



AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING

**EXPERIMENTAL STUDY OF RECYCLING
LUBRICATING OIL TO BE USED AS A DIESEL ENGINE
FUEL**

By

Mohamed Tarek Hamouda Abd El Aal Mahmoud

M.Sc. Mechanical Power Engineering Department, 2014

**A Thesis submitted in accordance with the
Requirements for the Degree of Doctor of Philosophy**

Under Supervision of

Prof. Dr. Gamal Mosaad Hennes

Professor

Mechanical Power Department
Faculty of Engineering
Ain Shams University

Prof. Dr. Mahmoud Mohamed Kamal

Professor

Mechanical Power Department
Faculty of Engineering
Ain Shams University

Dr. Ahmed Mohamed Taher Alaa

Assistant Professor

Mechanical Power Department
Faculty of Engineering
Ain Shams University

Cairo

2019

Examiner Committee

The undersigned certify that they have read and recommended to the faculty of engineering, Ain Shams University for acceptance a thesis entitled by " Experimental Study of Recycling Lubricating Oil to be used as a Diesel Engine Fuel ", submitted by Mohamed Tarek Hamouda Abd El Aal, in partial fulfilment of the requirements for the Degree of Doctor of Philosophy in Mechanical Power Engineering.

Name	Signature
1. Prof. Dr. Sameh Maher Metwally Faculty of Engineering Helwan University – Mataria Branch	-----
2. Prof. Dr. Adel Abd El Malek El Ahwany Faculty of Engineering Ain Shams University	-----
3. Prof. Dr. Gamal Mosaad Hennes Faculty of Engineering Ain Shams University	-----
4. Prof. Dr. Mahmoud Mohamed kamal Faculty of Engineering Ain Shams University	-----

STATEMENT

This dissertation is submitted to Ain Shams University in fulfilment of the requirements degree of Doctor of Philosophy.

The work included in this thesis was made by the author during the period from February 2015 to July 2018 at the Mechanical Power Engineering Department, Ain Shams University.

No part of this thesis has been submitted for degree or qualifications at any other university or institute.

Date :

Signature : _____

Name : Mohamed Tarek Hamouda Abd El Aal

RESEARCHER DATA

Name : Mohamed Tarek Hamouda Abd El Aal
Date of Birth : 09/12/1986
Place of Birth : Giza - Egypt
Last Academic Degree : Master of Science in Mechanical Engineering
Field of Specialization : Mechanical Engineering
University Issued the Degree : Ain Shams University
Date of Issued degree : 2014
Current Job : Mechanical Engineer

ABSTRACT

The comparative spray characteristics of petroleum diesel, RWLO (Recycled Waste Lubricating Oil)-diesel and RWLO-diesel-kerosene blends were reported by using diesel fuel injector and tested inside a pressurized injector chamber. Spray penetration increased by about 30 % and spray angle decreased by about 47 % when compared to W0 upon using 40 % by volume RWLO (W40). Using kerosene as an additive showed an opposite behaviour on the spray characteristics. The percentage by which kerosene was added as an additive was determined according to the spray behavior by adding kerosene gradually until reaching to the right mixture

Using RWLO as a fuel up to 40 % of the mixture reduced the brake thermal efficiency by about 12 % while the brake specific fuel consumption, unburned hydrocarbons emissions and carbon monoxide emissions increased by about 21, 52 and 22 % respectively when compared to pure diesel.

. Increasing the content of kerosene up to 30% in the mixture reduced the brake specific fuel consumption, unburned hydrocarbons and carbon monoxide emissions by about 12, 13 and 18% respectively while the brake thermal efficiency increased by about 12 % when compared to W40.

The injection pressure was raised from 165 bar to 193 bar in order to eliminate the undesirable effect of RWLO when used as a fuel and it was not possible to raise the injection pressure further more due to technical difficulties regarding the engine. Increasing the injection pressure to 193 bar enhanced the engine performance by increasing the BTE by about 10 % and reducing BSFC, CO and HC emissions by about 9, 15, 19 % respectively when compared to 165 bar injection pressure.

