of surfactant and the resulting emulsion is analysed based on their fuel characteristics and stability period. The reason is to identify the best method/ mixing condition in forming emulsion fuel that have the longest stability period. The findings are used as a reference to generate the conceptual design in the design process of the RTES. The third objective is the core of the research which is the design and development process. The design process include: generating conceptual designs, design evaluation and generation, final conceptual design, engineering analysis and engineering drawing. In engineering analysis, flow simulation analysis is conducted using Solid Work Flow Simulation 2013, to predict only the flow pattern, maximum pressure and flowrate. The design of the RTES is based on the configuration and dimension of the single cylinder, natural aspirated diesel electric generator. As for the last objective, RTES prototype is evaluated through its physical properties of the emulsion fuel produced by said device. This data is crucial to be identified as it may affect the combustion of the engine. RTES prototype is further evaluated through the analysis of the engine performance and exhaust emission testing using the prototype.

## 1.5 Thesis Outline

The thesis consists of seven chapters which include introduction, literature review, methodology, emulsion fuel experiment, design and develop process, RTES experiment and conclusion and recommendation respectively. The description of each chapter is given below.

Chapter 2 covers the literature studies regarding the emulsion fuel especially the impact of emulsion fuel on the engine performance and emission, and revealing the micro-explosion phenomena studies and how it affect to the engine. Related mixing device which widely used in industry for liquids mixing application and related emulsification machine are reviewed in detail.

Chapter 3 covers the experimental setup for engine testing. The specifications and functions of every measuring machines / devices in the experiment are reported. In addition, all the procedures to conduct the experiment are also being described in this chapter.

Chapter 4 covers the engine testing experiment fuelled with emulsion fuel with the surfactant added under varies water percentage. The effect of emulsion fuel especially on different water percentage to the engine and makes comparison with the neat diesel is discussed in detail. Plus, the experimental study for the stability period of emulsion also included in this chapter.

Chapter 5 covers the design and development process of the RTES. The steps of the design process from identifying objectives until the fabrication process is clearly shown in this chapter.

Chapter 6 discussed the two experimental works conducted to evaluate the RTES prototype which include; dispersed water droplet observation and measurement and the engine performance and exhaust emission. RTES is tested fuelled with three different fuels which are: water and diesel only, water with surfactant added and diesel, and only diesel.

Chapter 7 covers the conclusion of the work and listed the recommendation for the improvement of the device and future study.

## REFERENCES


1. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, “IPCC, 2007: Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,” United Kingdom and New York, USA., 2007.
2. T. Barker, “Climate Change 2007 : An Assessment of the Intergovernmental Panel on Climate Change,” no. November, pp. 12–17, 2007.
3. A. Srivastava and R. Prasad, “Triglycerides-based diesel fuels,” *Renew. Sustain. Energy Rev.*, vol. 4, no. 2, pp. 111–133, Jun. 2000.
4. N. Kumar and U. Khare, “Use of macro-emulsion of vegetable oil in compression ignition engine,” *SAE Pap.*, vol. 28–0040, 2004.
5. T. Tan, J. Lu, K. Nie, L. Deng, and F. Wang, “Biodiesel production with immobilized lipase: A review.,” *Biotechnol. Adv.*, vol. 28, no. 5, pp. 628–34, 2010.
6. K. R. Jegannathan, S. Abang, D. Poncelet, E. S. Chan, and P. Ravindra, “Production of Biodiesel Using Immobilized Lipase—A Critical Review,” *Crit. Rev. Biotechnol.*, vol. 28, pp. 253–264, 2008.
7. M. S. Kumar, J. Bellettre, and M. Tazerout, “The use of biofuel emulsions as fuel for diesel engines: a review,” *Proc. Inst. Mech. Eng. Part A J. Power Energy*, vol. 223, no. 7, pp. 729–742, Nov. 2009.
8. M. Nadeem, C. Rangkuti, K. Anuar, M. R. U. Haq, I. B. Tan, and S. S. Shah, “Diesel engine performance and emission evaluation using emulsified fuels stabilized by conventional and gemini surfactants,” *Fuel*, vol. 85, no. 14–15, pp. 2111–2119, Oct. 2006.
9. J. S. Basha and R. B. Anand, “An Experimental Study in a CI Engine Using Nanoadditive Blended Water–Diesel Emulsion Fuel,” *Int. J. Green Energy*, vol. 8, no. 3, pp. 332–348, Apr. 2011.

