Development of an Alternative Fuel from Coal Tar and Its Treatment for the Environmental Protection

KARTIKA KUS HENDRATNA

(Degree)
博士（工学）

(Date of Degree)
2011-09-25

(Date of Publication)
2012-01-05

(Resource Type)
doctoral thesis

(Report Number)
甲5380

(URL)
https://hdl.handle.net/20.500.14094/D1005380

DOCTORAL DISSERTATION

DEVELOPMENT OF AN ALTERNATIVE FUEL FROM COAL TAR AND ITS TREATMENT FOR THE ENVIRONMENT PROTECTION

(石炭の代替燃料とその燃料が環境に与える影響に関する研究)

September 2011

KOBE UNIVERSITY
GRADUATE SCHOOL OF MARITIME SCIENCES

KARTIKA KUS HENDRATNA

DOCTORAL DISSERTATION

DEVELOPMENT OF AN ALTERNATIVE FUEL FROM COAL TAR AND ITS TREATMENT FOR THE ENVIRONMENT PROTECTION
(石炭の代替燃料とその燃料が環境に与える影響に関する研究)

By
Kartika Kus Hendratna
063W951W

SUBMITTED IN PARTIAL FULFILLNESS OF THE REQUIREMENT FOR THE DEGREE OF DOCTORAL IN ENGINEERING
AT
KOBE UNIVERSITY, GRADUATE SCHOOL OF MARITIME SCIENCES
KOBE, JAPAN
JULY 2011

KOBE UNIVERSITY
GRADUATE SCHOOL OF MARITIME SCIENCES

The undersigned hereby certify that it is have been read and recommend to the Graduate School of Maritime Sciences, Kobe University for the acceptance a dissertation entitled "Development of an Alternative Fuel from Coal and Its Treatment for Environment Protection (石炭の代替燃料とその燃料が環境に与える影響に関する研究)" by Kartika Kus Hendratna in partial fulfillment of the requirements for the degree of Doctor of Engineering

Date: September 2011

Research Supervisor: 藤田浩嗣
Professor Hirotsugu Fujita

Examining Committee: 福田勝哉
Professor Katsuya Fukuda

Tomohisa Dan
Associate Professor Tomohisa Dan

Haruo Mimura
Professor Haruo Mimura

Abstract

Energy sources can be classified into three groups; fossil, renewable, and fissile. Fossil fuels were formed many years ago and it is not renewable. The fossil energy sources are petroleum, coal, bitumen's, natural gas, oil products, and tar sands. The main fissile energy sources are uranium and thorium. The rapidly expanding use of coal in the twentieth century made it necessary to devise acceptable methods for coal analysis as alternative fuel with the goal of steady combustion as liquid fuel and its application in the maritime field. The research is conducted by using analyses of coal with various aspects of coal usage that finally it can be achieved in an environmentally acceptable manner. As a part of the multifaceted program of coal evaluation, new methods are continually being developed for the application of coal for alternative fuel as the substitute of C bunker heavy oil type for ship operational. Furthermore, proper interpretation of the data resulting from the experiments was combined with the data analysis from several of equipments analysis to gain a proper of data analysis. This research was designed as the alternative ways of coal application as liquid fuel that can be normally uses in the marine diesel engine. In specific objective, these researches were aimed to: (1) converting tar of coal to the coal liquid fuel using liquefaction process. (2) Preparing the system and supporting equipment for coal combustion. (3) Control of combustion for steady condition and setting combustion parameters. (4) Investigation of exhaust gas condition and particulate emitted from combustion at the steady combustion to increase the accuracy of the technique as well as the precision of the results. (5) Making a comparative relation of combustion with C bunker heavy fuel. (6) Designing a system and methods for decreasing the contents of harmful particles and emitted exhaust gas control by an update technology.

Coal is an extremely complex material and exhibits a wide range of physical properties. Coal is a solid, brittle, combustible, carbonaceous, rock formed by the decomposition and alteration of vegetation by compaction, temperature, and pressure. It is varies in color from brown to black and is usually stratified. It consists of more that 50% by weight and more than 70% by volume of carbonaceous material and it is primarily used as a solid fuel to produce heat by burning. The problem occurs when the formed fuel made from a low quality of coal. It produces carbon dioxide, a greenhouse gas, along with sulfur dioxide. The liquid gasification of coal will be an alternative of the coal application for more environmental friendly. Liquefaction of coal mainly divided into two big parts; direct liquefaction, and indirect liquefaction. One of the results from these processes known as tar will be analysis for its ability as the substitute of C bunker heavy oil.

In the other hand, the environment problems are arising while several of energy sources were explored and applied. It extremely gives many impacts to the environment. Main sources of pollution were derived from industrial sector, human living, as well as transportation for land and sea. As increasingly stringent controls are placed on land-based sources of atmospheric emissions, there is mounting pressure to bring ship emissions more closely within air quality policy across. Ship emissions have not been as tightly controlled as many land-based emission sources since the international trans-boundary context of shipping sector has posed specific difficulties to achieving progress in improving environmental performance. International Maritime Organization (IMO) as the main society in Maritime has issued many roles for the exhaust gas from ship operational. More specific, it controls the pollutants gases from ship such as; NOx, SOx, and other organic contents as well as particulate emission. Relating to this issued, the research must accommodate the rules for its safe application while main purposed is gained. Firstly, an experiment at the laboratory scale for both boiler and small diesel engine is urgently needed before the real application on board of ship.

The first steps of experiment uses for the system preparation, including a complex of combustion support systems and data analysis. A horizontal boiler with fresh water jacket system for cooling was applied. The support system such centrifuge pump, service tank, blower, fuel line, strainers, burner, and compressor were set up. High viscosity of liquid fuel was controlled by applying heating system (heaters) with a digital temperature control. When all preparation was completely done, testing using light fuel oil (A bunker fuel oil) was carried out.

The steady combustion of liquid coal fuel was gained by manual setting of burner for both the air and fuel supply control. The steady combustion was gain when the combustion tail was steady, which physically marked by the steady length of flame. Then, data sampling from four sample`s points in each centre of the angular tube segments were conducted for exhaust gas, particulate component, and temperature measurement. Coal fuel and soluble organic fraction components were treated in GC&MS. Gained data then compared with C bunker type of heavy oil.

The condition of combustion that needs an improvement or treatments, and exhaust components shows a critical amount from limitation of IMO caused the importance of a treatment. The modification of coal by mixing process with water as emulsion is decided as first treatment. The results show effectiveness emulsion on decreasing of concentration of the exhaust gas components, more steady combustion, and manual setting was in an easy way. The best experimental results were gained at 20% of water content of emulsion. These results still not satisfied, and then the combine treatment of emulsion and electrostatic water spray treatment was applied. From this combine system, the particulate matter decrease up to 90%.

The last treatment was designed by modification of combustion process by applying secondary combustion process. At the end of the boiler tube, a new combustion tool with town gas support was applied. It is known as secondary combustion process. The treatment results show the effectiveness of its treatment for decreasing of PM concentration.

Acknowledgment

First, I Pray to Allah SWT, without his blessing this Doctoral program should not be completed. I am indebted to many people for the successful completion of this dissertation. It is extremely important to acknowledge the help, various supervise, patient, and guidance of Professor NISHIDA Osami and Professor FUJITA Hirotsugu during my tenure education in Kobe University from Master degree to Doctoral degree. In particularly, I would like to grateful and thanks for colleagues whom I had the pleasure to work with; Yoo Dong-Hoon, Furukawa Tadasu, Ikeda Masatoshi, Nakanishi Tetsuya, Senda Tetsuya, Kitagawa Hiroaki, Mizuguchi. It is one of best experiences having experiment together with all of you and Energy Research laboratory`s members.

I appreciate the collaboration of research and thankful to ECC company in Osaka and also to JFE Chemical Co JP, who gives and share knowledge and technology for both treatments system and also how to make a good coal liquid fuel. I also thank the members of my dissertation committees, Professor FUKUDA Katsuya, Associate Professor DAN Tomohisa, and Professor MIMURA Haruo for their valuable comments and suggestions.

The author wishes to thank for unending supports, assistances, pointed out errors and suggestions from Mr. HARANO Wataru, as technical expert in Energy Research laboratory. Without his help, the research will not smoothly conduct.

I am also thankful to Japan Ministry of Education, Culture, Sports, Science, and Technology for financial support along of my study in Japan.

Finally, I owe my greatest debts to my family. I thank my parents for life, the support and care, spirit, and the strength determination to live it. Most of all, I thank my beloved person Ardiana Hari Riyanti for her loves and support throughout my study.

Contents

Chapter 1 : Introduction

1.1 Motivation 1

1.2 Objectives 2

1.3 Outline of Dissertation 3

Chapter 2 : Literature and Theory Review

2.1 Coal 6

2.2 Coal Reserves and Energy Source 9

2.3 Technology for Coal Utilization 10

  2.3.1 Fluidized Bed Combustion 11

  2.3.2 Carbonization 12

  2.3.3 Gasification 13

  2.3.4 Liquefaction 15

2.4 Combustion Process 17

2.5 Emission from Coal Combustion 19

  2.5.1 Sulfur Oxides 19

    2.5.1.1 Environmental Effects 20

    2.5.1.1 Health Effects 21

  2.5.2 Nitrogen Oxides 21

    2.5.2.1 Environmental Effects 23

    2.5.2.1 Health Effects 23

  2.5.3 Particulate Matter 24

    2.5.3.1 Particle Dynamic and Particle to Particle Process 25

    2.5.3.2 Environmental Effects 28

    2.5.3.3 Health Effects 28

  2.5.4 Carbon Monoxide 28

    2.5.4.1 Environmental Effects 29

    2.5.4.1 Health Effects 29

  2.5.5 Trace Element 28

    2.5.5.1 Environmental Effects 29

  2.5.6 Carbon Dioxide 30

    2.5.6.1 Environmental Effects 31

    2.5.6.1 Health Effects 31

2.6 Applied Particulate Cleaning Treatment for Coal 32

  2.6.1 Filtration 32

2.6.2 Electrostatic Precipitator 36
2.7 Applied Exhaust Gas Cleaning Treatment for Coal 34
2.7.1 Emulsion Treatment 34
2.7.2 Secondary Combustion 35

Chapter 3 : Experiments

3.1 Scope of Experiment 36
3.2 Preparation 37
3.3 Combustion Equipments 38
3.4 Thermogravimetry (TD) and Differential Thermal Analysis 42
3.5 Combustion Process 42
3.6 GC/MS Equipment 44

Chapter 4 : Laboratory Scale of Liquid Coal Fuel Combustion Process and Exhaust Gas Formation

4.1 Introduction 47
4.2 Liquefaction of Coal 47
4.3 Steady Combustion Condition and Parameters 48
4.4 Particulate Matter Component 50
4.5 Exhaust Gas Components 51
4.6 Summaries 55

Chapter 5 : Comparison Study of C Heavy Oil and Coal Oil : Gas Pollutants Formation and Combustion Parameters

5.1 Introduction 56
5.2 The Combustion Parameter 57
5.3 Thermogravimetry (TG) and Differential Thermal Analysis 58
5.4 Combustion Temperature and Heat Release 60
5.5 Exceed Air 61
5.6 Exhaust Gas Components 62
2.6.1 Oxygen and Carbon Derivative 62
2.6.2 Derivative of Nitrogen 62
2.6.3 Sulfur Content 62
5.7 Summaries 66

Chapter 6 : Characterization of the Particulate from the Combustion of Coal Oil and C Heavy Oil

6.1 Introduction 68
6.2 Particulate Emission 69
6.3 Experiment Process 71
6.4 Setting Condition 71
6.5 Cooling Temperature 71
6.6 Characteristics Coarse of Particles 72
6.7 Concentration of the Particulate 74
6.8 Dry Soot 75
6.9 Soluble Organic Fractions 76
6.10 GC/MS Measurement 77
6.11 Summaries 77

Chapter 7 : Pollution Formation from the Combustion of Coal Fuel and Coal Emulsion Fuel

7.1 Introduction 80
7.2 Additive and Emulsion Condition 82
7.3 Combustion Condition 84
7.4 Temperature and Heat Release 85
7.5 Carbon Dioxide and Oxygen 86
7.6 Carbon Monoxide 87
7.7 Derivative of Nitrogen 88
7.8 Particulate Emission 89
    7.7.1 Dry Soot and Soluble Organic Fractions 91
    7.7.1 Poly Aromatic Hydrocarbon 92
7.9 Summaries 92

Chapter 8 : Particulate Reduction from the Combustion of Coal Emulsion Oil ~ Effect of 2nd Stage of Combustion~

8.1 Introduction 96
8.2 After Burner Position and Apparatus 98
8.3 Temperature and Heat Release 100
8.4 Particulate Matter 100
8.5 Soluble Organic Fractions 102
8.6 Dry Soot 103
8.7 Summaries 105

Chapter 9 : Particulate Matter and NOx Removal by Combination of Electrostatic Water Spraying Scrubber and Emulsion Fuel

9.1 Introduction 106
9.2 Experiment Procedure and Setup 108
  9.2.1 Experiment Setup 108
  9.2.2 Measurement of PM Mass Concentration 109
9.3 Result and Discussion 109
  9.3.1 Reduction of NOx and PM by Using Emulsion Oil 109
  9.3.2 Reduction of PM by Using Electrostatic Water Spraying Scrubber 112
  9.3.3 Effect of Corona Power on PM Collection Efficiency 114
9.4 Summaries 115

Chapter 10 : Conclusions and Recommendations

10.1 Conclusions 116
10.2 Recommendation 117

References 120

List of Figures

Figure 1.1 Flow cart of experiment process 5

Figure 2.1 Classification of coal and application 8
Figure 2.2 Formation process of coal 9
Figure 2.3 Distribution of recoverable coal reserves in the world 10
Figure 2.4 Fluidizing velocity of air for various bed systems 12
Figure 2.5 Characteristic carbonization temperature and stages 13
Figure 2.6 Classification and characteristics of the commercial gasification systems 14
Figure 2.7 Illustration of liquefaction methods 15
Figure 2.8 Physical requirements and thermo chemical path for fuel combustion 18
Figure 2.9 Typical structure of exhaust particles 25
Figure 2.10 Particulate formations 27
Figure 2.11 General classification of particle device 32
Figure 2.12 Micro-explosion process in the emulsion fuel 34
Figure 2.13 Secondary combustion process 35
Figure 3.1 Coal JBO process 37
Figure 3.2 Liquid coal fuel 38
Figure 3.3 Illustration of boiler and burner for experiment 39
Figure 3.4 Probe for taking the data 25
Figure 3.5 Exhaust gas measurement equipment flow cart 41
Figure 3.6 Design system for experiment 43
Figure 4.1 Photograph of coal combustion 48
Figure 4.2 Exhaust gas emitted from boiler 44
Figure 4.3 Concentration of particulate matter and its components 45
Figure 4.4 Composition of smoke from coal combustion 51
Figure 4.5 Derivative of nitrogen in the exhaust gas 52
Figure 4.6 Correlation between temperature and NOx concentration 50
Figure 4.7 Oxygen and carbon components 52
Figure 5.1 Photographs of coal and C heavy oil combustion 57
Figure 5.2 Result of DT/TGA analysis 59
Figure 5.3 In-out temperature of combustion 60

Figure 5.4 Average of heat release 60
Figure 5.5 Percentages of exceed air 61
Figure 5.6 Concentration of oxygen 62
Figure 5.7 Concentration of derivative carbon 63
Figure 5.8 Concentration of derivative nitrogen 64
Figure 5.9 Concentration of sulfur dioxide 65
Figure 6.1 In-out temperature of water cooling system 72
Figure 6.2 PM images using SEM 73
Figure 6.3 Filter for particulate measurement 74
Figure 6.4 Distribution of particulate by different of temperature 74
Figure 6.5 PM concentration form C heavy oil and coal oil 75
Figure 6.6 Dry soot concentration of C heavy oil and coal oil 76
Figure 6.7 Soluble organic fractions 76
Figure 6.8 GC/MS result for SOF in C heavy oil 72
Figure 6.9 Ratio, Mean diameter of PM in 8 PS Diesel Engines 73
Figure 7.1 Emulsion condition in different temperature 83
Figure 7.2 Photographs of coal and emulsion combustion 84
Figure 7.3 In out water cooling system 85
Figure 7.4 Concentration of carbon dioxide and oxygen 86
Figure 7.5 Concentration of carbon monoxide 87
Figure 7.6 Various concentration of nitrogen derivative 89
Figure 7.7 Photographs of particulate matter 90
Figure 7.8 Concentration of particulate matter 90
Figure 7.9 Soluble organic fractions concentration 91
Figure 7.10 Dry soot concentration 91
Figure 7.11 GC/MS for SOF of coal fuel 91
Figure 7.12 GC/MS for SOF of 20% emulsion fuel 91
Figure 8.1 Secondary combustion apparatus at the boiler 98
Figure 8.2 Design of secondary combustion 99
Figure 8.3 Combustion condition of secondary combustion 99
Figure 8.4 Filter condition for particulate concentration 100
Figure 8.5 Particulate condition at rate of 6% oxygen 101
Figure 8.6 Reduction efficiency of PM 102
Figure 8.7 SOF condition at rate of 6% oxygen 102

Figure 8.8	Reduction efficiency of SOF by secondary combustion	103
Figure 8.9	Dry soot condition at rate of 6% oxygen	104
Figure 8.10	Reduction efficiency of DS by secondary combustion	104
Figure 9.1	Schematic diagram of experimental setup	108
Figure 9.2	NO concentration at different positions of furnace	110
Figure 9.3	NOx concentration at different positions of furnace	110
Figure 9.4	PM mass concentration at different positions of furnace	111
Figure 9.5	Dry soot concentration at different positions of furnace	111
Figure 9.6	SOF concentration at different positions of furnace	112
Figure 9.7	PM concentration at scrubbing performance	113
Figure 9.8	PM mass efficiency at scrubbing performance	113

List of Tables

Table 3.1 Properties of JBO coal oil 37
Table 4.1 Steady combustion of coal fuel parameters 49
Table 6.1 the classification of particulate size 70
Table 7.1 Additive properties 82
Table 7.2 Parameters of combustion condition 85
Table 8.1 Temperature of in-out tube in sampling points 100

Publications

Journals and Scientific Explanations

[1] Osami Nishida, **Kartika Kus Hendratna**, Hirotsugu Fujita, Wataru Harano, Dong-Hoon Yoo, Tatsuya Nakanishi, Tetsuya Senda, Tadasu Furukawa, Masatoshi Ikeda, Hiromi Okamoto, Hideaki Okada, Saito Mariko, 2011. *PM Reduction from Combustion of Coal Oil Emulsion –Effect of* 2^{nd} *Stage Combustion*, Journal of the Japan Institute of Marine Engineering, Vol.46, No.3, pp.142-147

[2] **Kartika Kus Hendratna**, Osami Nishida, Hirotsugu Fujita, Wataru Harano, Dong-Hong Yoo, 2010. *Characterization of the particulate from the combustion of coal and C-heavy oil*, International Journal of Research and Reviews in Applied Sciences, Vol.5, No.2, pp.101-109

[3] **Kartika Kus Hendratna**, Osami Nishida, Hirotsugu Fujita, Wataru Harano, Dong-Hoon Yoo, Nohara Hirotsugu, 2010, *Evaluation of Pollutants in Exhaust Gas for Combustion of Coal Oil and Emulsion*, Journal of the Japan Institute of Marine Engineering, Special Issue of ISME, Vol.45, pp.45-49

[4] **Kartika Kus Hendratna**, Osami Nishida, Hirotsugu Fujita, Wataru Harano, 2010. *Laboratory Scale of Liquid Coal Fuel Combustion Process and Exhaust Gas Formation*, American Journal of Environmental Sciences, Science Publications,Vol.3, No.3, pp.204-211

[5] Than Hong Ha, Osami Nishida, Hirotsugu Fujita, **Kartika Kus Hendratna,** Wataru Harano, 2010. *Removal of Particulate Matter (PM) and* NO_x *from marine exhaust gas by combining electrostatic water-spraying scrubber and emulsion oil*, International Journal of Environmental Technology and Management, Inderscience Publication, Vol.13, No.2, pp.149-160

[6] Takashi Mastuoka, Osami Nishida, Hirotsugu Fujita, Wataru Harano, Dong-Hoon Yoo, **Kartika Kus Hendratna**, Tetsuya Nakanishi, Hiromi Okamoto, 2010. *Economic Method of marine* NO_x*,* SO_x*, and PM Emissions Reduction – Practical Test Result of Coal Oi (in Japanese)*, Journal of the Japan Institute of Marine Engineering, Vol.45, No.4, pp.141-146

[7] Takashi Matsuoka, Osami Nishida, Hirotsugu Fujita, Wataru Harano, Dong-Hoon Yoo, **Kartika Kus Hendratna,** 2010. *Combustion Characteristics and Environmental Countermeasures for Air Polluton of Coal Oil (in Japanese)*, Journal of Kobe University Graduate School of Maritime Sciences, No.7, pp.115-121

[8] Osami Nishida, Hirotsugu Fujita, Wataru Harano, **Kartika Kus Hendratna**, I Made Ariana, Ryo Kawazoe, Megumi Fujio, 2009. *New System for 80% Reduction of Marine* NO_x*,* SO_x*, and PM (in Japanese)*, Journal of the Japan Institute of Marine Engineering, Vol.44, No.1, pp.95-103

[9] Hirotsugu Nohara, Kohzo Tsucida, Osami Nishida, Hirotsugu Fujita, Wataru Harano, Dong-Hoon Yoo, I made Ariana, **Kartika Kus Hendratna**, 2008. *Test Result of Practical Engines for Reduction of Marine Air Pollutants by HFO/Water Emulsion Fuel Oil (in Japanese),* Journal of the Japan Institute of Marine Engineering, Vol.43, No.5, pp.122-129