Cerium oxide nanoparticles were dispersed in a mixture of RWLO and diesel fuel. The BTE improved by about 5% with a reduction in BSFC, carbon monoxide emissions (CO) and unburned hydrocarbons emissions (HC) by about 5, 4, 5 % respectively while adding cerium oxide nanoparticles as an additive to when compared to W40.

Keywords: Recycled Waste Lubricating Oil – Kerosene - Cerium Oxide – Injection pressure

ACKNOWLEDGMENT

This thesis is the end of my journey in obtaining my degree of Doctor of Philosophy. This thesis has been kept on track and been seen through to completion with the support and encouragement of numerous people including my parents, my friends and colleagues. At the end of my thesis I would like to thank all those people who made this thesis possible and an unforgettable experience for me.

Foremost, I would like to express my sincere gratitude to my advisors Prof. Dr. Gamal Hennes, Prof. Dr. Mahmoud Mohamed and Dr. Ahmed Taher for their continuous support in my research, for their patience, enthusiasm, and immense knowledge.

Of course no acknowledgments would be complete without giving thanks to Eng. Hamdy Abd El Raof, Mr. Mostafa Ahmed Hassan, Eng. Azab shaban, Eng. Wael Ramadan and Eng. Tamer Kamal for their motivation and help.

Last but not the least; I would like to thank my family for supporting me spiritually during the thesis preparation.

TABLE OF CONTENTS

Statement -----	II
Researcher Data -----	III
Abstract -----	IV
Acknowledgment -----	V
Table of Contents -----	VI
List of Figures -----	X
List of Tables -----	XXI
Abbreviations -----	XXII
Nomenclature -----	XXIII

CHAPTER (1): INTRODUCTION

1.1. Background -----	1
1.2. Environmental impacts of improper disposal of waste oils -----	5
1.2.1. Effect of improper disposal of waste lubricating oil on living organisms -----	6
1.2.2. Waste Oil Biodegradation -----	7
1.3. Aim of the Present Research -----	7
1.4. Thesis Organization -----	10

CHAPTER (2): LITERATURE REVIEW

2.1. Introduction -----	11
2.2. Waste Plastic Oil -----	11

2.2.1. Effect on Engine Performance when powered with Waste Plastic Oil -----	12
2.2.2. Effect on the Engine Emissions when powered with Waste Plastic Oil -----	14
2.3. Waste Cooking Oil -----	16
2.3.1. Effect on Engine Performance when powered with Waste Cooking Oil -----	16
2.3.2. Effect on the Engine Emissions when powered with Waste Cooking Oil -----	18
2.4. Waste Lubricating Oil -----	20
2.4.1. Effect on Engine Performance when powered with Waste Lubricating Oil -----	21
2.4.2. Effect on the Engine Emissions when powered with Waste Lubricating Oil -----	21
2.5. Spray Characteristics -----	25
2.6. Kerosene Addition -----	39
2.7. Injection Pressure -----	42
2.8. Nano Particles Addition -----	44
2.9. The Thesis Objectives -----	63

CHAPTER (3): EXPERIMENTAL EQUIPMENTS AND PROCEDURES

3.1. Introduction -----	64
3.2. RWLO Production Procedure -----	65
3.3. Waste Lubricating oil Physical properties -----	65
3.3.1. Oil Analysis -----	65

3.3.2. Viscosity Measurement -----	65
3.3.3. Bomb Calorimeter -----	66
3.3.4. Flash Point and Fire Point -----	68
3.3.5. Cetane Index Calculation (ASTM D4737-10) -----	69
3.4. Dispersion of Nano Particles (CeO ₂) -----	71
3.5. Experimental Equipment -----	73
3.5.1. Pressurized Injector Chamber -----	73
3.5.2. Nozzle Tester -----	79
3.5.3. Engine -----	80
3.5.4. Exhaust Gas Analyser -----	82
3.6. Assessment of the accuracy of the measured variables -----	82

CHAPTER (4): EXPERIMENTAL RESULTS AND DISCUSSION

4.1. Waste Lubricating oil Physical properties -----	84

4.1.1. Oil Analysis -----	84
4.1.2. Viscosity -----	86
4.1.3. Calorific Value -----	86
4.1.4. Flash Point and Fire Point -----	89
4.1.5. Cetane Number Index -----	91
4.2. Comparative Spray and Flame Analysis -----	92
4.3. Brake Specific Fuel Consumption (BSFC) -----	98
4.4. Brake Thermal Efficiency (BTE) -----	104