10. K. A. Subramanian and A. Ramesh, “Experimental Investigation on the use of Water Diesel Emulsion with Oxygen Enriched Air in a DI Diesel Engine,” *SAE Pap.*, vol. 2001–01–02, 2001.
11. M. Y. E. Selim and M. T. Ghannam, “Performance and Engine Roughness of a Diesel Engine Running on Stabilized Water Diesel Emulsion,” *SAE Pap.*, vol. 2007–24–01, 2007.
12. A. Bertola, R. Li, and K. Boulouchos, “Influence of Water-Diesel Fuel Emulsions and EGR on Combustion and Exhaust Emissions of Heavy Duty DI-Diesel Engines Equipped with Common-Rail Injection System,” *SAE Pap.*, vol. 2003–01–31, 2003.
13. M. A. A. Nazha, H. Rajakaruna, and S. A. Wagstaff, “The Use of Emulsion , Water Induction and EGR for Controlling Diesel Engine Emissions,” *SAE Pap.*, vol. 2001–01–19, 2001.
14. R. Udayakumar, S. Sundaram, and S. C. Johnson, “Reduction of NOx Emissions by Water Injection in to the Inlet Manifold of a DI Diesel Engine,” *SAE Pap.*, vol. 2003–01–02, 2003.
15. X. Tauzia, A. Maiboom, and S. R. Shah, “Experimental study of inlet manifold water injection on combustion and emissions of an automotive direct injection Diesel engine,” *Energy*, vol. 35, no. 9, pp. 3628–3639, Sep. 2010.
16. F. Bedford, C. Rutland, P. Dittrich, A. Raab, and F. Wirbeleit, “Effects of Direct Water Injection on DI Diesel Engine Combustion,” *SAE Pap.*, vol. 2000–01–29, pp. 1–10, 2000.
17. M. A. Psota, W. L. Easley, T. H. Fort, and A. M. Mellor, “Water Injection Effects on NO x Emissions for Engines Utilizing Diffusion Flame Combustion,” *SAE Pap.*, vol. 971657, 1997.
18. W. M. Yang, H. An, S. K. Chou, K. J. Chua, B. Mohan, V. Sivasankaralingam, V. Raman, A. Maghbouli, and J. Li, “Impact of emulsion fuel with nano-organic additives on the performance of diesel engine,” *Appl. Energy*, vol. doi.org/10, Mar. 2013.
19. M. Christensen and B. Johansson, “Homogeneous Charge Compression Ignition with Water Injection,” *SAE Pap.*, vol. 1999–01–01, 1999.
20. M. S. Kumar, J. Bellettre, and M. Tazerout, “Investigations on a CI Engine Using Animal Fat and Its Emulsions With Water and Methanol as Fuel,” *SAE Pap.*, vol. 2005–01–17, 2005.