Proceeding Conference`s in Japan

[1] Osami Nishida, **Kartika Kus Hendratna**, Dong-Hoon Yoo, Tetsuya Nakanishi, Tetsuya Senda, Tadasu Furukawa, Masatoshi Ikeda, Hirotsugu Fujita, Wataru Harano, et.,al., 2010. Evaluation of Exhaust Gas Control & Economic Cost by Water Utilize (水の有効利用による排ガス制御と経済性の評価－石炭油・水エマルジョン燃料), Proceeding of the 80th the Japan Institute of Marine Engineering, Toki Messe – Niigata, Japan, 30th August – 1st September 2010, pp.223-224

[2] Osami Nishida, Hirotsugu Fujita, Wataru Harano, Dong-Hoon Yoo, **Kartika Kus Hendratna**, Tetsuya Nakanishi, Tetsuya Senda, Tadasu Furukawa, Masatoshi Ikeda, et.,al., 2010. PM Reduction by Coal Oil Combustion (Effects of 2nd Stage Combution) (石炭油燃焼による排出 PM の削減について（二段燃焼の効果） Proceeding of the 80th the Japan Institute of Marine Engineering Conference, Toki Messe – Niigata, Japan, 30th August – 1st September 2010, pp.225-226

[3] Tadashi Matsuoka, Osami Nishida, Hirotsugu Fujita, Wataru Harano, Dong-Hoon Yoo, **Kartika Kus Hendratna**, Tetsuya Nakanishi, Hiromi Okamoto, 2009. Cenosphere Generation from the Combustion of Difficult Fuel (難燃燃料の燃焼による Cenosphere の生成について)、Proceeding of the 79th the Japan Institute of Marine Engineering Conference, MierParque – Hiroshima, Japan, 16th -18th September 2009, pp.71-72

[4] Tetsuya Nakanishi, Osami Nishida, Hirotsugu Fujita, Wataru Harano, Dong-Hoon Yoo, **Kartika Kus Hendratna**, Tadashi Matsuoka, Hiromi Okamoto, 2009.Reduction of PM, SOx and NOx from the Combustion of Coal Oil (石炭油の燃焼による NOx, SOx 及び PM の生成と低減策), Proceeding of the 79th the Japan Institute of Marine Engineering Conference, MierParque – Hiroshima, Japan, 16th -18th September 2009, pp.169-170

[5] **Kartika Kus Hendratna**, Osami Nishida, Hirotsugu Fujita, Wataru Harano, Hirotsugu Nohara, 2009. Measurement of PM and its Components from Coal and Coal Emulsified Fuel Oil (石炭油と石炭油エマルジョンのによる微粒子の測定), Proceeding of the 79th the Japan Institute of Marine Engineering Conference, Mier Parque – Hiroshima, Japan, 16th -18th September 2009, pp.181-182

[6] **Kartika Kus Hendratna,** Osami Nishida, Hirotsugu Fujita, Wataru Harano, 2009. *Save Energy and Marine Environment: Coal Oil as Alternative Sea Transportation Fuel and Its Impacts on Environment,* the 4th of Kobe University Home Coming Day Seminar, Kobe University – Kobe, 31st September 2009

International proceeding Conference`s

[1] **Kartika Kus Hendratna**, Osami Nishida, Hirotsugu Fujita, Wataru Harano, 2011. Pollution Formation from the Combustion of Coal Fuel and Coal Emulsion Fuel, Proceeding of International Maritime-Port Technology and Development (MTEC), Singapore, 13th -15th April 2011, pp.93-99

[2] **Kartika Kus Hendratna**, Osami Nishida, Hirotsugu Fujita, Wataru Harano, 2010. Comparation of Exhaust Gas Formation from Combustion of C Heavy Oil Mixed with Ethanol and Water, Proceeding of International Conference of Sustainable Future for Human Security, Kyoto University, Kyoto – Japan, 11th -12th December 2010,pp.271-274

[3] **Kartika Kus Hendratna**, Hirotsugu Fujita, Osami Nishida, Wataru Harano, Dong-Hoon Yoo, I Made Ariana, Hirotsugu Nohara, Kohzo Tsuchida, 2008. Heat Release and Exhaust Gas Components Measurement from the Application of Water C-Oil Emulsion Fuel in Diesel Engine, Proceeding of 3rd PAAMES and AMEC 2008, Makuhari Messe – Chiba Japan, 20th -22nd October 2008, pp.769-776

[4] **Kartika kus Hendratna**, Osami Nishida, Hirotsugu Fujita, Wataru Harano, Dong-Hoon Yoo, Hirotsugu Nohara, Hiromi Okamoto, 2008. Evaluation of Exhaust Gas Components and PM Formation Characteristics by Coal Oil, Proceeding of International Symposium on Marine Engineering (ISME) 2009, Bexco, Busan – Korea, 18th -22nd October 2008

[5] Dong-Hoon Yoo, Osami Nishida, Hirotsugu Fujita, Wataru Harano, **Kartika Kus Hendratna**, Jae-Keun Lim, Hirostugu Nohara, 2008. De-NOx Method by Combination Emulsified Fuel and EGR System in Diesel Engine, Proceeding of International Symposium on Marine Engineering (ISME) 2009, Bexco, Busan – Korea, 18th -22nd October 2008

Chapter 1

Chapter 1

Introduction

1.1 Motivation

In the modern countries, coal is currently a major energy beside the fossil fuel source as well as throughout the world, especially among many developing countries. The implementation of coal application is mainly use for industrial sector as energy source for electric generator, and for supporting daily live activities. Coal provides stability in price and availability will continue to be a major source of electricity generation, and it also will be the major source of hydrogen that has the potential to become an important source of liquid fuels. A strategic plan for research, development, demonstration, and commercialization activities for coal should be based on assumptions regarding the future supply and price of competing energy sources, the demand for products manufactured from these sources, technological opportunities, and the need to control the environmental impact of waste streams. These factors changes with time based on the needs for the production.

Conservation and renewable/sustainable energy are important in the overall energy picture but will play a lesser role in helping us satisfy our energy demands. It is recognized in the energy industry that coal used is potential of the most abundant of emissions and pollution source. Concerns over the environmental effects of coal utilization are resulting in better methods for controlling emissions during combustion, as well as more research and development into technologies to utilize coal more efficiently in a better method of applications. In this reports, the research will focus on how to make a liquid coal fuel from most unused of coal category then treats by many methods to minimize the effects to the environment. The direct combustion of coal tar (lowest category of coal) by burning process believes gives many impacts to the environment and needs a treatment process. In the relation with sea transportation that mostly uses the C bunker heavy oil, converting coal to be a liquid fuel will allow it as the substitute of C bunker heavy oil or nearly have the same characteristics like C heavy fuel. Many major advance treatments have been made in reducing the environmental impact when using coal either near commercialization or under development that will allow coal to be used in an even more environmental friendly manner. The roadblocks to implementing these technologies are the financial risks associated with new technologies, and the resulting higher costs of energy to the consumers. The main impact of its application should be derived as the pollutants formations in the exhaust gas.

Marine engine combustion produces large quantities of products that may be released into the atmosphere. The emissions are largely steam (i.e., water vapor) which this is the most often observed coming from the application of derivative fuel for the combustion. The emits atmospheric pollutants gas from this combustion mainly consists of carbon dioxide (CO_2), derivative of nitrogen (NO_x), derivative of sulfur (SO_x) content in the fuel as well as particulate as the product of incomplete combustion. The principal pollutants that can cause health problems are classified into; sulfur and nitrogen oxides, particulate matter, trace elements (including arsenic, lead, mercury, fluorine, selenium, and radionuclide), and organic compounds. The derivative of nitrogen (NO_x) which consists of two oxides as primary concerns to the air pollution are NO and NO_2. Nitric oxide and nitrogen dioxide are collectively referred to as NO_x due to their inter-convertibility in photochemical smog reactions.

Exhaust emissions from marine sources have been limited dramatically in modern times through the adoption of Annex VI 1997 in the "Regulations for the Prevention of Air Pollution from Ships" MARPOL 73/78 Convention. The regulations focus on regulating of maximum exhaust gas components. The Regulations are going to be extended to pollutants such as particulate matter (PM), greenhouse gases (GHG) and volatile organic compounds (VOC) [IMO, Annex VI of MARPOL 73/78 Regulations aimed for the Prevention of Air Pollution from Ships and NO_x Technical Code]. As the result of discussion, Tier 1 to Tier 3 was implemented for stringent rule in maritime environment. In MARPOL 73/78 Annex VI, concentration of SO_2 in diesel exhaust is required must of less than 6 g/kWh and NO_x emission limits on range from 9.8 g/kWh to 17 g/kWh depending on the engine maximum operating speed.

Exhaust gas is a complex mixture of noxious gases and diesel particulate matter (PM). PM consists of nonvolatile elementary carbon absorbed or condensed hydrocarbons, sulfates, and small quantities of metallic compounds. PM mainly divided into two clustering that consists of soluble organic fraction (SOF) and Dry soot (DS). SOF is composed from volatile materials produced from unburned fuel, unburned oil lubricating, polycyclic aromatic hydrocarbons (PAHs), and from partially oxidized fuel and oil while dry soot is incomplete combustion products that have a new its properties and different with former fuel's properties [1]. Dry soot was formed by the post combustion section that creates a substance of particle characterizes near combusted fuel.

There are many ways to control and reduce the concentration of PM, SO_x, and NO_x emissions from marine exhaust gas. The emission control strategy and technology of reducing emission can be classified as primary and secondary strategies. Primary strategy refers to the methods of controlling the harmful species formation during combustion process, while the later one aims to remove the emissions from the engine exhaust gas and known as after treatment. The particulate matter components measurement normally investigates using gas impacted tools as well as filtering method. In this paper, it is introduced the treatment for low quality of coal fuel treatments as the emulsion fuel, improving combustion by modifying the combustion chamber and creates a secondary combustion process, and application of electrostatic water spray (after treatment process) as exhaust gas treatment.

1.2 Objective

The combustion of liquid coal and its exhaust gas treatment was experimented at the laboratory scale. The overall objective of this research was aimed to evaluate the possibility of liquid coal fuel as the substitute of C bunker heavy oil by the application of low quality of coal. Moreover, specifics objectives were designed as the respond of environmental problems from the application of liquid coal as follows:

1 Preparing the best concept and combustion parameters for the steady combustion of liquid coal fuel. It is included the process of making coal liquid fuel in the factory scale of production.

2 Developing the tools and equipments that needs for the best combustion process for the steady combustion of liquid coal fuel for boiler.

3 Experimentally investigation was conducted to know the good parameters of combustion such as; air pressure, temperature, fuel flow rate, and any other important conditions.

4 Investigating the exhaust gas products of liquid coal fuel that categories as harmful and giving much damage to the environment. The investigation also includes the GC&MS measurement, and TG/DTA measurement.

5 Applying some treatments methods for reducing the exhaust gas components, such as emulsion, electrostatic water spraying, and secondary combustion process.

1.3 Outline of Thesis

This dissertation is written in many chapters that having correlation with the objective of the research. Chapter one carry out the reader to the introduction of why this research is so important for being conducted, than follow by literature and theory review for comparing the result of experiment with established paper work, and ended by experiment result for many treatments. Flow cart of research are illustrated in fig.1. Part of text and results in this dissertation was taken from the scientific paper work publication along the study time. For detail of content it shows bellow as follows:

Chapter 1: Introduction.
Chapter 2: Literature and theory review.
Chapter 3: Experimental Process.
Chapter 4: Laboratory scale of liquid coal fuel combustion.
Chapter 5: Comparison study of C heavy oil and coal oil.
Chapter 6: Particulate formation from combustion of coal and C heavy oil.
Chapter 7: Pollution formation from combustion of coal and emulsion fuel.
Chapter 8: Secondary combustion treatment.
Chapter 9: Electrostatic water spray treatment for combustion of liquid coal
Chapter 10: Conclusion, summary of research and future work.

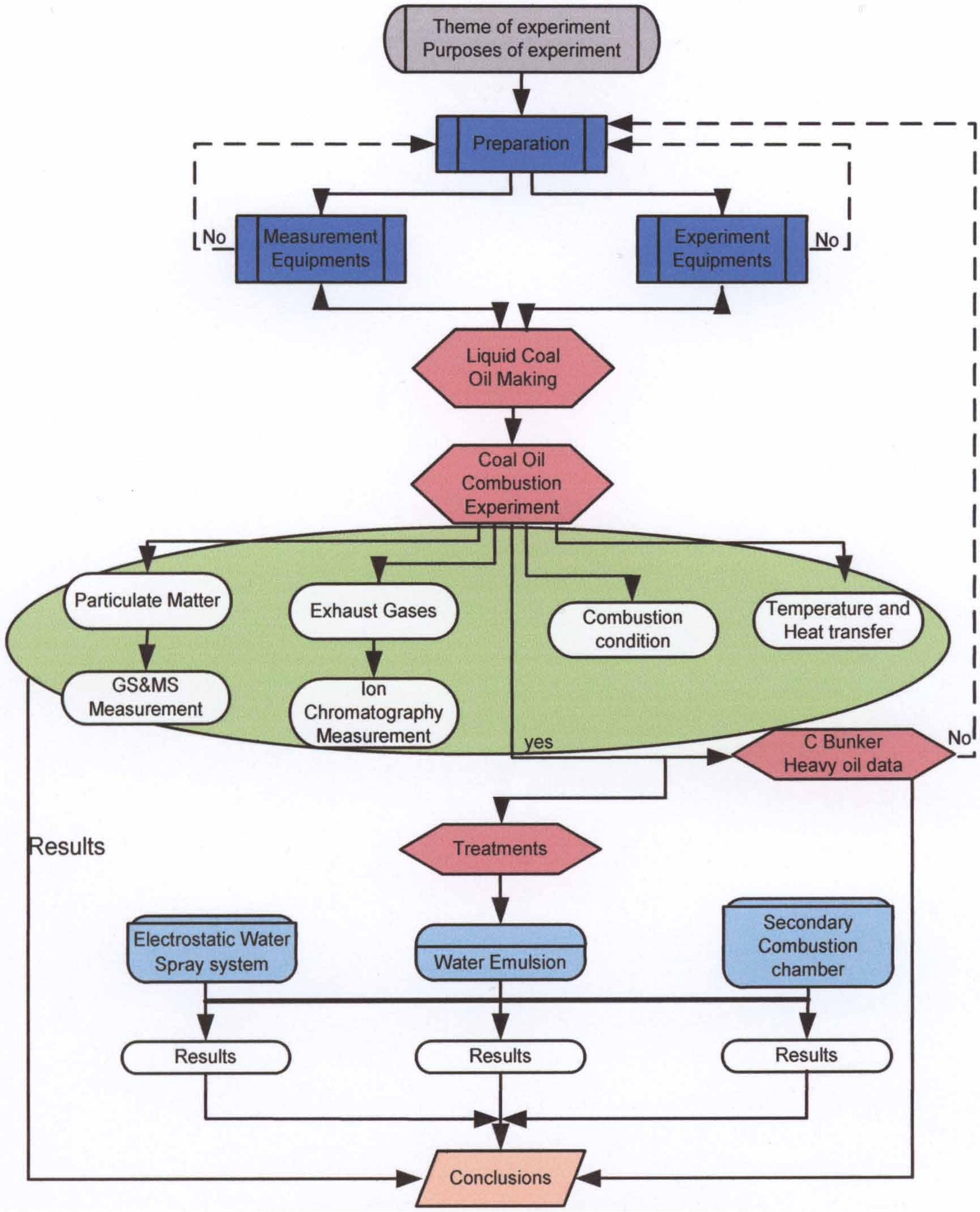


Fig. 1.1 *Flow cart of experiment process*

Chapter 2

Chapter 2

Literature and Theory Review

2.1 Coal

Coal is an organic sedimentary rock that contains varying amounts of carbon, hydrogen, nitrogen, oxygen, and sulfur as well as trace amounts of other elements, including mineral matter [1]. Organically, coal consists primarily of carbon, hydrogen, and oxygen, with lesser amounts of sulfur and nitrogen. Inorganically, coal consists of a diverse range of ash-forming compounds distributed throughout the coal. The inorganic constituents can vary in concentration from several percentage points down to parts per billion of the coal. Coal is a solid, brittle, combustible, carbonaceous rock formed by the decomposition and alteration of vegetation by compaction, temperature, and pressure. It varies in color from brown to black and is usually strained. The source of the vegetation is often moss and other low plant forms, but some coals contain significant amounts of materials that originated from woody precursors.

The plant precursors that eventually formed coal were compacted, hardened, chemically altered, and metamorphosed by heat and pressure over geologic time. It is suspected that coal was formed from prehistoric plants that grew in swamp ecosystems [2]. When such plants died, their biomass was deposited in anaerobic, aquatic environments where low oxygen levels prevented their reduction (rotting and release of carbon dioxide). Successive generations of this type of plant growth and death formed deep deposits of unoxidized organic matter that were subsequently covered by sediments and compacted into carboniferous deposits such as peat or bituminous or anthracite coal. Evidence of the types of plants that contributed to carboniferous deposits can occasionally be found in the shale and sandstone sediments that overlie coal deposits. Burial by sedimentary loading on top of the peat swamp converts the organic matter to coal by the following processes;

- Compaction, due to loading of the sediments on the coal which flattens the organic matter
- Removal of the water held within the peat in between the plant fragments
- with ongoing compaction, removal of water from the inter-cellular structure of fossilized plants
- With heat and compaction, removal of molecular water
- Methanogenesis; similar to treating wood in a pressure cooker, methane is produced, which removes hydrogen and some carbon, and some further oxygen (as water)
- Dehydrogenation, which removes hydroxyl groups from the cellulose and other plant molecules, resulting in the production of hydrogen-reduced coals

Coal consists of more than 50% by weight and more than 70% by volume of carbonaceous material (including inherent moisture). It is used primarily as a solid fuel to produce heat by burning, which produces carbon dioxide, a greenhouse gas, along with sulfur dioxide. This process also produces sulfuric acid, which is responsible for the formation of sulfate aerosol and acid rain. Coal contains many trace elements, including arsenic and mercury, which are dangerous if released into the environment. Coal also contains low levels of uranium, thorium, and other naturally occurring radioactive isotopes, whose release into the environment may lead to radioactive contamination.

Coal exists, consists of various types, and each type has distinctly different properties from the other types.

- *Anthracite*, the highest rank of coal, is used primarily for residential and commercial space heating. It is hard, brittle, and black lustrous coal, often referred to as hard coal, containing a high percentage of fixed carbon and a low percentage of volatile matter. The moisture content of fresh-mined anthracite generally is less than 15%. The heat content of anthracite ranges from 22 to 28 million Btu/ton on a moist, mineral-matter-free basis.
- *Bituminous* coal is a dense coal, usually black, sometimes dark brown, often with well-defined bands of bright and dull material, used primarily as fuel in steam-electric power generation, with substantial quantities also used for heat and power applications in manufacturing to make coke. The moisture

content of bituminous coal is usually less than 20% by weight. The heat content of bituminous coal ranges from 21 to 30 million Btu/ton on a moist, mineral-matter-free basis.

- *Subbituminous* coal is coal whose properties range from those of lignite to those of bituminous coal, used primarily as fuel for steam-electric power generation. It may be dull, dark brown to black, and soft and crumbly at the lower end of the range, to bright, black, hard, and relatively strong at the upper end. This type of coal contains 20 to 30% inherent moisture by weight. The heat content of coal ranges from 17 to 24 million Btu per ton on a moist, mineral-matter-free basis.
- *Lignite* is the lowest rank of coal, often referred to as *brown coal*, used almost exclusively as fuel for steam-electric power generation. It is brownish black and has high inherent moisture content, sometimes as high as 45%. The heat content of lignite ranges from 9 to 17 million Btu/ton on a moist, mineral-matter-free basis.

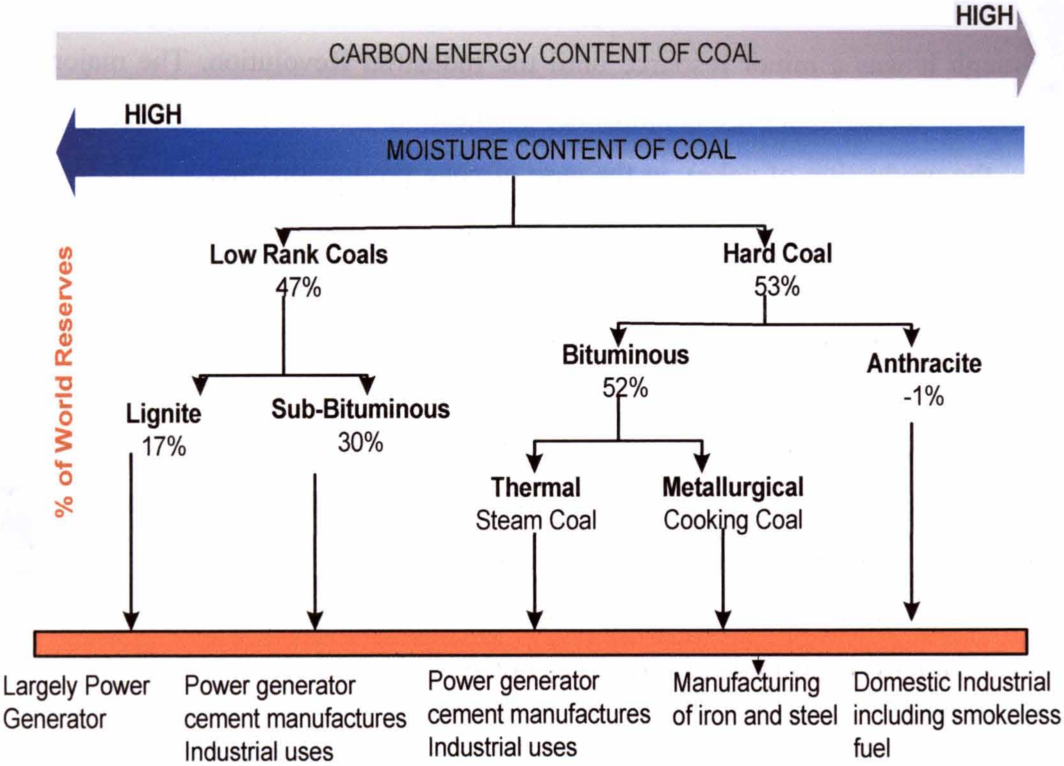


Fig.2.1 *Classification of coal and application*

Materials	Partial Processes	Main Chemical Reactions
Decaying Vegetaion ↓	Peatification	Baterial and Fungal life cycles
Peat ↓	Lignitification	Air Oxidation, followed by decarboxylation and dehydration
Lignite ↓	Bituminization	Decarboxylation and hydrogen disproportioning
Bituminous coal ↓	Preanthracitization	Condensation to small aromatic ring systems
Semianthracite ↓	Anthracitization	Condensation of small aromatic rings systems to larger ones; dehydrogenation
Anthracite	Graphitization	Complete carbonification

Fig.2.2 *Formation process of coal [2]*

2.2 Coal Reserves and Energy Source

The use of coal as an energy source has been known from ancient times, although it was a minor resource until the Industrial Revolution. The major coal-utilization technologies are combustion, gasification, liquefaction, and carbonization (i.e., the production of coke), in the case of coke production, made major strides in technology development and usage. Coal resources are broadly dispersed across geographical locations with appreciable reserves on every continent. Even if the utilization rate doubles, the coal resource will last several thousands of years available. Coal deposits are broadly categorized into resources and reserves. Resources refer to the quantity of coal that may be present in a deposit or coalfield but may not take into account the feasibility of mining the coal economically. Reserves generally tend to be classified as proven or measured and probable or indicated, depending on the level of exploration of the coalfield. Fig.2.2 shows the distribution of recoverable coal reserves in the world.