4.5. Exhaust Gas Temperature (EGT) -----	110
4.6. Unburned Hydrocarbons emissions (HC) -----	115
4.7. Carbon Dioxide emissions (CO ₂) -----	121
4.8. Carbon Monoxide emissions (CO) -----	125
4.9. Nitrogen Oxide emissions (NO _x) -----	131
4.10. Engine Performance Optimization -----	136
CHAPTER (5): CONCOLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK	
5.1. Conclusions -----	139
5.2. Recommendations for Future Work -----	140
REFERENCES -----	141

LIST OF FIGURES

Figure 1-1: Oil consumption by region -----	2
Figure 1-2: Global natural gas consumption by region -----	2
Figure 1-3: Coal consumption by region -----	3
Figure 1-4: Major oil trade movements 2016 (millions Tonnes) -----	3
Figure 1-5: Major Natural gas trade movements 2016 -----	4
Figure 1-6: Shares of global primary energy (%) -----	4
Figure 1-7: Crude oil prices 1970-2016 (US dollars per barrel) -----	5
Figure 1-8 : Some impacts of improper disposal used oil to the environment of used oil on humans, animals and environment -----	8
Figure 1-9: The effect of improper disposal of used oil on aquatic life -----	9
Figure 1-10 : Biodegradation process for used oil -----	9
Figure 2-1: Variation of cylinder pressure versus crank angle 2011) -----	12
Figure 2-2: Variation of ignition delay versus load -----	13
Figure 2-3: Variation of cylinder peak pressure versus load -----	13
Figure 2-4: Effect of the DLF on engine torque -----	22
Figure 2-5: Effect of the DLF on the brake mean effective pressure versus engine speed -----	22
Figure 2-6: Variation of brake thermal efficiency versus engine speed -----	23
Figure 2-7: Distillation curves of the DLF and a typical diesel -----	23
Figure 2-8: Variation of brake specific fuel consumption versus engine speed --	24

Figure 2-9: Variations of CO emissions versus engine speed -----	24
Figure 2-10: Variations of NO _x emissions versus engine speed -----	26
Figure 2-11: Spray images of B0 (a), B5 (b), B10 (c), B15 (d), B20 (e) and B25 (f) respectively -----	26
Figure 2-12: Experimental and numerical results of spray jet at 800 rev/min pump speed for diesel (left) and high viscosity fuel (right) -----	27
Figure 2-13: Experimental and numerical results of spray jet at 1100 rpm pump speed for diesel (left) and high viscous fuel (right) -----	27
Figure 2-14: Diesel spray development at 500 rev/min -----	28
Figure 2-15: High viscous fuel spray development at 500 rev/min -----	28
Figure 2-16: Spray evolution for injection pressure of 100 MPa under different ambient pressures -----	30
Figure 2-17: Spray tip penetration of different fuels -----	31
Figure 2-18: Spray angle of different fuels -----	31
Figure 2-19: Spray morphology (time in ms ASOI) of B0 and B100 at 50 MPa injection pressures -----	32
Figure 2-20: Spray tip penetration of B0 and B100 under different injection pressures -----	33
Figure 2-21: Aerodynamic spray cone angle of B0 and B100 under different injection pressures -----	33
Figure 2-22:. Counter of vapour phase fraction for B0 and B100 for various injection pressures -----	35
Figure 2-23: Counter of Turbulence Kinetic Energy (TKE) for B0 and B100 at various injection pressures -----	36