21. T. Kadota and H. Yamasaki, “Recent advances in the combustion of water fuel emulsion,” *Prog. Energy Combust. Sci.*, vol. 28, no. 5, pp. 385–404, Jan. 2002.
22. F. Y. Hagos, a. R. a. Aziz, and I. M. Tan, “Water-in-diesel emulsion and its micro-explosion phenomenon-review,” in *Communication Software and Networks (ICCSN), 2011 IEEE 3rd International Conference on*, 2011, pp. 314–318.
23. A. Alahmer, J. Yamin, A. Sakhrieh, and M. a. Hamdan, “Engine performance using emulsified diesel fuel,” *Energy Convers. Manag.*, vol. 51, no. 8, pp. 1708–1713, Aug. 2010.
24. V. N. Antonov, “Features of Preparation of Water-Fuel Emulsions for Diesel Engines,” *Chem. Technol. Fuels Oils*, vol. 19, no. 11–12, pp. 606–609, 1983.
25. A. Lif and K. Holmberg, “Water-in-diesel emulsions and related systems.,” *Adv. Colloid Interface Sci.*, vol. 123–126, no. 2, pp. 231–9, Nov. 2006.
26. R. S. S. and M. F. J. Schramm, “Bitumen / Water Emulsions as Fuels for High- Speed CI Engines Preliminary Investigations,” *SAE Pap.*, vol. 2003–01–31, 2003.
27. P. Sherman, *Encyclopedia of Emulsion Technology*, Becher, P. New York: Dekker, 1983.
28. P. Becher (Ed), *Encyclopedia of Emulsion Technology*, vol. 2. New York: Basic Theory, 1983.
29. J. Jiao and D. J. Burgess, “Rheology and Stability of Water-in-Oil-in Water Multiple Emulsions Containing Span 83 and Tween 80,” *AAPS PharmSci*, vol. 5(1), pp. 62–73, 2003.
30. A. K. Hasannuddin, A. M. Ithnin, M. Zahari, S. S. Mohd, A. B. Aiman, S. a. Aizam, and J. Y. Wira, “Stability Studies of Water-in-Diesel Emulsion,” *Appl. Mech. Mater.*, vol. 663, pp. 54–57, Oct. 2014.
31. E. Wiliam, *U.S Patent No.7930998B2*, Kanagawa: United State Patent, 2011.
32. A. M. Ithnin, H. Noge, H. Abdul Kadir, and W. Jazair, “An overview of utilizing water-in-diesel emulsion fuel in diesel engine and its potential research study,” *J. Energy Inst.*, vol. 87, no. 4, pp. 273–288, Nov. 2014.
33. M. E. A. Fahd, Y. Wenming, P. S. Lee, S. K. Chou, and C. R. Yap, “Experimental investigation of the performance and emission characteristics

of direct injection diesel engine by water emulsion diesel under varying engine load condition," *Appl. Energy*, vol. 102, pp. 1042–1049, Feb. 2013.

34. B. D. Hsu, "Combustion of Water-in-Diesel Emulsion in an Experimental Medium Speed Diesel Engine," *SAE Pap.*, vol. 860300, 1986.

35. T. Miyauchi, Y. Mori, and T. Yamaguchi, "Effect of steam addition on N O formation," *Symp. Combust.*, vol. 18, no. 1, pp. 43–51, Jan. 1981.

36. T. Murayama, "Experimental Reduction of N O x , Smoke , and BSFC in a Diesel Engine Using Uniquely Produced Water," *SAE Pap.*, vol. 780224, 1979.

37. H. Sheng, L. Chen, and C. Wu, "The Droplet Group Micro-Explosions in W / O Diesel Fuel Emulsion Sprays," *SAE Pap.*, vol. 950855, no. 412, 1995.

38. M. Abu-Zaid, "Performance of single cylinder, direct injection Diesel engine using water fuel emulsions," *Energy Convers. Manag.*, vol. 45, no. 5, pp. 697–705, Mar. 2004.

39. H. Transfer and E. Science, "An Experimental Investigation of the Burning Chracteristic of Water-Oil Emulsions," *Int. Comm. HeatMass Transf.*, vol. 23, no. 6, pp. 823–834, 1996.

40. M. Y. E. Selim and M. T. Ghannam, "Combustion Study of Stabilized Water-in-Diesel Fuel Emulsion," *Energy Sources, Part A Recover. Util. Environ. Eff.*, vol. 32, no. 3, pp. 256–274, Nov. 2009.

41. A. De Vita, "Multi-Cylinder D. I. Diesel Engine Tests with UnstabiHzed Emulsion of Water and Ethanol in Diesel Fuel," *SAE Pap.*, vol. 890450, 1989.