Power generation accounts for almost all of the projected growth in coal consumption worldwide. The application of coal mainly focuses on the electric generator by applying the heat from its combustion to product energy. Coal consumption is concentrated in the electricity generation sector, with about 65% of the coal consumed worldwide used for producing electricity. Oil has been the world's dominant source of primary energy for several decades. This is predicted to occur because many countries are expected to switch from oil to natural gas, coal, and other fuels, especially for electricity generation. The largest countries that still have a coal deposit are North America, with 282,444 million short tons. The lower one was located at Africa and central and south America with only 23.977 million tons. This process is less of the technology improvement, while the impacts to the environment such as; exhaust gas components, the waste of combustion, and particulate matter for uncompleted combustion still need to be considered as well. New development or treatments for the environmental friendly coal must also being taught in order to minimize its impacts of the combustion products. In correlation with marine transportation, the liquefaction of coal will have a possibility as the substitute of C bunker heavy oil that normally uses in ships operational.

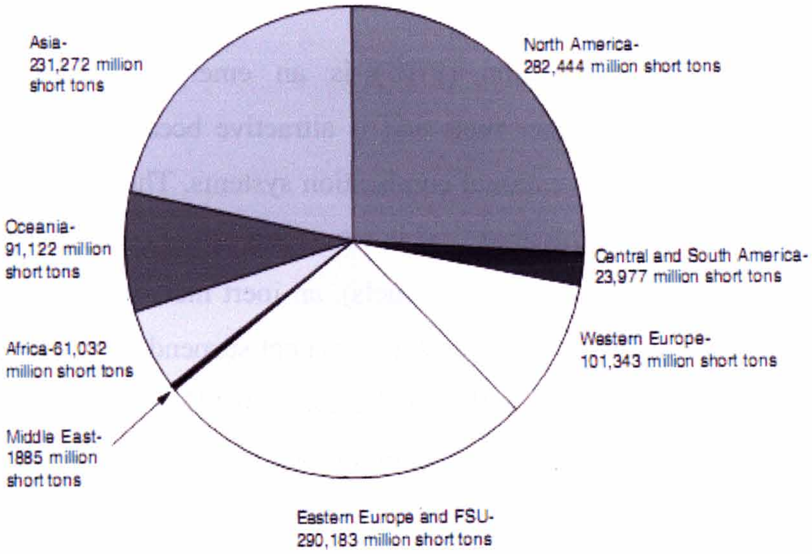


Fig.2.2 *Distribution of recoverable coal reserves in the world [3]*

2.3 Technology for Coal Utilization

Burning coal to generate heat is the most straightforward way of using coal. The heat that is generated from burning coal is used for warmth, cooking, and industrial processes. The use of coal for warmth, cooking, and metal works has been around for thousands of years. The primary use of coal is for burning in boilers to generate electricity. The combustion process consists of several steps. As the coal particles are heated, moisture is driven off the coal particles. Next, the coal particles undergo devolatilization and release volatile organic constituents. The volatile matter is combusted in the gas phase (homogenous reaction). This can occur prior to and simultaneously with combustion of the char particles, which is the last step. Combustion of the char is a surface (heterogeneous) reaction. These reactions are for the most part sequential, and the slowest of these will determine the rate of the overall process. There are many technology that have been applied in the coal treatment was derived from conventional combustion process to high technology of combustion. The process should be divided as follows:

- Fluidized Bed Combustion
- Carbonization
- Gasification
- Liquefaction

2.3.1 Fluidized Bed Combustion

Fluidized-bed combustion (FBC) is an emerging technology for the combustion of fossil and other fuels and is attractive because of several inherent advantages it has over conventional combustion systems. These advantages include fuel flexibility, low NOx emissions, and in situ control of SO_2 emissions. In a typical FBC, solid, liquid, or gaseous fuel (or fuels), an inert material such as sand or ash (referred to as bed material), and limestone are kept suspended through the action of combustion air distributed below the combustor floor [4]. The primary functions of the inert material are to disperse the incoming fuel particles throughout the bed, heat the fuel particles quickly to the ignition temperature, act as a flywheel for the combustion process by storing a large amount of thermal energy, and provide sufficient residence time for complete combustion. The FBC concept is attractive because it increases turbulence and permits lower combustion temperatures. Turbulence is promoted by fluidization making the entire mass of solids behave much like a liquid. Improved mixing (and hence enhanced heat transfer to the bed material) permits the generation of heat at a substantially lower and more uniformly distributed temperature than occurs in conventional. This operating temperature range is well below that at which significant thermally-induced NO_x production occurs. Staged combustion can be applied to minimize fuel-bound NO_x formation as well. With regard to SO_2 emissions, the operating temperature range is where the reactions of SO_2 with a suitable sorbent, commonly limestone, are thermodynamically and kinetically balanced [5].

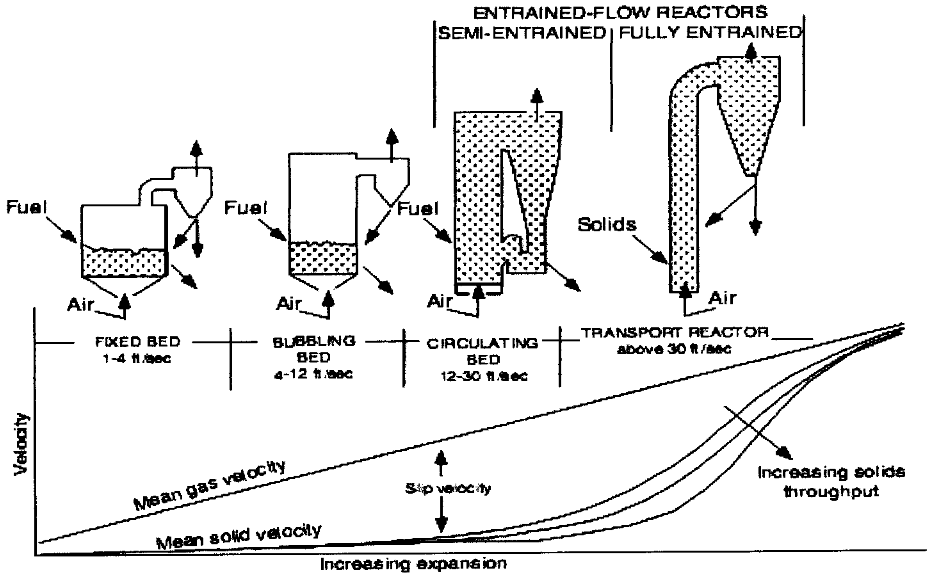
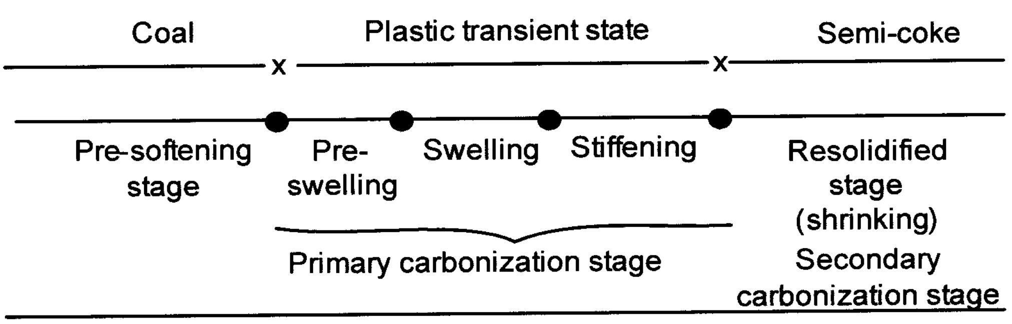


Fig.2.3 *Fluidizing velocity of air for various bed systems [6].*

2.3.2 Carbonization

Carbonization is the process by which coal is heated and volatile products gaseous and liquid—are driven off, leaving a solid reside called char or coke. Coal carbonization processes are classified into high-temperature operations if they are performed at temperatures greater than 1650°F or low-temperature operations if they are conducted below1350°F. These temperatures are somewhat arbitrary, as they reflects the pronounced physical changes that coal undergoes at temperatures between 1110°F and 1470°F [7]. Carbonization processes reaching into the 1350 to 1650°F range are termed medium temperature processes.



Ts = Softening temperature
T_{aw} = Temperature of initial swelling
T_{md} = Temperature of maximum devolatilization rate
T_f = Resolidification temperature

Fig.2.4 *Characteristic carbonization temperatures and stages [2]*

Coals of a very definite range of rank soften on heating, swell on decomposition, and resolidify on continued degasification [2]. Devolatilization is a continuous process but a distinction can be made between the primary carbonization stage, in which mainly tar is evolved, and the secondary carbonization stage, in which only gas is split off. The characteristic temperatures and stages of the carbonization process are illustrated in Figure 2.4.

The main purpose of high-temperature carbonization is the production of metallurgical coke for use in blast furnaces and foundries. Some coke is used for the manufacture of calcium carbide and electrode carbons, as reluctant in certain ferrous and nonferrous open-hearth operations, and in foundries to produce cast iron; however, more than 90% of the coke produced is used in blast furnaces to smelt iron ore and produce pig iron, and modern coke-making practices are virtually dictated by the coke quality in this market. Low-temperature carbonization has been mainly used to provide town gas for residential and street lighting, tars for use in chemical production, and smokeless fuels for domestic and industrial heating. The properties of the coke are influenced by the coal or coal blend from which the coke is made as well as by the carbonizing conditions used. The rank of the coal or the average rank of the coal blend used affects the properties of the coke product. The choice of a suitable coal is crucial to quality control of the coke, and coke produces blend coals to manipulate coke characteristics. The practice of blending coals was originally developed to eliminate difficulties that were encountered when carbonizing highly fluid coals but was later used to stretch supplies of scarce or costly ideal-caking coals and quickly became the principal method for manipulating coke characteristics.

2.3.3 Gasification

Gasification is a process to upgrade a solid feedstock, which is difficult to handle, by removing undesirable impurities and converting it into a gaseous form that can be purified and used directly as a fuel or further reacted to produce other gaseous or liquid fuels, or chemicals. There are many reasons for the interest in gasification as a process for utilizing coal. Liquid and gaseous fuels are easier to handle and use than coal, whether the fuel is used for heating, cooking, transportation, or power production. Shipping coal can be difficult and labor intensive and can have negative environmental impacts. Impurities in coal can be more readily removed through gasification than when utilized directly. Synthetic fuels burn more cleanly than coal, and fewer sulfur and nitrogen oxides are formed during combustion. Carbon capture and sequestration is easier in a gasification system than in a combustion system, which is important with carbon dioxide being considered for regulation as a pollutant. Gasification of coal reduces the concerns of volatile swings in availability and cost of gaseous or liquid fuels that are experienced with petroleum or natural gas. Although the use of coal gasification is currently rather limited, this technology is poised to be the technology of the future for the production of electricity, steam, chemicals, and fuels such as hydrogen.

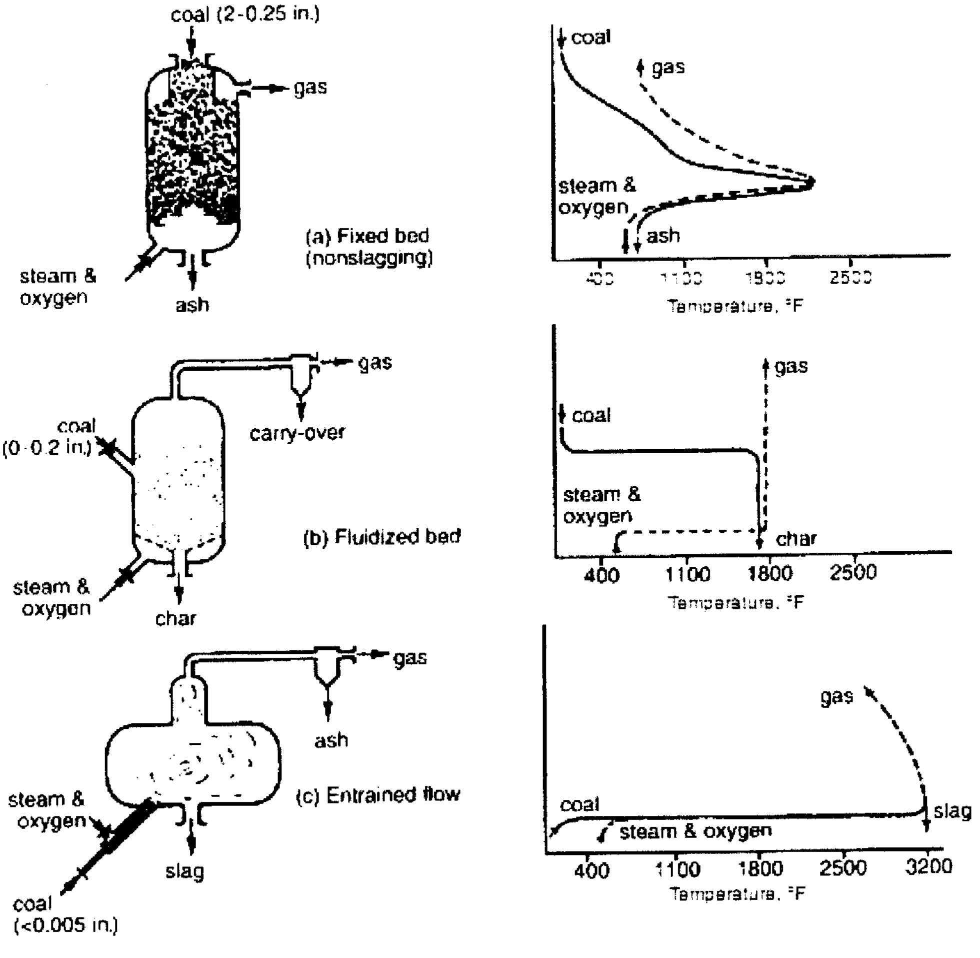


Fig. 2.5 *Classification and characteristics of the commercial gasification systems [9].*

Simple process of gasification is described as follows: Carbonization of coal to produce coal gas is a relatively simple process to perform and is done in a retort in the absence of air. The composition of the gas being produced varies depending on the coal being used but is typically comprised of hydrogen (40–50%) and methane

(30–40%), with minor amounts (2–10%) of nitrogen, carbon monoxide, ethylene, and carbon dioxide. The gas yield is approximately 10,000 scf per short ton of coal carbonized with a heating value of 550 to 700 Btu/scf. When carbonizing a bituminous coal, about 20% of the weight of the coal is converted to gas [8]. This gas is used as a fuel at coking operations. Although carbonization of coal is a simple process, only a small fraction of the coal is converted to gas; consequently, processes to convert all of the carbon in the coal to gas were developed. In one of these processes, air is slowly passed through a hot bed of coal, converting most of the carbon to carbon monoxide, with some carbon dioxide being formed. Some of the carbon dioxide is then converted to carbon monoxide by reacting with hot fuel carbon [8].

2.3.4 Liquefaction

Liquefaction is the conversion of coals into liquid products. The three methods by which liquids can be derived from coals are pyrolysis, indirect liquefaction, and direct liquefaction. The illustration of three methods of liquefaction can be seen in fig. 2.6 below;

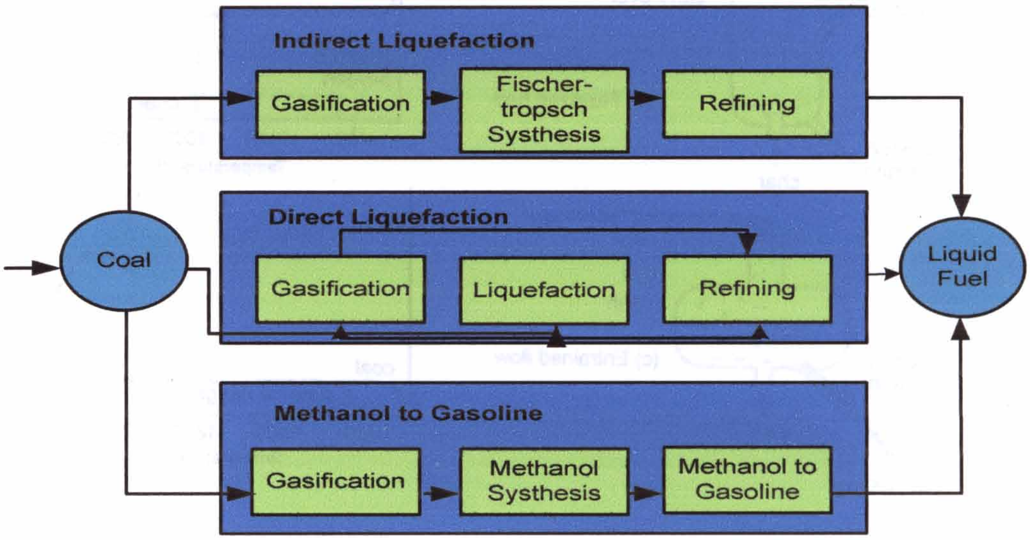


Fig.2.6 *Illustration of coal liquefaction methods*

In pyrolysis processes, the liquids are a by-product of coke production. The term liquefaction refers to the conversion of the coal to a product that is primarily a liquid. In indirect liquefaction, the coal is gasified into a mixture of carbon monoxide and hydrogen (i.e., syngas). The syngas is then processed into liquid products using Fischer–Tropsch synthesis and finished by the refining process. Indirect liquefaction involves, as a first step, the complete breakdown of the coal structure by gasification with steam. The composition of the gasification products is then adjusted to give the required mixture of H_2 and CO, and to remove sulfur-containing catalyst poisons. The resulting 'synthesis gas' is reacted over a catalyst at relatively low pressure and temperature. The products may be paraffin, olefin hydrocarbons or alcohols (particularly methanol), depending on the catalyst selected and the reaction conditions used.

Direct liquefaction, also referred to as coal hydrogenation, coal is mixed with a hydrogen-donor solvent and reacted with hydrogen or syngas under elevated pressures and temperatures to produce a liquid fuel. Direct liquefaction processes aim to add hydrogen to the organic structure of the coal, breaking it down only as far as is necessary to produce distillable liquids. Many different processes have been developed, but most are closely related in terms of underlying reaction chemistry. Common features are the dissolution of a high proportion of coal in a solvent at elevated temperature and pressure, followed by the hydro cracking of the dissolved coal with H_2 and a catalyst. Direct liquefaction is the most efficient route currently available. Liquid yields in excess of 70% by weight of the dry, mineral matter-free coal feed have been demonstrated for some processes in favorable circumstances. Overall thermal efficiencies for modern processes are generally in the range 60-70% if allowance is made for generating losses and other non-coal energy imports. The liquid products from direct liquefaction processes are of much higher quality than those from pyrolysis processes and can be used unblended for most stationary fuel application. Direct liquefaction processes can conveniently be divided into two main groups, depending on whether the initial dissolution of the coal is separated from the conversion of the dissolved coal into distillable products:

- A single-stage direct liquefaction process gives distillates via one primary reactor or a train of reactors in series. Such processes may include an integrated on-line hydro treating reactor, which is intended to upgrade the primary distillates without directly increasing the overall conversion.
- A two-stage direct liquefaction process is designed to give distillate products via two reactors or reactor trains in series. The primary function of the first stage is coal dissolution and is operated either without a catalyst or with only

a low-activity disposable catalyst. The heavy coal liquids produced in this way are hydro treated in the second stage in the presence of a high-activity catalyst to produce additional distillate.

2.4 Combustion Process

Combustion is defined as a rapid exothermic reaction that liberates substantial energy as heat and flames as combustion reactions with the ability to propagate through a suitable medium. This propagation results from the strong coupling of the reaction with the molecular transport process. The chemistry and physics of combustion, i.e. destruction and rearrangement of certain molecules, rapidly release energy within a few millionths of second. Combustion takes place when fuel, most commonly a fossil fuel, reacts with oxygen in the air to produce energy as heat. Along with heat, CO_2 (carbon dioxide) and H_2O (water) are created as byproducts of the exothermic reaction. Simplicity, the hydrocarbon chain in the fossil fuel will reacts with ion of oxygen, as follows:

$$CH_4 + 2O_2 \text{---->} CO_2 + 2H_2O + \text{Heat} \qquad (1)$$

$$C + O_2 \text{---->} CO_2 + \text{Heat} \qquad (2)$$

$$2H_2 + O_2 \text{---->} 2H_2O + \text{Heat} \qquad (3)$$

By monitoring and regulating some of the gases in the stack or exhaust, it is easy to improve combustion efficiency, which conserves fuel and lowers expenses. Combustion efficiency is the calculation of how effectively the combustion process runs. To achieve the highest levels of combustion efficiency, complete combustion should take place. Complete combustion occurs when all of the energy in the fuel being burned is extracted and none of the Carbon and Hydrogen compounds are left unburned. Complete combustion will occur when the proper amounts of fuel and air (fuel/air ratio) are mixed for the correct amount of time under the appropriate conditions of turbulence and temperature. Although theoretically stoichiometric combustion provides the perfect fuel to air ratio, which thus lowers losses and extracts all of the energy from the fuel; in reality, stoichiometric combustion is unattainable due to many varying factors. Heat losses are inevitable thus making 100% efficiency impossible.