Figure 2-24: Sauter mean diameter variation versus various injection pressures - --	37
Figure 2-25: Derived diameter parameters of Dv10, Dv50, and Dv90 for different fuels with injection pressure: (a) Dv10, (b) Dv50, and (c) Dv90 (axial distance: 8 cm, radius distance: 0 cm, injection duration: 1.5 ms) -----	37
Figure 2-26: Variation of specific fuel consumption as a function of rated load ----	40
Figure 2-27: Spray images of diesel and high viscous fuel under 100 MPa and 200 MPa injection pressures -----	43
Figure 2-28: Variation of ignition delay versus BMEP -----	47
Figure 2-29: Hot-plate evaporation characteristics of the tested fuels ----- --	48
Figure 2-30: Variation of brake thermal efficiency and brake specific fuel consumption versus BMEP -----	48
Figure 2-31: Variation of nitrogen oxides and smoke opacity versus BMEP ----- -	50
Figure 2-32: Variation of hydrocarbons and carbon monoxide versus BMEP ----- -	51
Figure 2-33: Reaction mechanism of water with an alumina-coated aluminium particle -----	52
Figure 2-34a: The variation of the engine thermal efficiency and the brake specific fuel consumption versus load at 1300 rpm -----	53
Figure 2-34b: The variation of the engine thermal efficiency and the brake specific fuel consumption versus load at 1500 rpm -----	53
Figure 2-35a: The variation of smoke opacity versus load at 1300 rpm ----- ---	54
Figure 2-35b: The variation of smoke opacity versus load at 1500 rpm -----	54
Figure 2-36a: The variation of CO emissions versus load at 1300 rpm -----	55
Figure 2-36b: The variation of CO emissions versus load at 1500 rpm ----- -	56

Figure 2-37a: The variation of UHC emissions versus load at 1300 rpm -----	56

Figure 2-37b: The variation of UHC emissions versus load at 1500 rpm -----	57

Figure 2-38: Ignition probability of pure diesel -----	58

Figure 2-39: Ignition probability of Al (50 nm) + diesel fuel at hot plate temperatures of 708, 728, and 748 °C -----	58
Figure 2-40: Ignition probability of Al ₂ O ₃ (50 nm) + diesel fuel at hot plate temperatures of 708, 728, and 748 °C -----	59
Figure 2-41: Ignition probability of Al ₂ O ₃ (15 nm) + diesel fuel at hot plate temperatures of 708, 728, and 748 °C -----	59
Figure 3-1: Engler Viscometer -----	67
Figure 3-2: Bomb Calorimeter -----	67
Figure 3-3: Flash and fire point measurement -----	68
Figure 3-4: Estimate CCI based on density and 50 % recovery temperature -----	70
Figure 3-5: Corrections for deviations in density and 90 % recovery temperature -	70
Figure 3-6: Corrections for deviations in density 10 % and 90 % recovery temperature from average values -----	71
Figure 3-7: Sonic Vibrocell VC505 -----	72
Figure 3-8a: TEM image of nanoparticles at 12000x direct magnification -----	74
Figure 3-8b: TEM image of nanoparticles at 2000x direct magnification -----	74
Figure 3-8c: TEM image of nanoparticles at 12000x direct magnification -----	75
Figure 3-8d: TEM image of nanoparticles at 2500x direct magnification -----	75
Figure 3-8e: TEM image of nanoparticles at 15000x direct magnification -----	76

Figure 3-8f: TEM image of nanoparticles at 12000x direct magnification -----	76
Figure 3-9a: Before dispersing nanoparticles -----	77
Figure 3-9b: After dispersing nanoparticles -----	77
Figure 3-10: Pressurized Injector chamber -----	77
Figure 3-11a: Front view of the pressurized chamber -----	78
Figure 3-11b: Plan view of the pressurized chamber -----	78
Figure 3-11c: Side view of the pressurized chamber -----	79
Figure 3-12: Electrically operated nozzle tester -----	79
Figure 3-13: DEUTZ F2L-511 -----	80
Figure 3-14: LANCOM Series II gas analyser -----	82
Figure 4-1: Engler viscosity scale for diesel-RWLO blends -----	87
Figure 4-2: Percentage increase of Engler viscosity at various RWLO - diesel blends when compared to W0 -----	87
Figure 4-3: Engler viscosity scale for RWLO- kerosene blends -----	88
Figure 4-4: Percentage reduction of Engler viscosity at various RWLO - kerosene blends when compared to W0 -----	88
Figure 4-5: Closed cup method for measuring flash point -----	90
Figure 4-6: Open cup method for measuring flash and fire point -----	90
Figure 4-7: W0 spray development -----	93
Figure 4-8: W20 spray development -----	93
Figure 4-9: W40 spray development -----	93
Figure 4-10: W40K5 spray development -----	95