42. J. I. Ghojel and X.-T. Tran, "Ignition Characteristics of Diesel−Water Emulsion Sprays in a Constant-Volume Vessel: Effect of Injection Pressure and Water Content," *Energy & Fuels*, vol. 24, no. 7, pp. 3860–3866, Jul. 2010.

43. J. E. Dec, "A Conceptual Model of DI Diesel Combustion Based on Laser-Sheet Imaging," *SAE Pap.*, vol. 970873, 1997.

44. F. L. Dryer, "Water addition to practical combustion systems, concepts and application," *Symp. Combust.*, vol. 16, no. 1, pp. 279–295, 1976.

45. A. B. Koc and M. Abdullah, "Performance and NOx emissions of a diesel engine fueled with biodiesel-diesel-water nanoemulsions," *Fuel Process. Technol.*, vol. 109, pp. 70–77, Oct. 2012.

46. C. W. Coon, "Multi-Cylinder Diesel Engine Tests with Unstabilized Water-in-Fuel Emulsions," *SAE Pap.*, vol. 810250, pp. 21–33, 1981.

47. M. Tsukahara and Y. Yoshimoto, “Influence of Emulsified Fuel Properties on the Reduction of BSFC in a Diesel Engine,” *SAE Pap.*, vol. 891841, 1989.

48. X. Cui, A. Helmantel, V. Golovichev, and I. Denbratt, “Combustion and Emissions in a Light-Duty Diesel Engine Using Diesel-Water Emulsion and Diesel-Ethanol Blends,” *SAE Pap.*, vol. 2009–01–26, 2009.

49. C.-Y. Lin and K.-H. Wang, “The fuel properties of three-phase emulsions as an alternative fuel for diesel engines,” *Fuel*, vol. 82, no. 11, pp. 1367–1375, Jul. 2003.

50. C.-Y. Lin and K.-H. Wang, “Diesel engine performance and emission characteristics using three-phase emulsions as fuel,” *Fuel*, vol. 83, no. 4–5, pp. 537–545, Mar. 2004.

51. A. Farfaletti, C. Astorga, G. Martini, U. Manfredi, A. Mueller, M. Rey, G. De Santi, A. Krasenbrink, and B. R. Larsen, “Effect of water/fuel emulsions and a cerium-based combustion improver additive on HD and LD diesel exhaust emissions.,” *Environ. Sci. Technol.*, vol. 39, no. 17, pp. 6792–9, Sep. 2005.

52. K. A. Subramanian, “A comparison of water–diesel emulsion and timed injection of water into the intake manifold of a diesel engine for simultaneous control of NO and smoke emissions,” *Energy Convers. Manag.*, vol. 52, no. 2, pp. 849–857, Feb. 2011.

53. K. A. Subramanian and I. I. T. Madras, “Use of Hydrogen Peroxide to Improve the Performance and Reduce Emissions of a CI Engine Fuelled with Water Diesel Emulsions,” *SAE Pap.*, vol. 2008–01–06, 2008.

54. J.-K. Park, J.-M. Oh, H.-I. Kim, C.-H. Lee, and K.-H. Lee, “Combustion Characteristics of MDO and MDO Emulsion in Automotive Diesel Engine,” *Trans. Korean Soc. Mech. Eng. B*, vol. 36, no. 9, pp. 945–951, Sep. 2012.

55. S. Henningsen, “Influence of the Fuel Injection Equipment on NOx Emissions and Particulates on a Large Heavy-Duty Two-Stroke Diesel Engine Operating on Water-in- Fuel Emulsion,” *SAE Pap.*, vol. 941783, 1994.

56. S. Ganesan and A. Ramesh, “Investigation on the use of Water - Diesel Emulsion in a L P G - Diesel Dual Fuel Engine,” *SAE Pap.*, vol. 2001–28–00, pp. 223–230, 2001.

57. A. Maiboom and X. Tauzia, “NOx and PM emissions reduction on an automotive HSDI Diesel engine with water-in-diesel emulsion and EGR: An experimental study,” *Fuel*, vol. 90, no. 11, pp. 3179–3192, Nov. 2011.