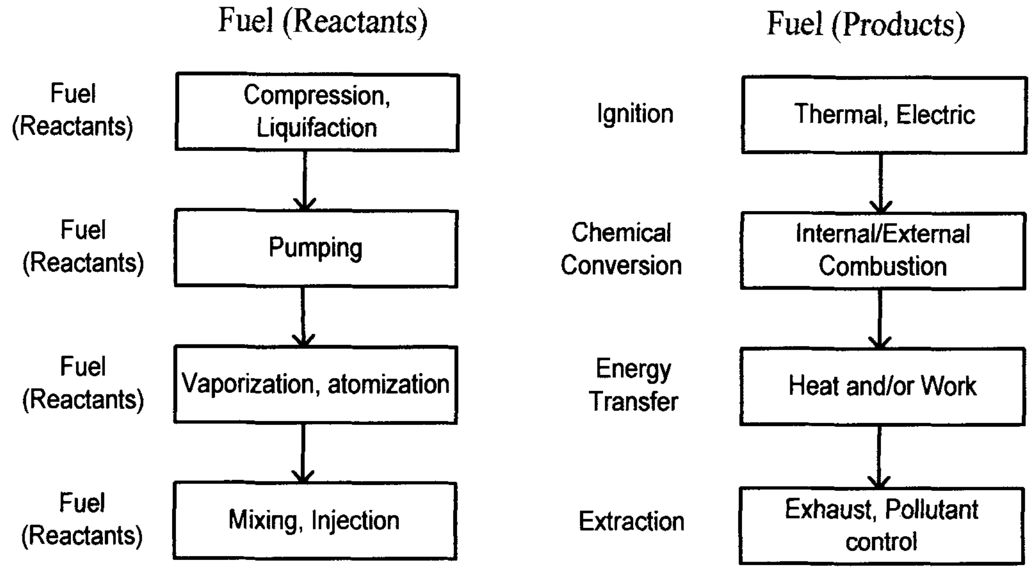


Fig 2. 7 *Physical Requirements and Thermo Chemical path for Fuel Combustion [10]*

In practice, in order to achieve complete combustion, it is necessary to increase the amounts of air to the combustion process to ensure the burning of all of the fuel. The amount of air that must be added to make certain all energy is retrieved is known as excess air. It is important to strive for complete combustion to preserve fuel and improve the cost efficiency of the combustion process. There must be enough air in the combustion chamber for complete combustion to occur. The addition of excess air greatly lowers the formation of CO (carbon monoxide) by allowing CO to react with O_2. The less CO remaining in the flue gas, the closer to complete combustion the reaction becomes. This is because the toxic gas carbon monoxide (CO) still contains a very significant amount of energy that should be completely burned. One of parameter in successful of combustion process is fuel-air ratio. Fuel-air ratio is the proportion of fuel to air during combustion. The optimal ratio (the stoichiometric ratio) occurs when all of the fuel and all of the oxygen in the reaction chamber balance each other out perfectly. Rich burning is when there is more fuel than air in the combustion chamber while lean burning occurs when there is more air than fuel in the combustion chamber.

2.5 Emissions from Coal Combustion

Coal combustion produces large quantities of products that may be released into the atmosphere. The emissions are largely steam (i.e., water vapor), which is what is most often observed coming from the stack of a power plant, carbon dioxide, and nitrogen fromthe air and do not present any direct health hazard. However, the emissions do contain small concentrations of atmospheric pollutants, which translate into large quantities emitted due to the vast amount of coal consumed. The principal pollutants that can cause health problems are sulfur and nitrogen oxides, particulate matter, trace elements (including arsenic, lead, mercury, fluorine, selenium, and radionuclides), and organic compounds. The environmental impacts and health effects of these pollutants, along with carbon monoxide and carbon dioxide, are discussed here. The definition of air pollution is the addition to the atmosphere of any material that may have a deleterious effect on life [11]. Air pollution is produced by natural processes or by anthropogenic, or manmade, actions. The legal definition of an air pollutant is any air pollution agent or combination of such agents, including any physical, chemical, biological, or radioactive substance, or matter that is emitted into or otherwise enters the ambient air [12]. These agents include primary and secondary pollutants, which are classifications that indicate how the various pollutants are formed. Primary pollutants have the same state and chemical composition in the ambient atmosphere as when emitted from sources, but secondary pollutants have changed in form after leaving the source due to oxidation, decay, or reaction with other primary pollutants.

2.5.1 Sulfur Oxides

Gaseous emissions of sulfur oxides from coal combustion are mainly sulfur dioxide (SO_2) and, to a much lesser extent, sulfur trioxide (SO_3) and gaseous sulfates. The sulfur in the coal reacts with oxygen to form the sulfur oxides:

Fuel devolatilisation / "pyrolysis"

Fuel-S (s) + heat 6 H_2S + COS + ... + Char-S (s) (4)

Char oxidation

Char-S (s) + O_2 6 SO_2 (5)

Char-S (s)+ CO_2 6 COS (6)

Char-S (s) + H2O 6 H_2 (7)

Gas phase reactions

H2S + 1½O_2 6 SO_2 + H_2O (8)

$$CO_2 + H_2S \text{ W } COS + H_2O \tag{9}$$

$$CO + H_2S \text{ W } H_2 + COS \tag{10}$$

$$COS + H_2S \text{ W } CS_2 + H_2O \tag{11}$$

$$CS_2 \text{ W } C(s) + 2/x\ Sx\ (s) \tag{12}$$

Sulfuric oxide formation

$$SO_2 + \tfrac{1}{2}\,O2 \text{ W } SO_3 \tag{13}$$

$$H_2O + SO_3 \text{ W } H_2SO_4 \tag{14}$$

In gasification or pyrolysis plants hydrogen sulphide H_2S will be the most important sulfur compound. Upon release to the environment, H_2S will be oxidised to SO_2. One fact remaining, though, is that sulfur must eventually be disposed of in some chemical form. Unlike fuel-related nitrogen, that without any environmental concern may be released partly as molecular nitrogen N_2, there is no such “escape route” for sulfur. Fuel-related sulfur that is captured may end up as molecular sulfur, sulfuric acid, or bound in flue gas desulfurization (FGD) residues like gypsum, and partly in bottom ashes and fly ashes. In other cases, such as cement kilns, the cement product may contain a significant amount of the sulfur from the fuels used (coals, pet coke, alternative fuels) without causing problems. Currently much of that sulfur is found in heavy fuel oils used on ships without emissions control, that is, at those seawaters where high-sulfur fuels for shipping are accepted

2.5.1.1 Environmental Effects

Environmental effects of sulfur compounds include impaired visibility, damage to materials, damage to vegetation, and deposition as acid rain. Fine particles in the atmosphere reduce the visual range by scattering and absorbing light [13]. Aerosols of sulfuric acid and other sulfates comprise from 5 to 20% of the total suspended particulate matter in urban air, thus contributing to the reduction in visibility. Sulfur compounds are responsible for major damage to materials. Sulfur oxides generally accelerate metal corrosion by first forming sulfuric acid either in the atmosphere or on the metal surface. Sulfur dioxide is the most detrimental pollutant with regard to metal corrosion [13]. Temperature and relative humidity are also significantly influence to the rate of corrosion. Acidic deposition or acid rain occurs when emissions of sulfur dioxide and oxides of nitrogen in the atmosphere react with water, oxygen, and oxidants to form acidic compounds. These compounds fall to the ground in either dry form (i.e., gas and particles) or wet form (i.e., rain, snow, and fog).

2.5.1.2 Health Effects

Few epidemiological studies have been able to differentiate adequately the effects of individual pollutants because sulfur oxides tend to occur in the same kinds of atmospheres as particulate matter and high humidity. High concentrations of sulfur dioxide can result in temporary breathing impairment in asthmatic children and adults who are active outdoors [14]. Short-term exposures of asthmatic individuals at moderate exertion to elevated sulfur dioxide levels may result in reduced lung function. Other effects that have been associated with longer term exposures to high concentrations of sulfur dioxide in conjunction with high levels of particulate matter include respiratory illness, alterations in the lung's defenses, and aggravation of existing cardiovascular disease.

2.5.2 Nitrogen Oxides (NOx)

Probably the most damaging of the hazardous nitrogen compounds formed during combustion are nitric oxide (NO) and nitrogen dioxide (NO_2). These are commonly referred to as NO_X. Of the NO_X emissions, some 95 % or more usually is NO, whereas the fraction of NO_2 remains less than 5 %. Later on, in the atmosphere a large part of the nitric oxide is oxidized to nitrogen dioxide, so the environmental effects of emissions of both these compounds are very similar. Acid fall-out and participation in the formation of photochemical smog and ozone in big cities with lively traffic are some of the well-known harmful effects of NO_X for the environment. The Formation process of NO oxidation should be derived from many processes.

Nitrogen in fuels

The amounts of nitrogen found in different types of fuel vary significantly. Fuel NO is the primary source of NOx in flue gas from coal combustion and is formed from the gas-phase oxidation of devolatilized nitrogen containing species and the heterogeneous combustion of nitrogen-containing char in the tail of the flame Whilst in natural gases nitrogen is usually present as N_2, it is found in a chemically bound organic form in other fuels. In coal, a large part of the fuel-nitrogen ("fuel-N") is bound in aromatic structures such as pyridines and pyrroles. A second factor of importance is what fraction of the fuel-N is released from the fuel as volatile nitrogen compounds and what fraction remains in the char as char-N. NOx abatement techniques, i.e. furnace design and operation methods aiming at NOx emission reduction are less effective in controlling the fate of char-N than volatile-N. Hence, information on the nitrogen content of char is essential for the prediction of NOx emissions from furnaces and boilers

Thermal NOx

Formation of nitric oxide from molecular nitrogen requires breaking of the strong bond between the nitrogen atoms in N_2 (bondage energy approx. 950 kJ/mol). Under combustion conditions an oxygen molecule or atom is not capable of breaking this bond and even at higher temperatures a direct reaction between molecular nitrogen and molecular oxygen is too slow to take place, which are referred to as the extended Zeldovich mechanism:

$$N_2 + O_2 \rightarrow 2NO \qquad (15)$$

$$N_2 + O \rightarrow NO + N \qquad (16)$$

$$N + O_2 \rightarrow NO + O \qquad (17)$$

$$N + OH \rightarrow NO + H \qquad (18)$$

The production of thermal NO is a function of the combustion temperature and fuel-to-air ratio and increases exponentially at temperatures above 2650°F.

Prompt NOx

Prompt NO is produced by the reaction of hydrocarbon fragments and molecular nitrogen in the flame front. Prompt NO is most significant in fuel rich flames, where the concentration of radicals such as O and OH can exceed equilibrium values, thereby enhancing the rate of NO formation. Prompt NO occurs due to the collision of hydrocarbons with molecular nitrogen in the fuel-rich flames to form HCN (hydrogen cyanide) and N.

$$\text{Fuel N}\left[\frac{\text{NH3}}{\text{HCN}}\right] \text{NO/Ox} \left(\frac{\text{N2}}{\text{NO}}\right) \qquad (19)$$

The amount of prompt NO generated is proportional to the concentration of N_2 and the number of carbon atoms present in the gas phase, but the total amount produced is low in comparison to the total thermal and fuel NO in coal combustion. The conditions the nitrogen in the combustion air reacts into nitric oxide through another mechanism, which is initiated by a reaction between N_2 and a CH radical as follows:

$$N_2 + CH \rightarrow HCN + N \qquad (20)$$

If oxygen-containing components are present, the hydrogen cyanide (HCN) produced in the reaction and the nitrogen atom (N) react further to nitric oxide through several reaction phases. Under most conditions, the main reaction path is as follows:

$$HCN + O \rightarrow NCO + H \rightarrow NH + H \rightarrow N + O_2 + OH \rightarrow NO \qquad (21)$$

Formation of nitric oxide according to the above-mentioned mechanism occurs only in a combustion zone of the flame where the combustion is incomplete and hydrocarbon radicals necessary for reaction R4-6 are present. The formation of nitric oxide is usually very fast, and the nitric oxide formed is called prompt NO. In contrast to thermal NO, prompt NO depends only slightly on temperature.

2.5.2.1 Environmental Effects

NOx has been shown to accelerate damage to materials in the ambient air. In the presence of sunlight, nitrogen oxides react with unburned hydrocarbons volatile organic compounds (VOCs) that are emitted primarily from motor vehicles but also from chemical plants, refineries, factories, consumer and commercial products, and other industrial sources to form photochemical smog. Nitrogen oxides also contribute to the formation of acid rain. NO and NO_2 in the ambient air can react with moisture to form NO^{-3} and H^+ in the aqueous phase (i.e., nitric acid), which can cause considerable corrosion of metal surfaces. Nitrogen oxides contribute to changes in the composition and competition of some species of vegetation in wetland and terrestrial systems, acidification of freshwater bodies, eutrophication (i.e., explosive algae growth leading to depletion of oxygen in the water) of estuarine and coastal waters, and increases in the levels of toxins harmful to fish and other aquatic life [15].

2.5.2.2 Health Effects

Nitrogen dioxide acts as an acute irritant and in equal concentrations is more injurious than NO; however, at concentrations found in the atmosphere, NO_2 is only potentially irritating and related to chronic obstructive pulmonary disease [15].

Current NO_2 concentrations may lead to changes in airway responsiveness and lung function in individuals with preexisting respiratory illnesses and increases in respiratory illnesses in children from 5 to 12 years in age [15]. It is reports that long-term exposures to NO_2 may lead to increased susceptibility to respiratory infection and may cause alterations in the lung. Atmospheric transformation of NO_x can lead to the formation of ozone and nitrogen-bearing particles that are associated with adverse health effects [19].

2.5.3 Particulate Matter

Particulate matter is the general term used for a mixture of solid particles and liquid droplets found in the air. Some particles are large or dark enough to be seen as soot or smoke, while others are so small they cannot be seen with the naked eye. These small particles, which come in a wide range of sizes, originate from many different stationary and mobile sources as well as natural sources [15]. Fine particles, those less than 2.5 μm ($PM_{2.5}$), result from fuel combustion from motor vehicles, power generation, industrial facilities, and residential fire places and woodstoves. Coarse particles, those larger than 2.5 μm but classified as less than 10 μm (PM_{10}), are generally emitted from sources such as vehicles traveling on unpaved roads, materials handling, crushing and grinding operations, and windblown dust [15]. Some particles are emitted directly from their sources, such as smokestacks and cars. In other cases, gases such as SO_2, NO_x, and VOC_s react with other compounds in the air to form fine particles.

Coal generally contains from 5 to 20 weight percent (wt.%) mineral matter (i.e., ash content per a proximate analysis) [10]. During combustion, most of the minerals are transformed into dust-sized glassy particles and, along with some unaltered mineral grains and unburned carbon, are emitted from smokestacks. Particle composition and emission levels are complex functions of firing configuration, boiler operation, and coal properties [16]. In dry-bottom, pulverized coal-fired systems, combustion is very good, and the particles are largely composed of inorganic ash residue. Inner-bottom, pulverized coal-fired units and cyclone-fired boilers, the amount of fly ash is less than in dry-bottom units because some of the ash melts and is removed from the system as slag. Fly ash reinjection for increased consumption of unburned carbon or load changes can also affect particulate emissions.

Particulate matter consists mainly of highly agglomerated solid carbonaceous material and ash, and volatile organic and sulfur compounds. The structure is illustrated schematically in Fig. 4. Solid carbon is formed during combustion in locally fuel rich regions. Much of the carbon is subsequently oxidized with the residue exhausted in the form of solid agglomerates. A tiny fraction of the fuel and atomized and evaporated lube oil escape oxidation and appear as volatile or soluble organic compounds (generally described as the soluble organic fraction, SOF) in the exhaust. The SOF contains polycyclic aromatic compounds containing oxygen, nitrogen, and sulfur. Most of the sulfur in the fuel is oxidized to SO_2, but a small fraction is oxidized to SO_3 that leads to sulfuric acid and sulfate aerosol. Metal compounds in the fuel and lube oil lead to a small amount of inorganic ash. Another one is called by dry soot which defined as a solid substance consisting of roughly carbon and hydrogen that did not completely burned, nucleates from vapor phase to a solid phase in fuel-rich region at elevated temperature. The density is reported to be 1.84 ± 0.1 g/cm^3. The other molecule or unburned hydrocarbon may condense on, or absorbed by soot depend on the time available and condition.

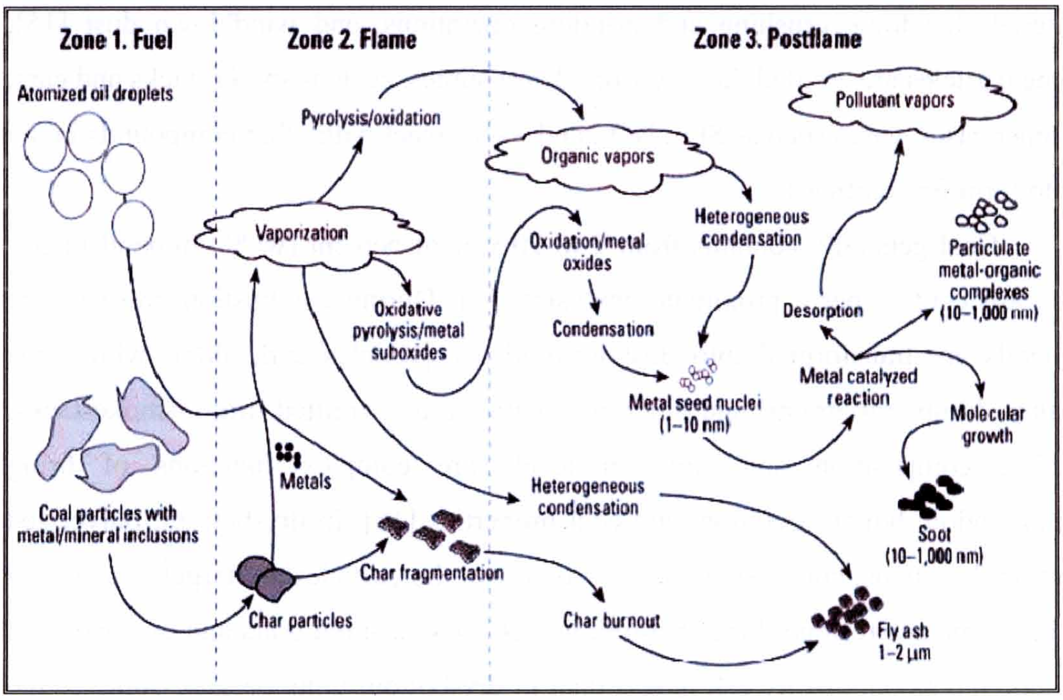


***Fig 2.8** Typical Structure of Exhausts Particles*

2.5.3.1 Particle Dynamic and Particle to Particle Process

Particles may be lost traveling through a sampling system due to inertial impaction, thermophoresis, diffusion, and deposition on electrically charged sampling system surfaces. The evolution of particle in the form of liquid phase hydrocarbons to solid particles and somehow change to be gaseous phase involved in some several processes as follows:

- Pyrolysis and thermophoresis
- Diffusion
- Coagulation
- Inertial Impaction
- Oxidation

Pyrolysis and thermophoresis

Thermophoresis is the motion of a particle from asymmetrical forces that arise from a temperature gradient. This process occurred soon after of process pyrolysis happened. Pyrolysis is the process of organic compounds, such as fuels, altering their molecular structure in the presence of high temperature without significant oxidation even though oxygen species may be present. The importance of thermophoresis increases as particle diameter decreases with the greatest impact on particles in the free molecule regime, it plays a role with all but the largest particulates. Thermophoretic forces cause soot to form a layer on the cool condition. High velocities during blow down cause high shear forces that strip the soot off the walls. Re-entrainment of deposited soot into the exhaust is unpredictable and may account for as much as 20-45% of the measured soot mass.

Diffusion

Diffusion of particles can occurred from both Brownian motion and the movement of particles down a particle concentration gradient. Particles may be lost by diffusion through the boundary layer to the walls of the sampling system. The diffusion coefficient of a particle varies inversely with particle size which the smaller particles diffusing more quickly than larger particles. Loss of particles by diffusion is much faster in highly turbulent flows which have thin boundary layers. Diffusion is most important for particles smaller than about 0.05 μm in diameter.

Coagulation

Coagulation is the process of agglomeration from particle to particle collisions. Small particles may grow by collision with larger particles or with one another. Coagulation changes the size of particles, but does not change the total particle mass concentration. However, it is important to take coagulation into account when attempting to understand particle formation mechanisms. Furthermore, since coagulation changes particle size, it will indirectly influence size dependant loss mechanisms

Inertial Impaction

Inertial Impaction arises from the inability of particles to follow fluid streamlines as a result of their inertia. Particles may be preferentially excluded or included from a sampling stream or lost to the walls by inertial impaction. Particle deposition in bends and contractions will affect the indicated particle measurements. Particles that are deposited through inertial impaction may also be re-entrained into the exhaust stream in an unpredictable manner.

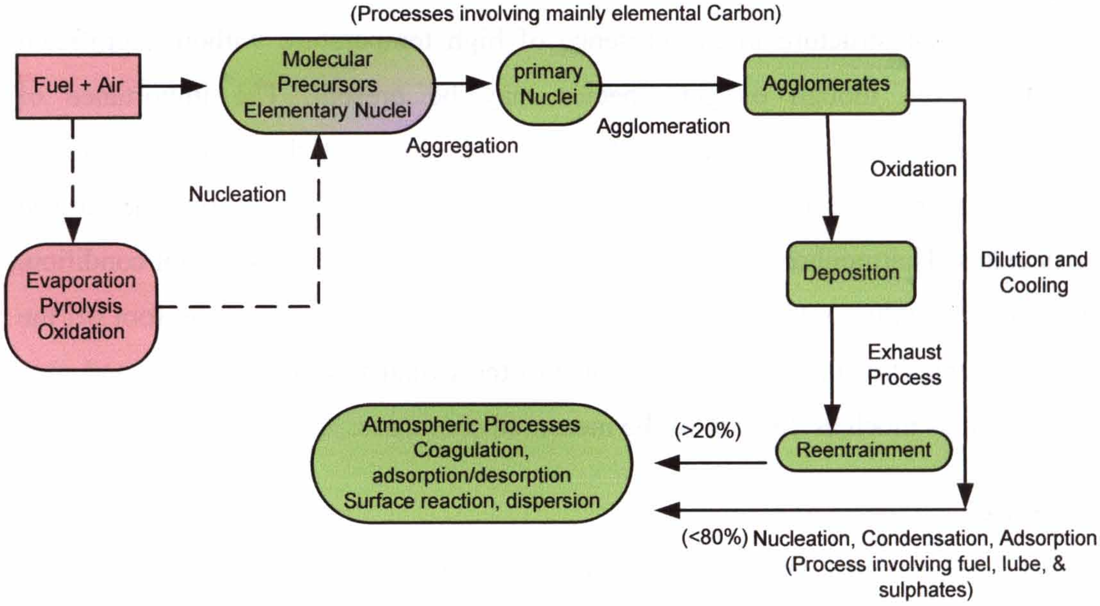


Fig 2. 9 Particulate Formations

Oxidation

Once carbon has been partially oxidized to CO, the carbon will no longer evolve into a soot particle even if entering a fuel-rich zone. Oxidation can take place at any time during the soot formation process from pyrolysis through agglomeration. The most active oxidation species depends on the process and state of the mixture at the time.

Soot particle oxidation occurs when the temperature is higher than 1300 K. There are two process for the oxidation of small particles, First, chemical attachment of oxygen to the surface (absorption), and second, de-absorption of the oxygen with the attached fuel component from the surface as a product.

2.5.3.2 Environmental Effects

Particulate matter is responsible for reduction in visibility. Although these particles are not directly visible, carbon dioxide, water vapor, and ozone in increased concentrations change the absorption and transmission characteristics of the atmosphere [13]. Particulate matter can cause corrosive damage to metals either by intrinsic corrosiveness or by the action of corrosive chemicals absorbed or adsorbed by inert particles. The combination of particulate matter and other pollutants such as sulfur dioxide may affect plant growth. Coarse particles, such as dust, may be deposited directly onto leaf surfaces and reduce gas exchange, increase leaf surface temperature, and decrease photosynthesis.

2.5.3.3 Health Effects

Particulate matter alone or in combination with other pollutants constitutes a very serious health hazard. The pollutants enter the human body mainly via the respiratory system. Inhalable particulate matter includes both fine and coarse particles. These particles can accumulate in the respiratory system and are associated with numerous health effects [17]. Exposure to coarse particles is primarily associated with the aggravation of respiratory conditions such as asthma. Fine particles are most closely associated with such health effects as increased hospital admissions and emergency room visits for heart and lung disease, increased respiratory symptoms and disease, decreased lung function, and even premature death. Sensitive groups that appear to be at greatest risk include the elderly, individuals with cardiopulmonary disease such as asthma, and children [18].

2.5.4 Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless gas that is very stable and has a life of 2 to 4 months in the atmosphere [13]. Similar to organic compounds, it is formed when fuel is not burned completely. It is a component of motor vehicle exhaust, which contributes about 60% of all CO emissions nationwide [18]. High concentrations of CO occur in areas with heavy traffic congestion where as much as 95% of all CO emissions may come from automobile exhaust. Other sources include industrial processes, non-transportation fuel combustion, and natural sources such as wildfires. Carbon monoxide emissions from coal-fired boilers are generally low. Like organic hydrocarbon emissions, CO can be formed during system startup or upset. Also, systems with good combustion control, which is typical of power generation plants, produce little CO.

2.5.4.1 Environmental Effects

Carbon monoxide appears to have no detrimental effects non material surfaces [13]. Experiments have not shown that CO at ambient concentrations produces harmful effects on plant life. Carbon monoxide has been found to be a minor participant in photochemical reactions leading to ozone formation.

2.5.4.2 Health Effects

High concentrations of CO can cause physiological and pathological changes and ultimately death. Carbon monoxide enters the bloodstream through the lungs and reduces the delivery of oxygen to the body's organs and tissues [13]. The health threat from lower levels of CO is most serious for those who suffer from cardiovascular disease, such as angina pectoris. At much higher levels of exposure, CO can be poisonous and even healthy individuals can be affected.

2.5.5 Trace Elements

Human activities, such as power generation and industrial and commercial sectors, also lead to emissions of some elements. Although these elements are present in small concentrations in the coal (i.e., parts per million, ppm, by weight), the large amount of coal burned annually mobilizes tons of these pollutants as particles or gases [19]. The distribution of trace elements in the bottom ash, ash collected in the air pollution control device, and fly ash and gaseous constituents emitted into the atmosphere depends on many factors, including the volatility of the elements, temperature profiles across the system, pollution control devices, and operating conditions [16]. Included in the list are eleven trace elements: antimony

(Sb), arsenic (As), beryllium (Be), cadmium (Cd), chromium (Cr), cobalt (Co), lead (Pb), manganese (Mn), mercury (Hg), nickel (Ni), and selenium(Se). Other elements, such as fluorine (F) and chlorine (Cl), which produce acid gases (i.e., HF and HCl) upon combustion, and radionuclides such as radon (Rn), thorium (Th), and uranium (U) are also of interest. Numerous studies have shown that trace elements can be classified into three broad categories based on their partitioning during coal combustion.

Class I elements are the least volatile and are concentrated in the coarse residues (i.e., bottom ash) or are equally divided between coarse residues and finer particles (i.e., fly ash). ***Class II*** elements will volatilize in the boiler but condense downstream and are concentrated in the finer-sized particles. ***Class III*** elements are themost volatile and exist entirely in the vapor phase. Overlap between classification exists and is a function of fuel, combustion system design, and operating conditions, especially temperature [19].

2.5.5.1 Environmental Effects

The environmental effects of trace elements are a function of the chemical and physical form in which they are found [19]. Environmental effects may occur due to the element itself or as a result of a combination of the element and other compounds. Some trace elements may have an immediate effect in the atmosphere. Trace element metals such as Mn (II) and Fe (III) may contribute to acid rain by promoting oxidation of sulfur dioxide to sulfate in water droplets [19]. Trace elements may also be involved in the complex atmospheric chemistry that forms photochemical smog and may affect cloud formation. Soils may contain high concentrations of certain trace elements due to natural minerals and ores. In addition, deposition of trace elements downwind from power plants can lead to high concentrations in the soils and uptake by plants.

2.5.6 Carbon Dioxide

The Earth naturally absorbs and reflects incoming solar radiation and emits longer wavelength terrestrial (thermal) radiation back into space and known as green gas. These gases includewater vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and, to a lesser extent, halocarbons consisting of hydrochlorofluoro carbons, perfluoro carbons, and sulfur hexafluoride (SF_6). The energy from this absorbed terrestrial radiation warms the Earth's surface and atmosphere. Without the natural heat-trapping properties of these atmospheric gases, the average surface temperature of the Earth would be about 60°F lower. composition of the greenhouse gases is [20]:

- Energy-related CO_2—81%;
- Methane (CH_4)—9%;
- Nitrous oxide (N_2O)—6%;
- Other CO_2—2%;
- Other gases—2%.

Carbon dioxide, methane, and nitrous oxide are continuously emitted to and removed from the atmosphere by natural processes on earth. Climatic changes, which are long-term fluctuations in temperature, precipitation, wind, and other elements of the Earth's climate system. In nature, carbon dioxide is cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. Methane is primarily produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes, such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes, emit methane, as does the decomposition of municipal solid wastes [20].

2.5.6.1 Environmental Effects

Complex climate change models have been developed but the various modelers consider different feedbacks to be more important so markedly different predictions regarding the Earth's climate are obtained. This correlation indicates that increased concentrations of greenhouse gases in the atmosphere have likely increased the amount of heat from the sun that stays within the Earth's ecosystem, thereby contributing to increased global temperatures.

2.5.6.2 Health Effects

Human health is also predicted to be impacted by global climate change. This includes increases in weather-related mortality, infectious diseases, and air-quality respiratory illnesses. Small increases in average temperatures can increase the spread of diseases, such as malaria and dengue fever, and lead to a significant rise in the number of extreme heat waves. Elderly people are particularly vulnerable to heat stress. Heat waves could also aggravate local air quality problems, which pose threats to young children and individuals with asthma.

2.6 Applied Particulate Cleaning Treatment for Coal

Selecting the most suitable device for the removal of particles from a gas stream depends on many things, partly determined by the process i.e. gas stream, partly determined by the particles that are to be removed. Size and size distribution are the most important particle-related factors, followed by their physical and chemical properties: the particles should not destroy the control device, but they should not be "invisible" to the control device either. For larger particles (> 10 μm) gravity and centrifugal forces can be effective, for fine particles (< 2 μm) an electrostatic force can be applied, in combination with particle charging.

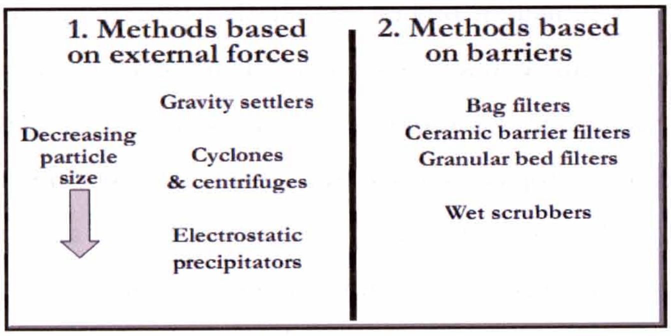


Fig. 2.10 *General classification of particulate device*

2.6.1 Filtration

Filtration of particle derived from combustion in the air commonly employs he fabric bag as filter media, then porous ceramic candles and paper cartridges also in used for cleaning gas steams. The primary collection mechanisms of filtration includes; impaction, interception, and diffusion. Filtration is effective at removing submicron particles because of diffusion mechanism. In the combustion of coal particulate filters are open-pore wall-flow systems, designed either as foams or loosely sintered grains or as textile fiber structures. Three types of fabric filter systems can be distinguished based on the filter cleaning method that is used:

1) Reverse air cleaning,
2) Pulse-jet cleaning and
3) Shake/deflate systems,

Reverse-gas and shake/deflate methods operate off-line, i.e. the dusty gas stream must be temporarily interrupted or by past. The pulse-jet method operates on-line, cleaning a few bags at a time while the rest of the filter bags continue filtration, and is most suitable for outside in filter systems. Although filtration is suitable for removing solids, and both gases and liquids, it is important that the filter remain dry when gases are filtered. In the gas flow, many solids are deliquescent, and if moisture is present, these materials will have a decrease the ability of filtration process.

2.6.2 Electrostatic Precipitator

The removal of particles using electrostatic precipitator (ESP), is based on applying a surface force instead of a body force to fine particles. The surface of the particles is where the electrostatic charge is residing. It is combined effects of the particle production or formation process and further processing such as transport along a conveying system or flue gas duct result in sometimes-large electrostatic charges on solid particulates or droplets. The combination of particle charging, extracting the particle or droplet from the gas stream and deposition on a collection plate system is referred to as electrostatic precipitation. For fly ash emission control from combustion and gasification of fossil fuels, mainly coal and peat,

Four process steps are involved in particle (or droplet) removal by ESP: 1. charging of the particle, 2. Particle movement relative to the gas flow, 3. Particle deposition on a collection surface, 4. Removal of the deposited particles from the system.

Corona particle charging employs ions that are generated at the discharge electrodes which, together with the collector plates produce a highly non-uniform electric field. In general this is accomplished by putting direct current (DC) high voltages of the order of 30 to 75 kV on the discharge electrodes and grounding the collector plates. When operating at negative potential the electrons will travel towards the other electrode, whilst the positive ions will move to and collide with the electrode and become neutralised. Under positive corona operation the positive ions will move across the space between the electrodes after the discharge electrode has taken up the electron.

2.7 Applied Exhaust Gas Cleaning Treatment for Coal

2.7.1 Emulsion Treatment

Mixing of amount of water with a fuel to increase it combustibility by meaning that water molecules are enveloped by fuel molecules called by emulsion fuel type. The emulsification technology was developed to increase the completion of combustion by providing enough oxygen from water. Then, it is followed by the reduction of pollutants formation. The main purposes of emulsion are to convert high viscosity of fuel from semi-solid materials into liquids by mixing process that makes it easier to be handled and transported. The augmentation of water is believed: (1) reducing the combustion temperature, which reduces the nitrogen dioxide production, (2) altering combustion in order to inhibit the soot formation, (3) minimizing the formation of unburned hydrocarbon by providing enough O_2 [21]. In the emulsion treatment, adding water and mixing it with the coal will not smoothly occurred, and needs a surfactant to creates a chemical bonds and good mixing for both water and coal fuel.

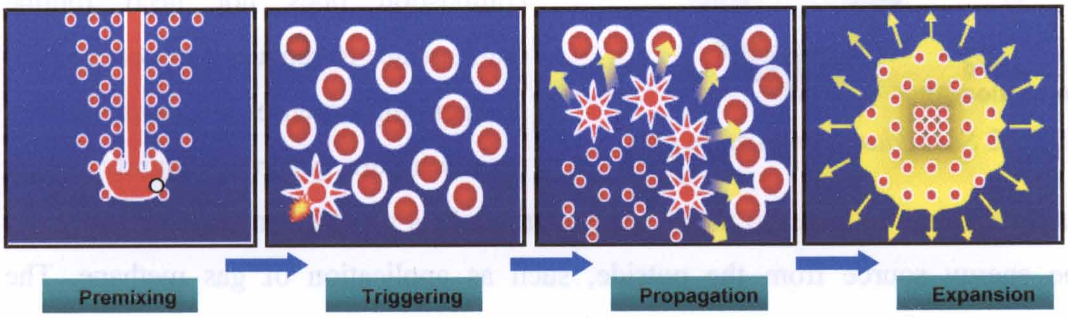


Fig.2.11 *Micro explosion process in the emulsion fuel*

In the emulsion, a phenomena called by micro explosion was happened. Micro explosion occurred as the effect of the presence of water. This phenomenon is believed as the cause of emulsion fuel creates a better combustion and minimizes the formation of pollution. Micro explosion of water droplet normally consist of 4 steps; premixing, triggering, propagation, and expansion. When the emulsion is made, the water droplets were trapped inside the molecules of fuel. In the condition of droplet is heated, the minute particles of mixed droplet can be overheated, but vaporization of water droplet is still suppressed by the fuel surrounding the droplet. At a certain point, the droplet will explode if the suppression is broken [22]. When the emulsion droplet is burning, the mixed components with different boiling points will vaporize and temperature of components with higher boiling point will increase. In the time of temperature becomes higher than the limit of water, overheating and its micro-explosion. The micro-explosion is illustrated in fig.2.11

2.7.2 Secondary combustion

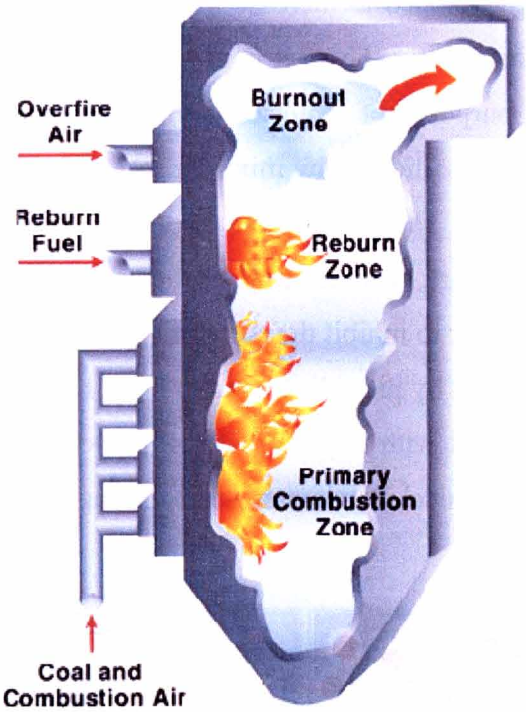


Fig.2.12 *Secondary combustion process*

One way to reduce emissions from coal fuel burning in the boiler is by inserting second line chamber to utilize another combustion chamber downstream from the fireplace where the logs burn. This process, called secondary combustion, re-burns the hot gasses at very high temperature in a small chamber just after they exit the first burner combustion. In contrast to catalytic converters, secondary combustion does not need routine maintenance to replace spent converters, so operating expenses are lower. While, emissions are generally slightly higher become lighter in order to meet the regulation. This treatment normally provide by the energy source from the outside, such as application of gas methane. The application of secondary combustion is applied for the low grade fuel and cannot completely combusted only by one system of combustion process.

Chapter 3

Chapter 3

Experiment

3.1 Scope of Experiment

The treatment of low grade coal by liquefaction process has been conducted in the laboratory scale of research. The main specific objective of the research is to design supporting and measuring system for both the steady combustion of liquid coal oil and emitted exhaust gas components from its combustion. In detail scope of experiments are divided into following steps:

- Setting a flame and combustion from low grade of coal. The process consists of preparation of making experimented fuel, designing the parameter of combustion, and follow by the setting for a steady combustion conditions. The measurement of emitted exhaust gas components and particles by several type of measurement such as; GC&MS, TG/TDA, scanning electron microscope, and pollutants components from exhaust gas.
- By knowing the condition of exhaust gas components, then the treatment of its harmful components must being a consideration. Firstly, the comparison of the combustion conditions and parameters with the emitted exhaust gas components with the one from the C bunker heavy oil combustion is investigated. The results from this comparison will be the input of the treatment process.
- The treatments that applied in this research are divided into two big parts; first one by modification on the composition of coal oil by adding water to lowering the density and to make it easier to be combusted as the effects of enough supply oxygen from the water. Second one by applying after treatments using water spying combine with electrostatic precipitator, and secondary combustion process by designing new combustion process after main combustion process.

3.2 Preparation

In this section, the preparation of combustion is explained. It consists of how making a liquid fuel oil in big scale of industrial process, beside the process of designing the system from the combustor.

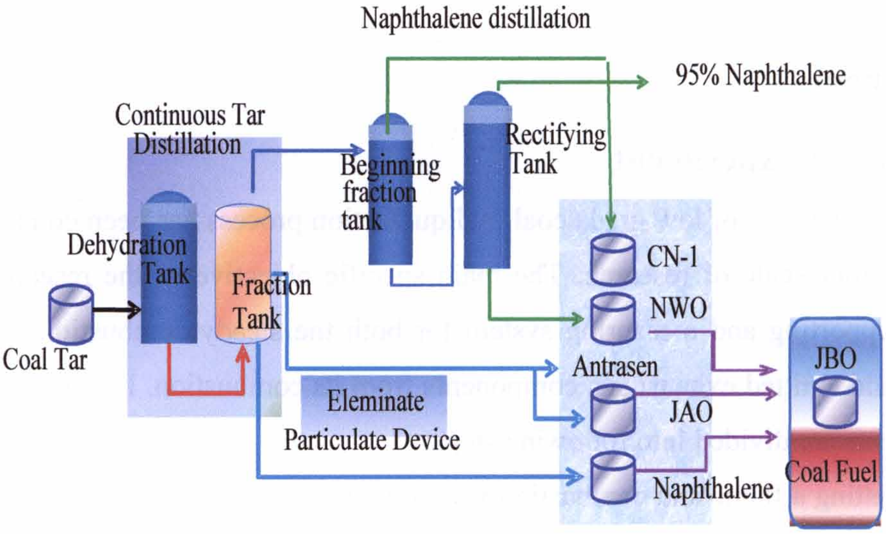


Fig. 3.1 *Coal JBO process*

Fuel for experiments was JBO coal fuel, produced by JFE Chemical Co. Japan. The process of JFO production is categorized as direct liquefaction.

Table 3.1: *Properties of JBO coal fuel*

Components	Unit	Amount
Density (15/4°C)	g/cm^3	1.1937
Kinematic viscosity	cSt	100
Residual carbon	Wt%	250
Flash point	°C	116
Pour point	°C	-7.5
H_2O	Vol.%	0.1
Ash content	Vol.%	0.05
Sulfur	Vol.%	0.50
N	Vol.%	0.72
Vanadium	Vol.%	--
High calorific value	MJ/ kg	38.260
Low calorific value	MJ /kg	37.170

Detail of the liquid coal fuel (JBO) production process can be seen in Fig. 3.1. From the coal tar tank, coal was supplied to a continuous tar distillation process system, and then followed by the naphthalene distillation process which fraction process was undertaken. Slurry from a continuous tar distillation process was treated by using the particle elimination device to eliminate particles inside and naphthalene left in the process was directly come to the tank for mixing process. JBO coal oil was created from the mixing of NWO, antrasen and naphthalene. The photograph 3.2 shows the liquid coal oil. Physically, the fuel was high density, black in color and strong in smell and is not easily transported at room temperature. The properties of JBO coal fuel can be seen in Table 3.1.