58. J. M. Ballester, N. Fueyo, and C. Dopazo, “Combustion characteristics of heavy oil-water emulsions,” *Fuel*, vol. 75, no. 6, pp. 695–705, May 1996.

59. K. P. Duffy and A. M. Mellor, “Further Developments on a Characteristic Time Model for NOx Emissions from Diesel Engines,” *SAE Pap.*, vol. 982460, 1998.

60. M. Y. E. Selim and S. M. S. Elfeky, “Effects of diesel / water emulsion on heat flow and thermal loading in a precombustion chamber diesel engine,” *Appl. Therm. Eng.*, vol. 21, no. x, pp. 1565–1582, 2001.

61. W. B. Fu, L. Y. Hou, L. Wang, and F. H. Ma, “A unified model for the micro-explosion of emulsified droplets of oil and water,” *Fuel Process. Technol.*, vol. 79, no. 2, pp. 107–119, Oct. 2002.

62. R. J. C. M.A.A. Nazha, “Effect of water content on pollutant formation in a burning spray of water-in-diesel fuel emulsion,” *Symp. Combust.*, vol. pp.2001–20, 1984.

63. K. Park, I. Kwak, and Seungmook Oh, “The Effect of Water Emulsified Fuel on a Motorway - Bus Diesel Engine Aparatus and Method,” *KSME International Journal.*, vol. 18, no. 11, pp.2049-2057, 2004.

64. R. Ochoterena, A. Lif, M. Nydén, S. Andersson, and I. Denbratt, “Optical studies of spray development and combustion of water-in-diesel emulsion and microemulsion fuels,” *Fuel*, vol. 89, no. 1, pp. 122–132, Jan. 2010.

65. A. Lif, M. Stark, M. Nydén, and K. Holmberg, “Fuel emulsions and microemulsions based on Fischer–Tropsch diesel,” *Colloids Surfaces A Physicochem. Eng. Asp.*, vol. 354, no. 1–3, pp. 91–98, Feb. 2010.

66. M. S. So, “Experimental Investigation of the Effects of Water Addition on the Exhaust Emissions of a Naturally Aspirated , Liquefied-Petroleum-Gas-Fueled Engine,” *Energy & Fuels*, vol. 19, no. 960033, pp. 1468–1472, 2005.

67. E. Tzirakis, G. Karavalakis, P. Schinas, D. Korres, D. Karonis, S. Stournas, and F. Zannikos, “Diesel-water Emulsion Emissions and Performance Evaluation in Public Buses in Attica Basin,” *SAE Pap.*, vol. 2006–01–33, no. 2006–01–3398, 2006.

68. John B. Heywood, *Internal combustion engine fundamentals*. New York: McGraw Hill Book Company, 1988.

69. V. M. Ivanov and P. I. Nefedov, “Experimental Investigation of the Combustion Process in Natural and Emulsified Fuels,” *NASA Tech. Transla*, vol. TIF-258, 1965.

70. H. Watanabe, Y. Suzuki, T. Harada, Y. Matsushita, H. Aoki, and T. Miura, “An experimental investigation of the breakup characteristics of secondary atomization of emulsified fuel droplet,” *Energy*, vol. 35, no. 2, pp. 806–813, Feb. 2010.

71. H. Watanabe, Y. Matsushita, H. Aoki, and T. Miura, “Numerical simulation of emulsified fuel spray combustion with puffing and micro-explosion,” *Combust. Flame*, vol. 157, no. 5, pp. 839–852, 2010.

72. M. Tsue, H. Yamasaki, T. Kadota, and D. Segawa, “Effect of Gravity on Onset of Microexplosion for an Oil-in-Water Emulsion Droplet,” *Twenty-Seventh Symp. Combust. Combust. Inst.*, pp. 2587–2593, 1998.

73. I. C. Jeong and K. H. Lee, “Auto-Ignition and Micro-Explosion Behaviour of Droplet Array of Water-in-Fuel Emulsion,” *Int. J. Automot. Technol.*, vol. 9, no. 6, pp. 735–740, 2008.