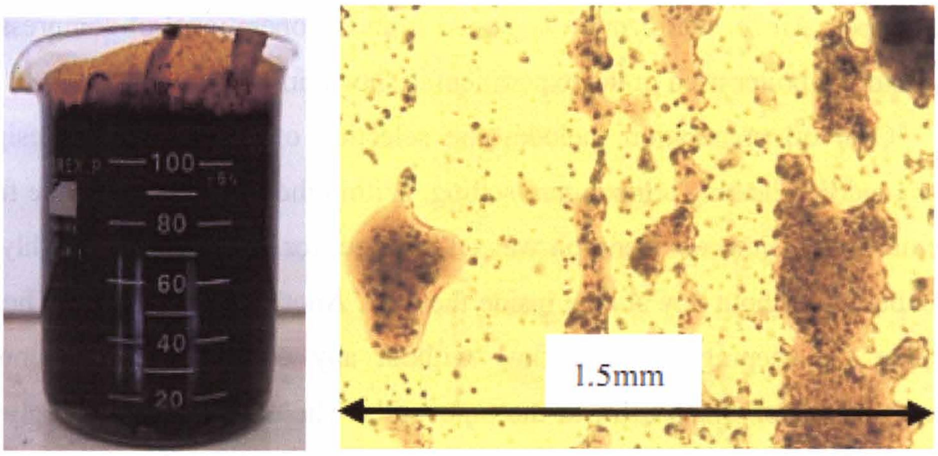


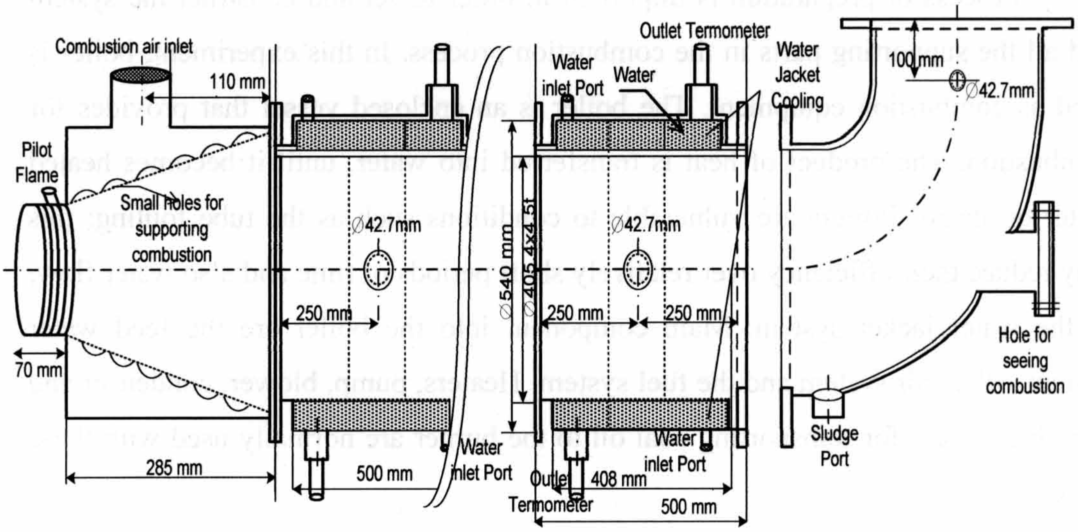
Fig. 3.2 *Liquid coal fuel*

3.3 Combustion Equipments

Process of preparation is important in order to set and construct the system and all the supporting parts in the combustion process. In this experiment, boiler is used as combustion equipment. The boiler is an enclosed vessel that provides for combustion. The product of heat is transferred into water, until it becomes heated water or steam. Boilers are vulnerable to conditions such as the tube fouling; this may reduce their efficiency over relatively short periods of time and also water flow, in the water jacket system. Main component into the boiler are the feed water system, the air system and the fuel system. Heaters, pump, blower, condenser and fuel line system for transporting coal oil to the burner are normally used with these systems.

Feed water system provides water to the boiler. The flow rate of the water inlet was monitored for measuring heat release from combustion, for transferring heat from flue gases to the water inside the boiler`s wall. Two thermometers were located at each of the block tube, with the water jacket system receiving heat by transfer. The block of boiler near to the burner receives the biggest heat via transfer from combustion. In the experiment, 24 ℓ/min of fresh water was supplied by the media of heat transfer inside water jacket system. Two separated systems of air for the combustion process proved important for combustion air support and for air atomization. Air atomization is used to atomize the fuel inside the burner which has a lower speed, surrounded with a high speed stream of air inside the burner. Then, air combustion in the oxygen supply that integrated into the system keeps the fuel burning. Combustion air was supplied by the operation of a blower on a series of air supply pipes. Air for atomization is gained from the operational of compressor. The illustration of boiler used in the experiment is shown in fig. 3.3.

Coal oil preparation includes the selection of tank material, designing a system and line heating temperature setting. Within the construction of the fuel line, there are two major consideration was taken. One, for the coal oil smoothly supply to the burner without any sludge inside the pipe. Another purpose is that heating of the pipe for keeping the fuel flow without any disturbance from unmovable disperses particle, which affix to the pipe walls. The entire coal oil supply system pipe is covered by 45 mm in width and 500 mm length of rope heaters on which the entire normally will be heated up to 130°C and automatically control by a unit on the digital control panel.



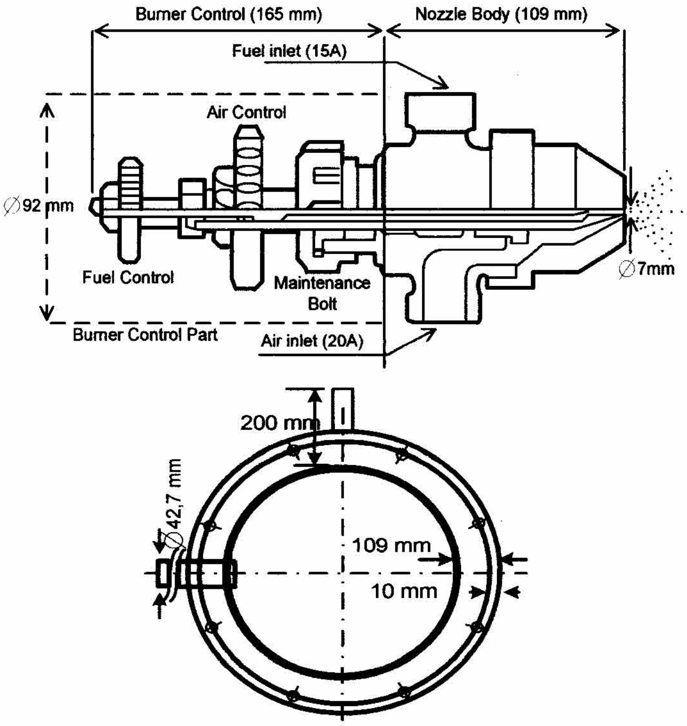


Fig.3.3 *Illustration of boiler and burner for experiment*

Gas, liquid and solid samples were removed from the combustion zone and water-quenched by using a stainless steel sampling probe with 6 mm exhaust gas inlet 500 mm length, produced by Akano illustrated in Fig. 3.4. A thermocouple for temperature measurement on real time sampling is located in the tail of the eyes probe. Sampled exhaust gas flow to different water cooling system to turn down the temperature of exhaust gas before measurement process begin. The sampling exhaust gas from probe was passed though gas cooler before entering several of measurement equipments without dilution air. The coolers prevent the excess water in the gas entering the equipments, which may lead to the malfunction of the equipments. Exhaust gas Concentration of such as; O_2, NO. SO_2, CO, and CO_2 are analyzed by exhaust gas analyzer (Testo 3000). The illustration of sampling point and measurement equipments are shown in fig. 3.5 below.

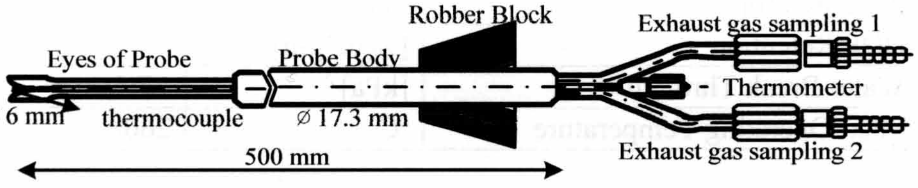


Fig. 3.4 *Probe for taking the data*

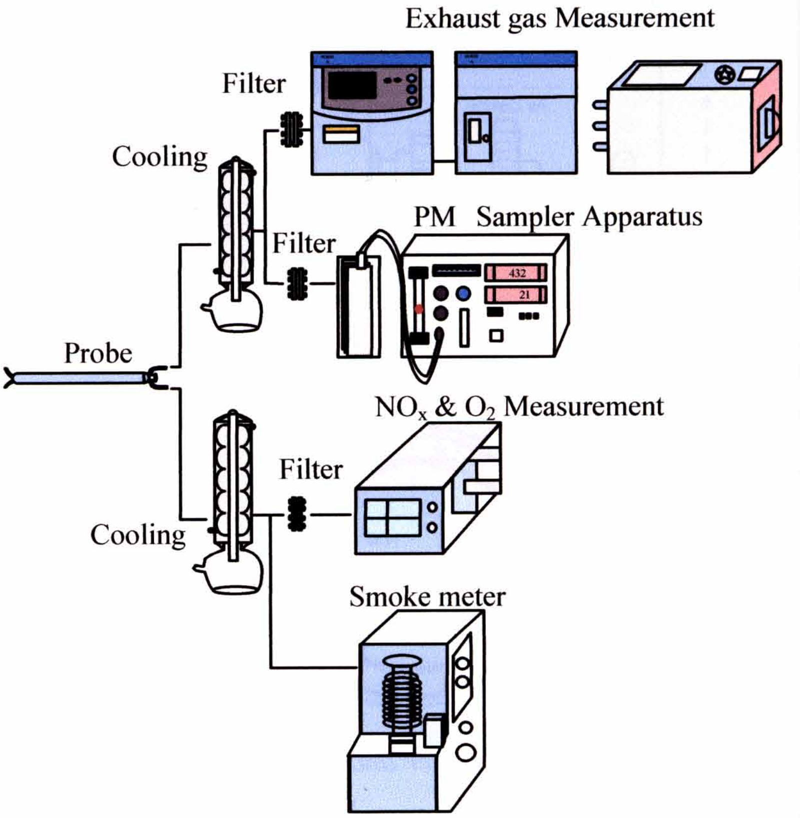


Fig. 3.5 *Exhaust gas measurement equipment flow*

While the Particulate matter samples are taken by composite filter paper at the flow rate of 10 ℓ/m, with total sampling 25 liters per each of samples. Properties of the filter are shown in table 3.2. The heating process for the filter before and after experiment for 50°C in two hours to control weight under strict temperature and relative humidity. Soluble organic fractions (SOF) and soluble organic fraction are separated by using chemical product dichloromethane. Physically, the particulate formation is measured and analyze by using scanning electron microscope.

Table 3. 2. Characteristics of filter

Grade	PG-60	
Weight	g cm^{-2}	60
Thickness	mm	0.15
Pressure drop	kPa	0.3
DOP Retention	[%,0.3μm]^2	99.9
Water Break Through	[kPa]^3	>7.8
Max. Operating Temperature	°C	260

3.4 Thermogravimetry (TD) and Differential Thermal Analysis

Thermogravimetric analysis (TGA) is an experimental technique in which the weight or, strictly speaking, the mass of a sample is measured as a function of sample temperature or time. The sample is typically heated at a constant heating rate (so-called dynamic measurement) or held at a constant temperature (isothermal measurement), but may also be subjected to non-linear temperature programs such as those used in sample controlled TGA (so-called SCTA) experiments. The choice of temperature program will depend upon the type of information required about the sample.

Additionally, the atmosphere used in the TGA experiment plays an important role and can be reactive, oxidizing or inert. Changes in the atmosphere during a measurement may also be made. The results of a TGA measurement are usually displayed as a TGA curve in which mass or is plotted against temperature and/or time. An alternative and complementary presentation is to use the first derivative of the TGA curve with respect to temperature or time. This shows the rate at which the mass changes and is known as the differential thermogravimetric or DTG curve. Mass changes occur when the sample looses material in one of several different ways or reacts with the surrounding atmosphere. This produces steps in the TGA curve or peaks in the DTG curve. Different effects can cause a sample to lose, or even gain, mass and so produce steps in the TGA curve.

3.5 Combustion Process

The system in the experiment has two main lines; Light oil and Coal oil. All lines were designed as an independent system and have no relation to each other. Light oil is used in the beginning and end of an experiment for a cleansing process, this within 10 min of combustion. While no heating process in the whole of the fuel oil's line. When the coal oil is supplied to the burner, heating is the important in order to make liquid coal fuel easier to flow inside pipes. High viscosity of coal fuel must be lowered by heating process. Sampling point for data was created as 60, 110, 160, 210 and 270 cm from the centre of burner (Lc). The sample hole was created with 42.7 mm in diameter, further the probe was inserted to 202.5 mm, the centre of the boiler.

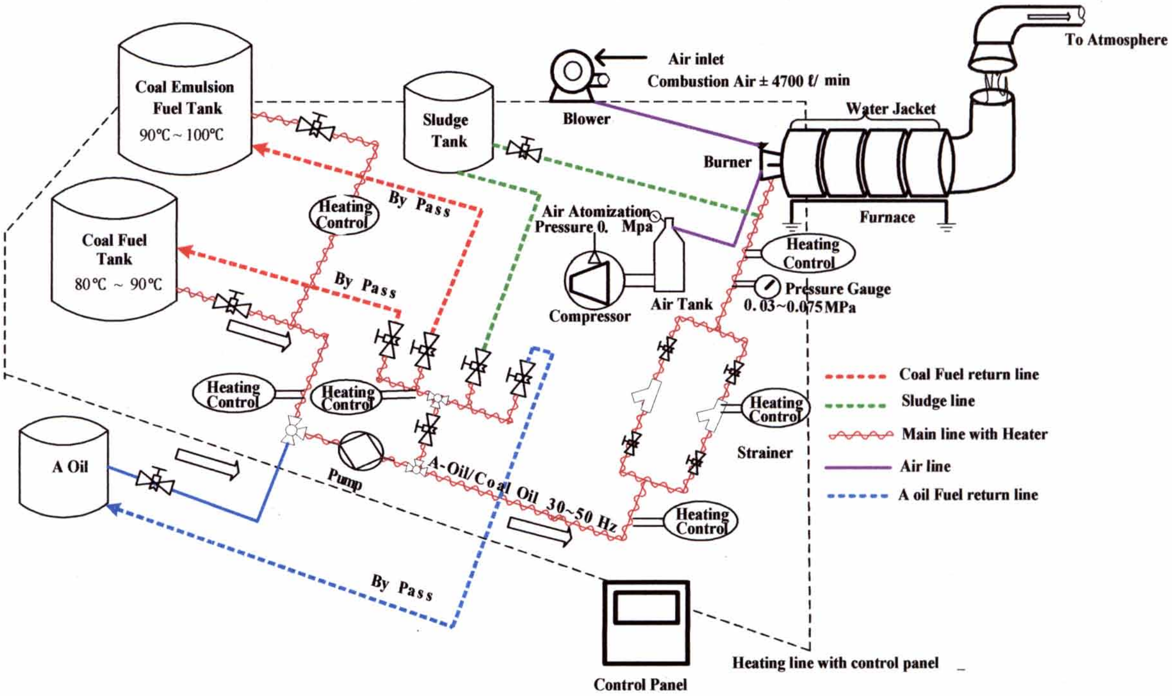


Fig. 3.6 *Design System for the experiment*

The heating temperature for the coal tank and fuel line was set at 120°C. A fuel gear pump is operated at 50~60 Hz with average of fuel flow rate at 2.5 ℓ/min. Two strainers are located before the burner to sludge the macro-molecules inside the oil. In order to keep the pressure in constant flow, a compressor with 0.2 MPa of pressure capacity was used to supply 0.08 MPa pressure air to high pressure air drum, then transferred to the burner to keep a steady supply of air for atomization. Detail of the system use to support liquid coal combustion in the experiment can be seen in Fig. 3.6. All of the apparatus is kept at a stable condition to make the combustion run properly. Probe is put in each of the sampling point hole to get a sample data. The high temperature of exhaust gas must be cooled down before entering a measurement tools needed for the consistence data collection in the measurement process. Two century water coolers were used for cooling and followed by filtering system, to catch disperse particles and minimize particles in the gas sampler equipments.

3.6 GC/MS equipment

Gas chromatography- mass spectrometry (GC/MS) has been widely used for the analysis of chemicals in environment because of its high selectivity of GC column resolution and mass spectrometry. GC/MS is suitable for the analysis of low polar compounds. However, it is difficult to detect polar compounds directly by GC/MS. Several compounds of environment mutagens are highly polar compounds, and it is difficult to apply GC/MS to analyze the trace amounts of them in environment. Gas chromatography and mass spectrum are important measurement process to identify the soluble material and chemical type of material occurred along the combustion process during the thermal decomposition of coal. In this experiment, GCMS – QP 2010 Plus product of Shimadzu are used to analyzed the soluble organic fractions in dichloromethane.

Chapter 4

Chapter 4

Laboratory Scale of Liquid Coal Fuel Combustion Process and Exhaust Gas Formation

Abstract

Much research of coal has been already undertaken to ascertain the possibilities of coal being used as substitute for heavy fuel oil in the transportation sector. This study will review several aspects of the coal oil combustion process including combustion behavior, flame stability, some emissions from exhaust gas; CO, NO_x and the particulate matter in a well insulated laboratory scale furnace for more stable of combustion. New way for preparation for liquid coal oil steady combustion on a 2.75 m horizontal boiler with four annular segment tubes, a water jacket system and a system for measurement of water temperature inside was archived. Preparation for coal oil combustion is an important point in the successful of combustion. Heating coal fuel to than 100°C, heating the fuel line to the same temperature and providing enough air pressure for atomization of coal oil until 0.1 MPa allows coal fuel smoothly atomized in the semi gas phase. There was enough of air combustion via a blower with 4500 ℓ/min of flow rate and a 24 ℓ/min of water flow rate in the water jacket transforms the energy of the fuel to the heat. Uncolored of the exhaust gas and the physical inspection describes the completion of combustion. This result close-relates with the pollutants formation in the exhaust gas. By conducting a deep research process, there is a chance for the substitute of heavy fuel oil with liquid coal fuel with no special treatment needed in combustion process without ignoring the contribution of the combustion results as an environmental problem.

4.1 Introduction

Coal is believed by some to be one of the energy sources for the future, besides alternative energy and others renewable energy sources. The availability of coal as a fossil fuel is approximately predicted to be up to three times in normal use. There are coal deposits in many countries, which is an enormous estate advantage in comparison to crude oil and natural gas. Coal oil is categories as heavy fuel, in same grade with other residual of fossil fuel. Special treatment is needed in order to completely burns and transform the energy inside. Nowadays, coal is expected as the second option of energy source for future transportation. Coal as an alternative energy resource is an attractive technology since it is well developed and thus could be implemented fairly and rapidly. There are comparatively large quantities of coal reserves and its contents less of sulfur that minimizes the formation of SO_x [23]. Many countries have conducted experiment for the possibility of using coal as second alternative fuel for ships and others long distance sea transportation. It can reduce the operational cost. In this study, the pollutants formation for a stable condition of liquid coal fuel, preparation of the combustion process and the condition parameters of the combustion are reported.

4.2 Liquefaction of coal

Coal liquefaction is the process of conversion of coal into synthetic oil. Coal would be gasified to make syngas (a balanced purified mixture of CO and H_2 gas) and the syngas is then condensed, using catalysts to make light hydrocarbons. These can be further processed into lighter fuel. Syngas can also be converted to methanol, which can be used as a fuel, fuel additive, or converted into coal liquid fuel. There are two different methods for converting coal into liquid fuels:

- **Direct liquefaction:** This liquefaction works by dissolving the coal in a solvent at high temperature and pressure. This process is generally achieved by reacting coal as slurry in a process-derived solvent. Different processes may use only hydrogen with the solvent and may operate with or without a reaction catalyst. The process conditions used for this step vary considerably, with temperatures in the range of 300-400°C and pressures of 50-300 bar [24]. Processes that do not use hydrogen at this point tend to operate at low pressures. The more severe conditions are generally associated with processes that carry out both the dissolution of the coal and the hydrocracking of the dissolved products.

- **Indirect liquefaction:** This process was mainly consisted of the complete breakdown of the coal structure by gasification and with steam and oxygen. The composition of gasification products is adjusted to filling the required mixture of hydrogen and carbon monoxide and cleaned to remove the sulfur containing catalyst. This leads for producing high quality and ultra-clean products. In the synthesis step, the resulting synthesis gas is reacted over a catalyst, but at a relatively low pressure operating temperatures in the range of 200-350°C, with operating pressures in the range of 20-30 bars [24].

4.3 Steady Combustion Condition and Parameters

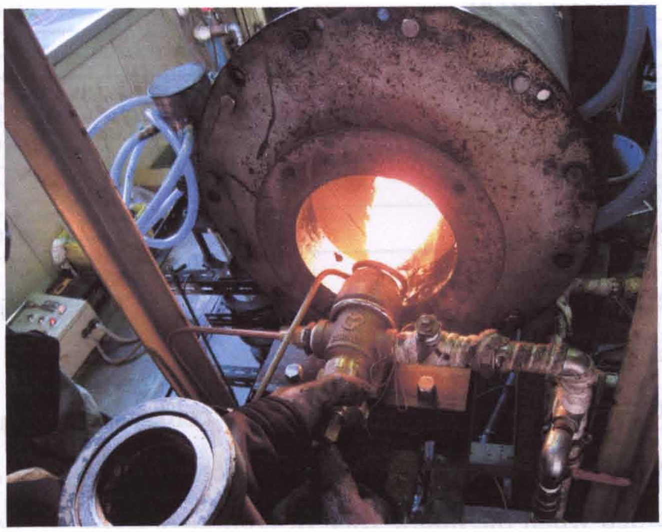


Fig.4.1 *Photograph of coal combustion*

During the combustion process, only gas and Particulate were sampled and analyzed. Temperature exhaust gas and water cooling system were also measured. Combustion process was maintained in the stable condition when data collection was collected. Visual observations of the flame during combustion were made through small windows near the end of four annular tubes. As the combustion and atomization air increased, the flame zone rose being longer in the boiler. Setting process for good mixing between air and coal fuel was the most difficult part since the fuel oil have high density and still contains small particles which flow together inside the pipe. Manual setting on burner for proper combustion took long time. If the fuel was too much atomized, the exhaust gas was black in color, but if less fuel was atomized, the exhaust gas turned into thin white. For this condition, stable flame could not be sustained. The stable condition of combustion is shown in fig. 4.1.Otherwise, when proper of air and fuel were mixed, the exhaust gas was without color. Only heat flux around the wall of the exhaust gas appeared.

Table 4.1 *Steady combustion of coal fuel*

Components	**Coal Oil**
Water Cooling **(ON** / OFF), Flow rate **(l/min)**	23.3 ℓ/min
Exhaust Gas Fan (**On** / OFF), Flow rate **(l/min)**	**On**
Tank Heating (ON /**OFF**), Temperature **(°C)**	**On** (80°C)
Fuel line Heating (ON / **OFF**), Temperature **(°C)**	**On** (120°C)
Pressure from Compressor **(MPa)**	0.86
Pressure inlet of Burner (**MPa)**	0.05
Temperature inlet of Burner **(°C)**	110
Heater setting of inlet Burner **(°C)**	On (110°C)
Pressure of Fuel oil **(MPa)**	0.05
Pump flow Rate **(l/min)**	2.45
Fuel oil Flow Rate (ℓ/min)	0.25
Water Jacket cooling inlet **(°C)**	10
Water jacket cooling outlet **(°C)**	47
Combustion Air **(l/min)**	4700

Air pressure also took an important role in the successful in combustion. Steady supply of air pressure for both atomization and combustion influent to the steady combustion. Air flow rate was varied to achieve the range of air/fuel stoichiometric ratios. Based on the exhaust gas color, a best visual observation of combustion was gained when the major zone of combustion was 80-90 cm, or more, from the nozzle. From an observation of flame in the upside hole near the nozzle, no separation of burner nozzle and point of ignition could be observed. This indicated good combustion. The heat release rate that measured from the difference of inlet and outlet of the water cooling shows at 877.17 kJ/min in 60 cm from the centre of burner and it increase by the longer axial boiler distance 275 cm to 1267.03 kJ/min. Figure 6 shows the combustion and the exhaust gas condition pictures of liquid coal oil combustion when the cover block was opened. It followed by the Table 1 that describes of the condition parameters of the coal combustion, when stability is gained. Best parameters for the combustion was gained and formulated in table 4.1.

4.4 Particulate Matter Component

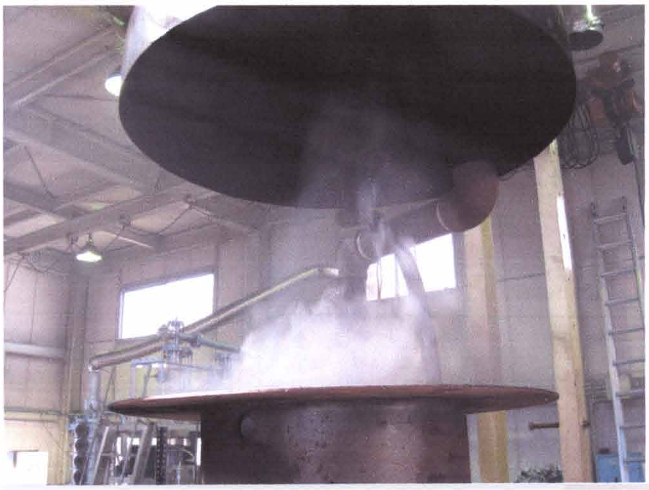


Fig.4.1 *exhaust gas emitted from boiler*

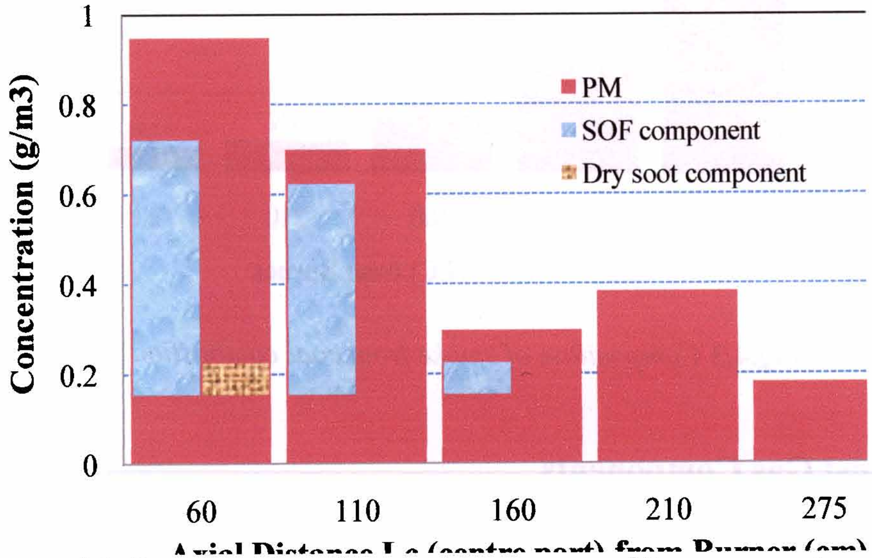


Fig.4.2 *Concentration of particulate matter and its components*

Particulate matter: Particulate Matter (PM) contains a solid part, as well as soluble organic material and sulfuric acid. The solid part consists of carbon (soot) which it was formed during the combustion process [25]. Primary particles formed during period of combustion, is merged by another to be agglomerate particles. Measurement of physical of pm is difficult since the agglomeration process between particles happened rapidly and in sort time. From Fig. 4.2, we saw the build-up of pm mostly occurring in the rich region of combustion and as a result of incomplete combustion. Hydrocarbon inside fuel was not completely burned, which forms soluble organic fraction component. The particulate was identified at 0.948 g/m^3, which inside consist 0.7225 g/m^3 of soluble organic fraction and 0.2255 g/m^3 of dry soot. Then, the increase of axial distance and end of combustion remain 0.179 g/m^3 particulate which inside consist 0.104 g/m^3 of soluble organic fraction and 0.0075 g/m^3 of dry soot. Fig. 4.3 indicates that the smoke percentage when combustion occurred was on axial distance (LC) from Burner 53% at place near the combustion region then decrease until 3% in 275 cm from burner.

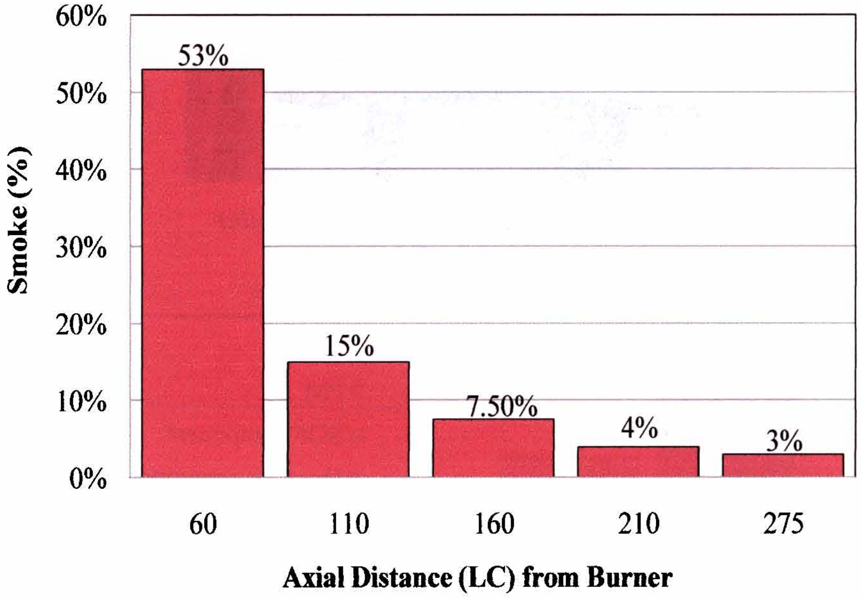


Fig.4.3 *Composition of smoke from coal combustion*

4.5 Exhaust Gas Components

Nitrogen component: Nitrogen is considered an environment problem since it initiates reactions that result in production of ozone and acid rain. The principle pollutants generated by nitrogen are nitric acid (NO) and its derivative, collectively referred to as NO_x [26]. NO forms rapidly than its derivative. From the experiment, the highest NO formation gained at 386 ppm in the 60 cm from the burner then slowly turned down to 229 ppm in the 275 cm from the centre of burner.

There was a not big difference for the concentration of NOx. NOx was 396 ppm at highest concentration and 242 ppm for the lowest one.The NOx formation cannot be separated with the temperature of combustion. Thermal NOx is formed when nitrogen and oxygen in combustion air combine with one another at the high temperature of flame [27].

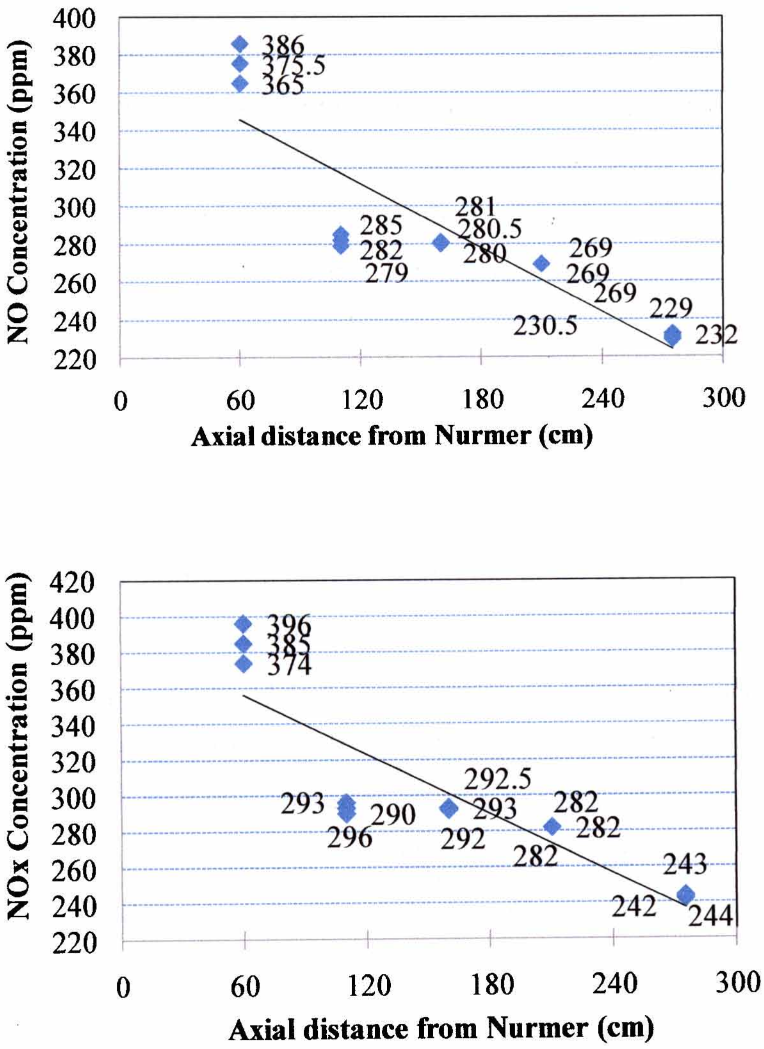


Fig.4.4 *Derivative of nitrogen in the exhaust gas*

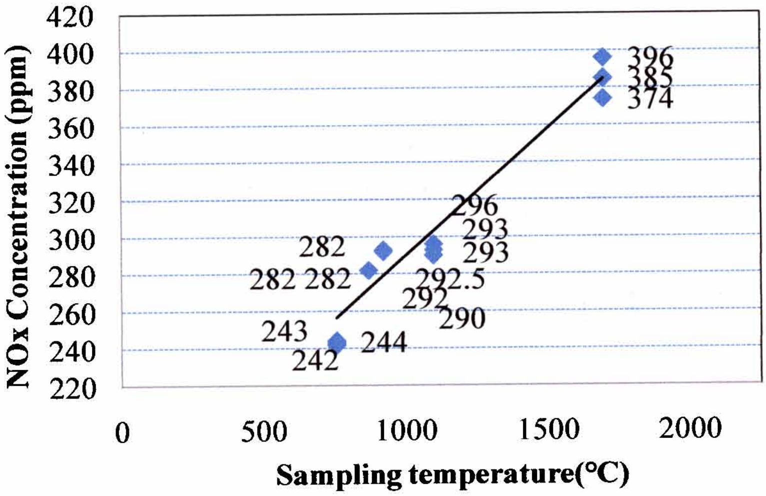
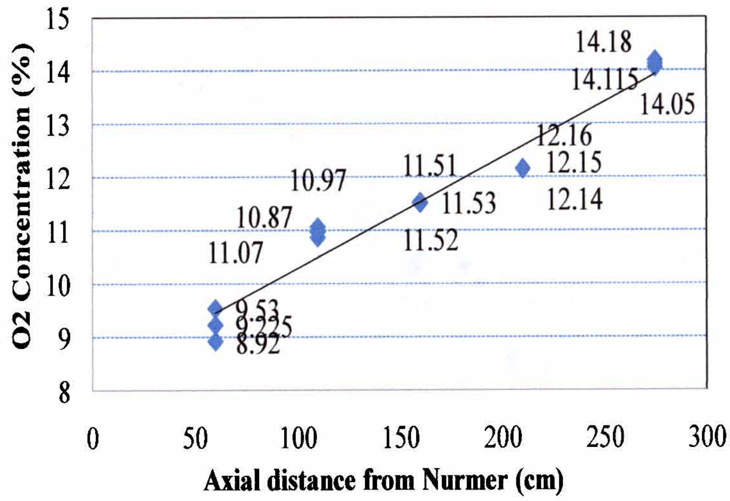


Fig.4.5 *Correlation between temperature and NO$_x$ concentration*

Fig.4.5 clearly describes the correlation between NO_x formation and combustion temperature, based on a sampling temperature. The highest NOx at 396 ppm was measured when the temperature of sampling point was at 400°C and it decreases to 242 ppm while the sampling temperature was on around at 240°C. Figure 4.4 shows the formation for both NO and its derivative. NO and NO_x formation was formed in the same way but different in formation timing.

Carbon and oxygen component: Hydrogen and carbon ware the main component inside fuel. Carbon monoxide (CO) was created as incomplete oxidation of normal result of flame, carbon dioxide. High flame temperature and initiate of air and fuel mixing are the essential for low formation of CO [28]. Figure 4.6 shows the formation of CO, CO_2 and O_2 in the flame. In the combustion, carbon in the fuel oxidizes through a series of reactions to form carbon dioxide. However, it is impossible of 100% conversion of carbon to CO_2. CO emission primarily results from incomplete combustion due to poor combustion and firing condition. Limited time in the rich zone of combustion process caused incomplete formation of CO_2 which created the high value for CO. This concentration will decrease by the increase length from the burner. Proper of modification in ratio of air and fuel mixing patterns will reduce the CO formation. Concentration of CO_2 varying from 7.9-4.4% while concentration of CO as incomplete oxidation was gained from 2000-776 ppm in 275 cm horizontal length from the centre of burner. Length of combustion flame and limited reaction region affects to the formation CO_2 and CO.



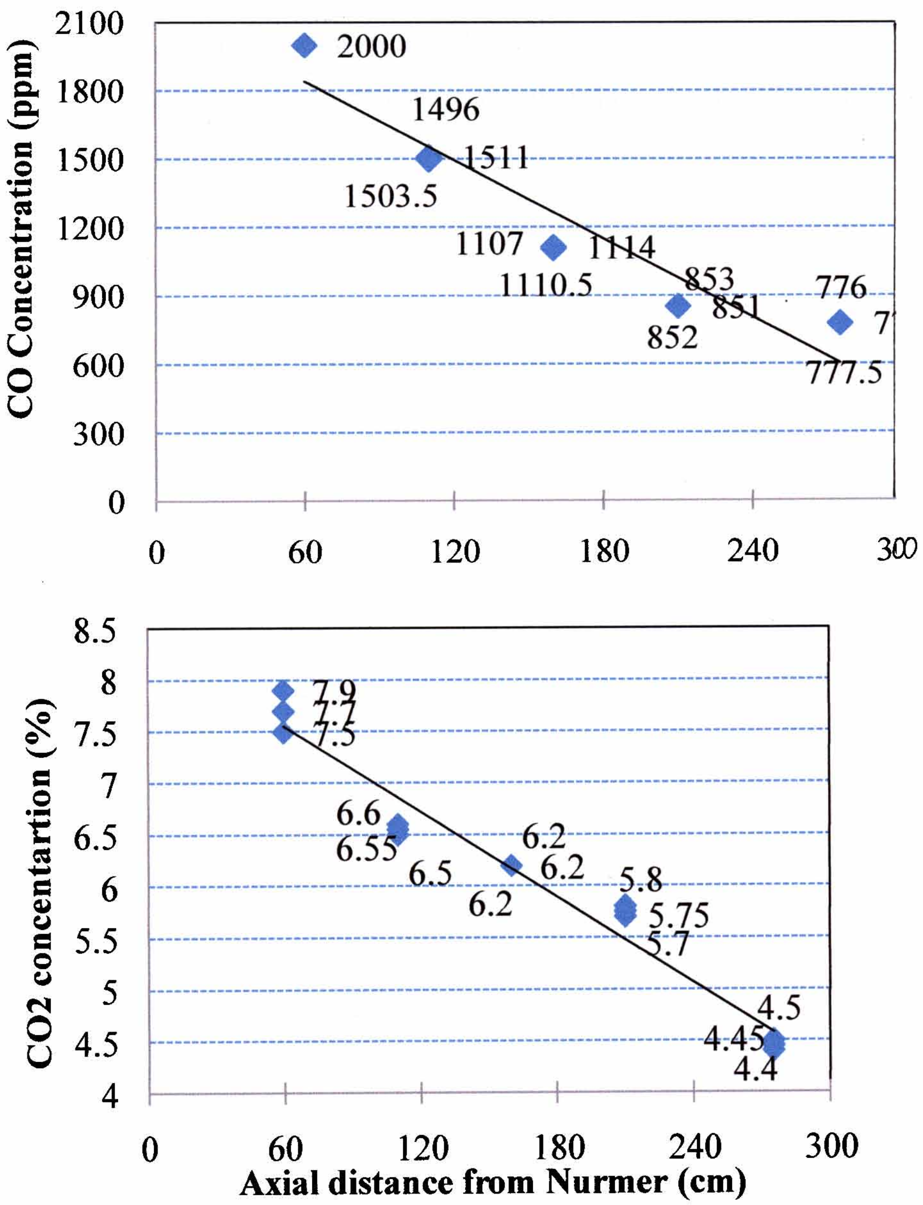


Fig.4.6 *Oxygen and carbon components*

4.6 Conclusions

An experimental study was conducted on the laboratory scale for liquid coal fuel combustion process and exhaust gas formation. Detail of combustion process, beginning from the preparation of the system for fuel line, the heating system and the boiler setting for steady combustion of liquid coal have been explained. The side product of combustion which contributes to the formation of emission and pollution was also investigated. The particulate component was measured at 0.948 g/m^3 in 60 cm from the centre of the burner to 0.179 g/m^3 in the 275 cm from the centre of the burner. While the NOx component was measured at 396-242 ppm. From this experiment, by good preparation for steady combustion, there is a chance for the substitute of derivative fossil fuel with coal fuel with no special treatment is needed.

Chapter 5

Chapter 5

Comparison Study of C heavy oil and Coal Oil: Gas Pollutants Formation and Combustion Parameters

Abstract

The process of finding a new energy and the consideration for its effects to the environmental problem have been being the focus of many researchers to create a better of environment living as green environment. The diversity of oils that used in the transportation operational will carry out the different pollutant concentration. A ship, as one of the important transportation in the operational always uses the C heavy fuel in the operational, and A heavy oil for the up/down loading process. In this research, the possibility of coal fuel from the liquefaction process is tested in the horizontal boiler with the fresh water cooling system. The results of an experiment then compare with the C heavy oil for both parameters of the stable combustion and the emitted exhaust gas. The results of comparison shows that coal oil produced higher concentration of exhaust gas pollutants components, and stable condition is easer gained by manual setting of C heavy oil then coal oil. Making of stable condition needs more effort and more supply for both coal fuel and air. The treatment for its result should be applied whether coal oil being applied in the marine transportation.

5.1 Introduction

Attempts to reduce greenhouse gas emissions and rising oil prices have favored a change from fossil oil to renewable bio fuels or finding sources in energy production in the past years. Particularly in transportation sector that most taking consumption of fossil fuel besides the electricity and industrial sectors. The economical feasibility, steady on supply and long time of consumable energy source being the basic consideration for the substitute of the fossil fuel. Many of these may be replaced to ones operating on solid or converting solid fuel to the liquid. The depletion of light petroleum reserves and light oil production has forced refiners to process crudes containing a considerable amount of heavy ends. The politically controlled availability of the lighter petroleum, emphasizes the need for technology that provides greater flexibility in feedstock selection and process ability. The conversion of coal oil and residual into distillate liquids by employing conventional petroleum catalytic cracking or hydro-cracking technology is not straightforward. Furthermore, this change may significantly affect to the particle emissions as well as the pollutants from the exhaust gas of combustion and heat production. The objective of this research was to create a steady combustion of liquid coal fuel and compare with the C heavy fuel to know its feasibility as the substitute for marine applications.