74. R. Ocampo-Barrera, R. Villasenor, and A. Diego-Marin, “An experimental study of the effect of water contents on combustion of heavy fuel oil/water emulsion droplets,” *Combust. Flame*, vol. 126, no. 4, pp. 1845–1855., 2001.

75. M. Abu-Zaid, “An experimental study of the evaporation characteristics of emulsified liquid droplets,” *Heat Mass Transf.*, vol. 40, pp. 737–741, Jun. 2004.

76. E. Mura, P. Massoli, C. Josset, K. Loubar, and J. Bellettre, “Study of the micro-explosion temperature of water in oil emulsion droplets during the Leidenfrost effect,” *Exp. Therm. Fluid Sci.*, vol. 43, pp. 63–70, Nov. 2012.

77. H. Tanaka, T. Kadota, D. Segawa, S. Nakaya, and H. Yamasaki, “Effect of Ambient Pressure on Micro-Explosion of an Emulsion Droplet Evaporating on a Hot Surface,” *JSME Int. J. Ser. B*, vol. 49, no. 4, pp. 1345–1350, 2006.

78. M. Fuchihata, S. Takeda, and T. Ida, “Observation of Micro-Explosions in Spray Flames of Light Oil-Water Emulsions.,” *Trans. Japan Soc. Mech. Eng. B*, vol. 66, pp. 1544–1549, 2000.

79. Y. Zeng and C. F. Lee, “Modeling droplet breakup processes under micro-explosion conditions,” *Proc. Combust. Inst.*, vol. 31, no. 2, pp. 2185–2193, Jan. 2007.

80. N. J. Marrone, I. M. Kennedy, and F. L. Dryer, “Internal Phase Size Effects on Combustion of Emulsions,” *Combust. Sci. Technol.*, vol. 33, pp. 299–307, 1983.

81. E. Mura, C. Josset, K. Loubar, G. Huchet, and J. Bellettre, “Effect of Dispersed Water Droplet Size in Microexplosion Phenomenon Forwater in Oil Emulsion,” *At. Sprays*, vol. 20, no. 9, pp. 791–799, 2010.

82. J. W. Park, K. Y. Huh, and K. H. Park, “Experimental Study on the Combustion Characteristics of Emulsified Diesel in a RCEM,” *Seoul 2000 FISITA World Automot. Congr.*, no. 6, pp. 1–6, 2000.

83. Y. Morozumi and Y. Saito, “Effect of Physical Properties on Microexplosion Occurrence in Water-in-Oil Emulsion Droplets,” *Energy & Fuels*, vol. 24, no. 3, pp. 1854–1859, Mar. 2010.

84. J. Zhang, S. Xu, and W. Li, “High shear mixers: A review of typical applications and studies on power draw, flow pattern, energy dissipation and transfer properties,” *Chem. Eng. Process. Process Intensif.*, vol. 57–58, pp. 25–41, Jul. 2012.

85. “Emulsions and Emulsification,” *Part. Sci. Drug Dev. Serv.*, 2009.

86. C. Ross, “*Overview of Mixing Technologies for the Production of Low to High Viscosity Adhesives Overview of Mixing Technologies for the Production of Low to High Viscosity Adhesives*.” (Brochure). Ross White Paper: Charles Ross

87. C. Ross, “*The Art of High Shear Mixing*,” (Brochure). Ross White Paper: Charles Ross

88. A. S. Badday, A. Z. Abdullah, K. T. Lee, and M. S. Khayoon, “Intensification of biodiesel production via ultrasonic-assisted process: A critical review on fundamentals and recent development,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 7, pp. 4574–4587, Sep. 2012.

89. J. Ji, J. Wang, Y. Li, Y. Yu, and Z. Xu, “Preparation of biodiesel with the help of ultrasonic and hydrodynamic cavitation.,” *Ultrasonics*, vol. 44 Suppl 1, pp. e411–4, Dec. 2006.

90. R. V. C. V.A. Atiemo-Obeng, *Rotor–stator mixing devices Handbook of Industrial Mixing: Science and Practice*. New Jersey: John Wiley & Sons, Inc, 2004.

91. A. Ghanem, T. Lemenand, D. Della Valle, and H. Peerhossaini, “Static mixers: Mechanisms, applications, and characterization methods – A review,” *Chem. Eng. Res. Des.*, vol. 92, no. 2, pp. 205–228, Feb. 2014.

92. N. Hsue c. Tsien, Livingston.(1978) *U.S Patent No.4087862,* Germany :United State Patent

93. A. Todorovic, (2011) *U.S Patent No.* 7938934B2, Germany :United State Patent .

94. A. Kessler, (1996) *U.S Patent No.* 5542379, Moenchaltorf Switzerland :United State Patent .

95. G. Kunz, (1990) *U.S Patent No.* 4938606, Switzerland :United State Patent .

96. Mohd Farid Muhamad Said, “Performance and Emission Tests of Biodiesel Fuels using a Conventional Diesel Engine,” Universiti Teknologi Malaysia, 2006.

97. John B. Heywood, *Internal Combustion Engine Fundamental*, Hill Serie. New York: McGraw-Hili, Inc., 1986.

98. “Engine Power Test Code Spark Ignition and Compression Ignition—Net Power Rating,” *SAE Int. Surf. Veh. Stand.*, vol. SAE J1349, 2004.

99. D. H. Qi, C. Bae, Y. M. Feng, C. C. Jia, and Y. Z. Bian, “Combustion and emission characteristics of a direct injection compression ignition engine using rapeseed oil based micro-emulsions,” *Fuel*, vol. 107, pp. 570–577, May 2013.

100. K.-B. Nguyen, T. Dan, and I. Asano, “Combustion, performance and emission characteristics of direct injection diesel engine fueled by Jatropha hydrogen peroxide emulsion,” *Energy*, pp. 1–8, Jul. 2014.

101. W. Jazair, S. Kubo, M. Takayasu, T. Yatsufusa, and Y. Kidoguchi, “Performance and emission characteristics of a diesel engine fueled by rapeseed oil bio-fuel,” *J. Mek.*, no. 33, pp. 32–39, 2011.

102. M. T. Ghannam and M. Y. E. Selim, “Stability Behavior of Water-in-Diesel Fuel Emulsion,” *Pet. Sci. Technol.*, vol. 27, no. 4, pp. 396–411, Mar. 2009.

103. A. K. Hasannudin, M. I. Ahmad, M. Zahari, S. S. Mohd, A. B. Aiman, S. A. Aizam, and J. Wira, “Stability Studies of Water-in-Diesel Emulsion,” *Period. Appl. Mech. Mater.*, vol. 663, 2013.

104. C.-Y. Lin and L.-W. Chen, “Comparison of fuel properties and emission characteristics of two- and three-phase emulsions prepared by ultrasonically

vibrating and mechanically homogenizing emulsification methods," *Fuel*, vol. 87, no. 10–11, pp. 2154–2161, Aug. 2008.

105. Z. G. Guo, Q. Q. Yin, and S. R. Wang, "Bio-Oil Emulsion Fuels Production Using Power Ultrasound," *Adv. Mater. Res.*, vol. 347–353, pp. 2709–2712, Oct. 2011.

106. Yanmar Ltd"Yanmar Service Manual L40-L100 Air Cooled LA Series."(brochure), 2004.

107. T. Edition, *Strategies for Product Design.*, (Third ed. )John Wiley and Sons, Ltd:Wiley.2005.

108. A. Utomo, M. Baker, and a. W. Pacek, "The effect of stator geometry on the flow pattern and energy dissipation rate in a rotor–stator mixer," *Chem. Eng. Res. Des.*, vol. 87, no. 4, pp. 533–542, Apr. 2009.

109. Koyo Sealing Techno Co., Ltd"Oil seals & o-rings." (Brochure):The Timken Corporation, 2011