5.2 The Combustion Parameters

The photographs of combustion for both C heavy oil and coal oil are shown in fig. 5.1 below. Physically, the combustion of C heavy oil create a better combustion condition with more steady combustion control, and it is believed also giving impacts to the pollutants formation from the exhaust gas, which it will be less formation then coal oil one.

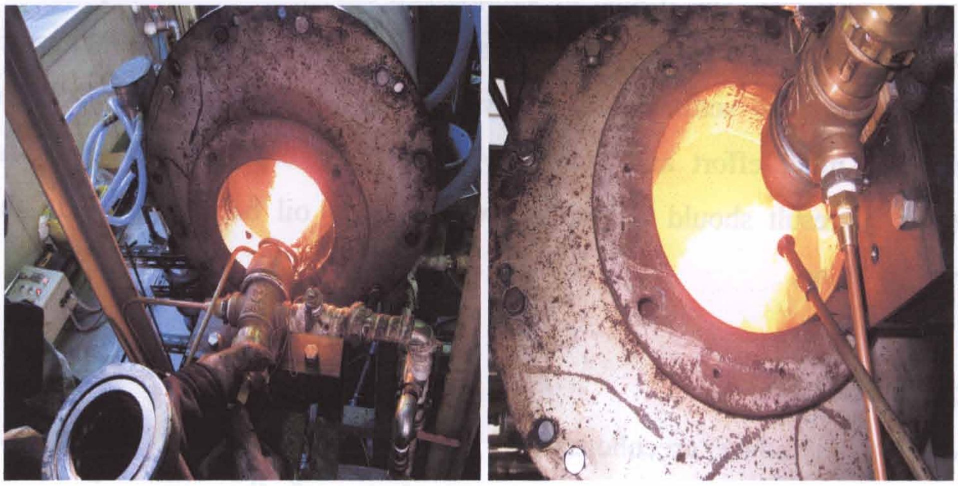


Fig.5.1 *Photograph of coal (left) and C heavy oil (right) Combustion*

The steady combustion of coal oil gained by many preparation beginning from the heating process in the fuel line, fuel tank, and burner parts. Air for combustion also needed in bigger amount of air, and a support of combustion air was needed. The properties of fuels make a different of combustion parameters. The detail of experimented fuel`s properties, and combustion parameters for a steady combustion were shown in table 5.1 and 5.2

Table 5.1. *The properties of experimented fuels*

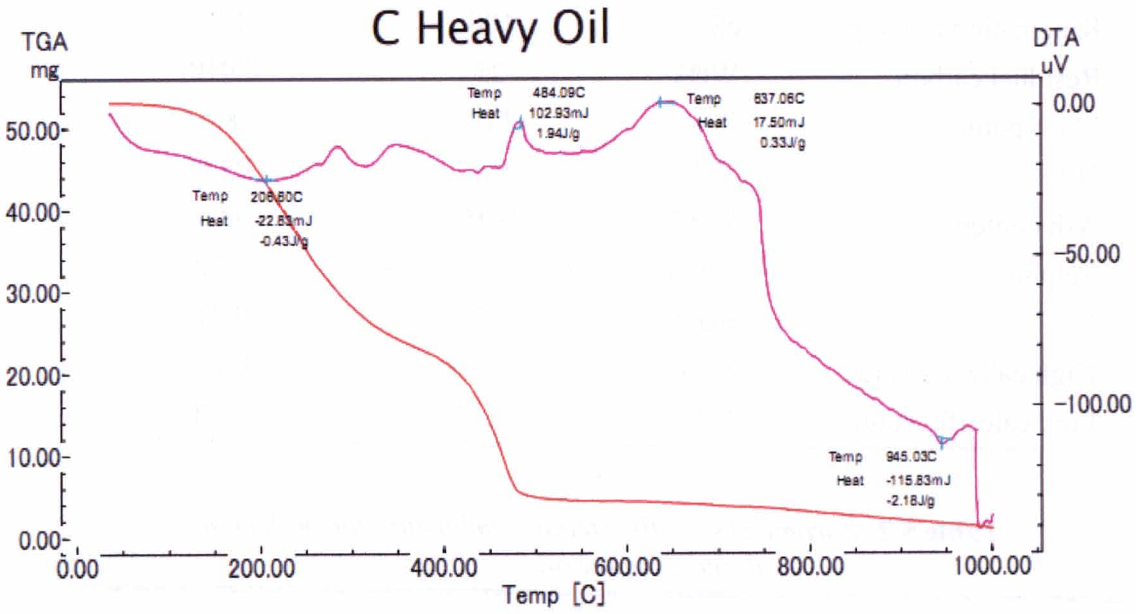
Components	Unit	Fuel oils	
		Coal oil	C Heavy Oil
Density (15/4°C)	g cm^{-3}	1.1937	0.9612
Kinematic viscosity	cSt	100	170
Residual carbon	Wt%	25	0.010
Flash point	°C	116	82
H_2O	Vol.%	0.1	0.00
Ash content	Vol.%	0.05	0.01
Sulphur	Vol.%	0.5	2.20
N	Vol.%	0.72	0.21
High calorific value	MJ kg^{-1}	38.26	43.29
Low calorific value	MJ kg^{-1}	37.17	40.90

Table 5.2. *Parameters for the steady combustion for both coal oil and C heavy oil*

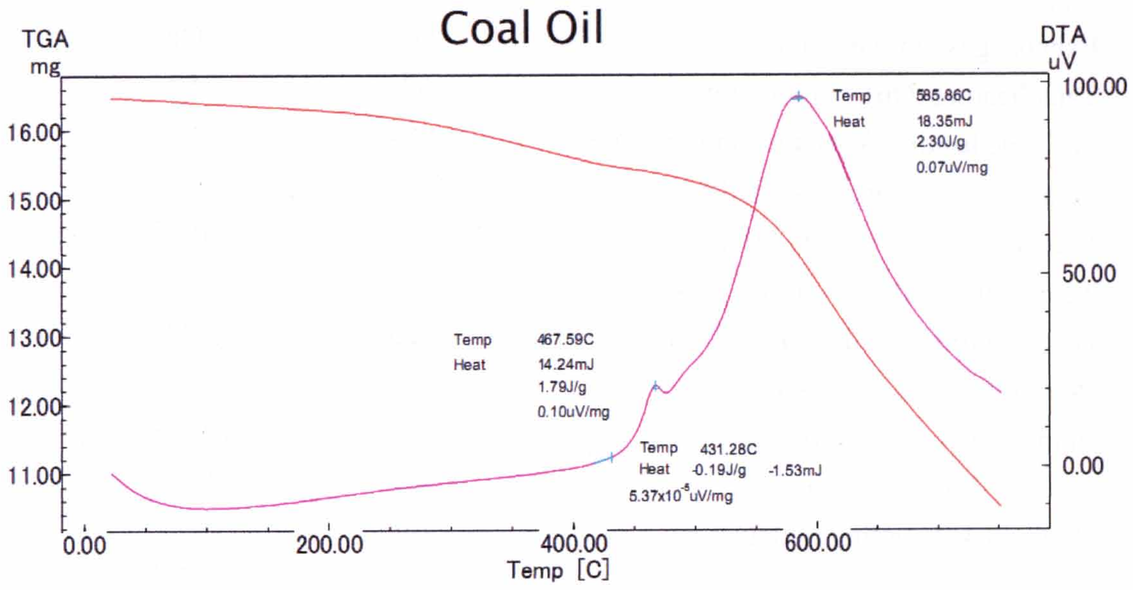
Components	Coal Oil	C Heavy Oil
Water cooling (On), flow rate (l/min)	24.09	24.09
Exhaust gas fan (On/Off)	On	On
Tank heating (On), temperature (°C)	90	80
Fuel line heating (On), temperature (°C)	120	96
Pressure from compressor (MPa)	0.86	0.1
Pressure inlet of burner (MPa)	0.1	0.09
Temperature inlet of burner (°C)	110	90
Heater setting of inlet burner (°C)	110	100
Pressure of fuel oil (MPa)	0.07	0.08
Pump flow rate (l/min)	0.25	0.21
Fuel oil flow rate (l/ min)	2.5	2.2137
Water jacket cooling outlet (°C)	60	65
Combustion air (l/ min)	4700	4700

5.3 Thermogravimetry (TG) and Differential Thermal Analysis

Thermogravimetry (TG/DTA) has been used to obtain information on the temperature controlled combustion characteristics of experimented coal fuel and C heavy fuel. Experiments were performed in air atmosphere up to 750°C at a heating rate of 10°C per minutes. The TG/DTA curves clearly demonstrate distinct transitional stages in the entire coal oil samples studied.



(a) DT/TGA of C heavy oil



(b) DT/TGA of coal oil

Fig.5.2 *Results of DT/TGA analysis*

Reaction intervals, peak and burn-out temperatures of the coal samples are also determined. In addition to showing the energetic nature of weight loss events, the DTA signal can so show thermal effects that are not accompanied by a change in mass, e.g. melting, crystallization or a glass transition. The evaluation is usually restricted to the determination of onset and peak temperatures. Processes involving a loss of mass usually give rise to endothermic DTA effects because of the work of expansion. Fig.5.2 shows the TG/DTA analysis for experimented fuels. Coal oil combustion need more time to be combusted, while the C heavy oil commonly creates continuously combustion by the increase of temperature combustion. The maximum temperature combustion of C heavy oil is higher than coal oil one.

5.4 Combustion Temperature and Heat Release

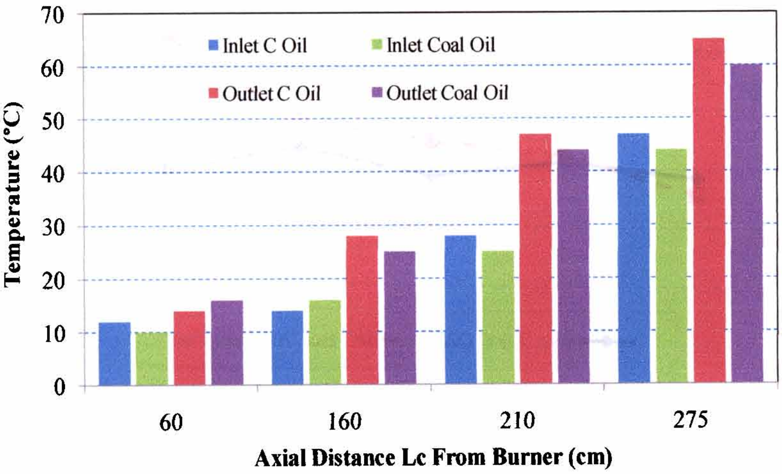


Fig.5.3 *In-out temperature of combustion for experimented fuels*

Fig. 5.3 shows the temperature of combustion process that being transferred to the fresh water as the cooling system for the boiler. The average of fuel oil consumption from the experiments shows that C heavy oil up to 2.214 ℓ/min, and 2.54 ℓ/min for coal oil. The emitted energy that derived from the result of combustion to the media of cooling indicated the increasing trend. It can be one denote that the transfer energy is getting bigger. From the in-out thermometer that located in the wall of boiler as row data, the heat release can be determinate by using a mathematical approach. The heat release of both experimented fuels confirms that coal oil is lower than C heavy oil.

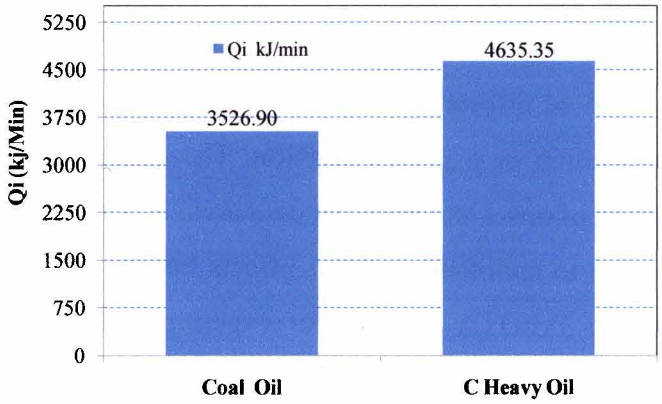


Fig.5.4 *Average of heat release for experimented fuels*

5.5 Exceed Air

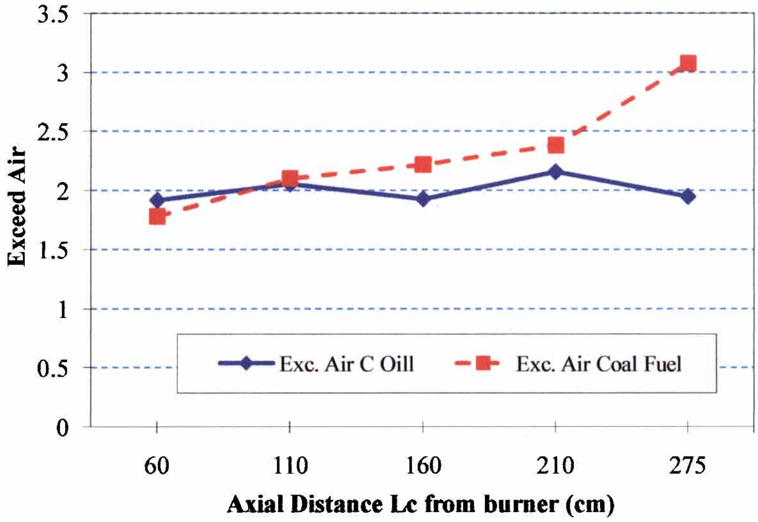


Fig.5.5 *Percentage of exceed air*

Insufficient combustion air causes a reduction in fuel efficiency, creates highly toxic carbon monoxide gas and produces soot. To ensure there is enough oxygen to completely react with the fuel, extra combustion air is usually supplied. This extra air, called *exceed air* is expressed as the percent air above the amount theoretically needed for complete combustion. Adding additional excess air is often done to reduce the CO concentration. Too much excess air can actually have the reverse effect of increasing CO. This results when fuel and air no longer mix properly in the burner, reducing the time of contact between oxygen and fuel and inhibiting a complete reaction. From fig. 5.5, the exceed air of coal oil and C heavy oil for the same steady condition shows same concentration.

5.6 Exhaust gas components

5.6.1 Oxygen and Carbon derivative

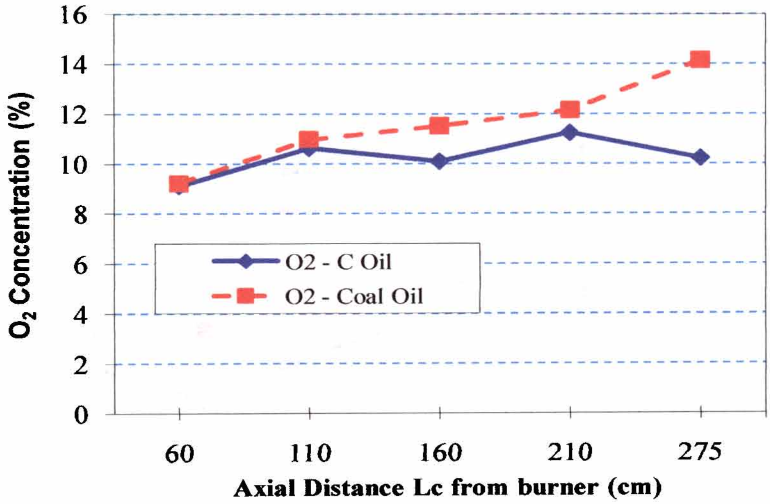
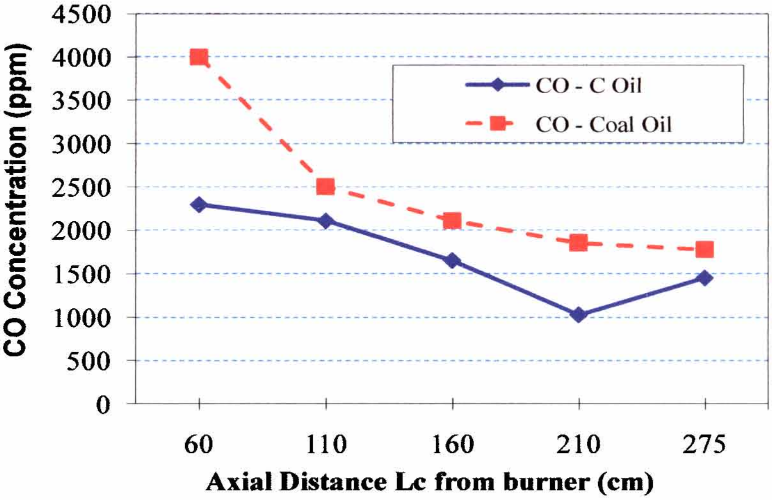


Fig.5.6 *Concentration of oxygen*

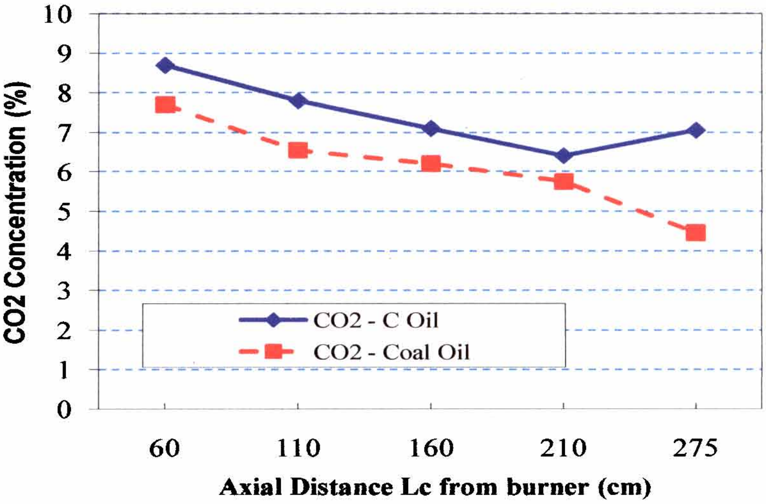
The close-relation between concentration of oxygen and carbon derivative in the combustion are figured out in the fig. 5.6 for the oxygen, and fig. 5.7 for the derivative of carbon. From fig. 5.6, the concentration for both of C heavy oil and coal oil increased by the longer of measurement point from the centre of boiler with the C heavy oil one lower than coal oil. Simple combustion involves reaction of oxygen in the air with carbon and hydrogen in the fuel to form carbon dioxide, water, and produce heat. Under ideal conditions, the only gases in the exhaust flue are CO_2, water vapor and nitrogen from the combustion air. When too small supply air is supplied to the burner, there is not enough oxygen to completely form CO_2 with all the carbon in the fuel. Instead, some oxygen combines with carbon to form carbon monoxide (CO). CO is a highly toxic gas associated with incomplete combustion and efforts must be made to minimize its formation.

The most efficient and cost-effective use of fuel takes place when the CO_2 concentration in the exhaust is maximized. This occurs when there is enough O_2 in the supplied air to react with all the carbon in the fuel supplied. As the air level is increased and approaches 100% air, the concentration of CO molecules decreases rapidly as they pick up additional oxygen atoms and forms CO_2. It will give more combustion air and CO_2 reaches a maximum value. After that, air begins to dilute the exhaust gases, causing the CO_2 concentration to drop. The maximum value of

CO_2 is dependent on the type of experimented fuels. The details of experiment result were figured out in fig. 5.7 (a) and (b). The average difference of C heavy oil and coal oil; O_2 (11.59%), CO (30.32%), and CO_2 (20.88%) with coal oil concentration is higher respectively.



(a) Concentration of cabon monixide

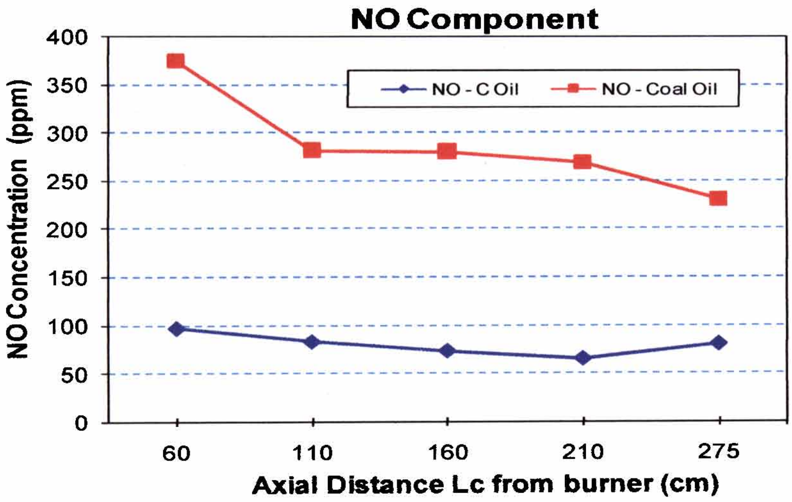


(b) Concentration of carbon dioxide

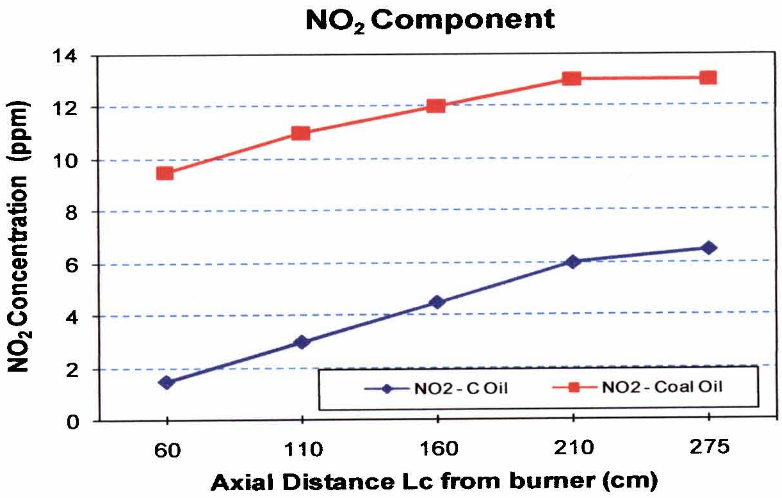
Fig.5.7 *Concentration of derivate carbon*

5.6.2 Derivative of Nitrogen

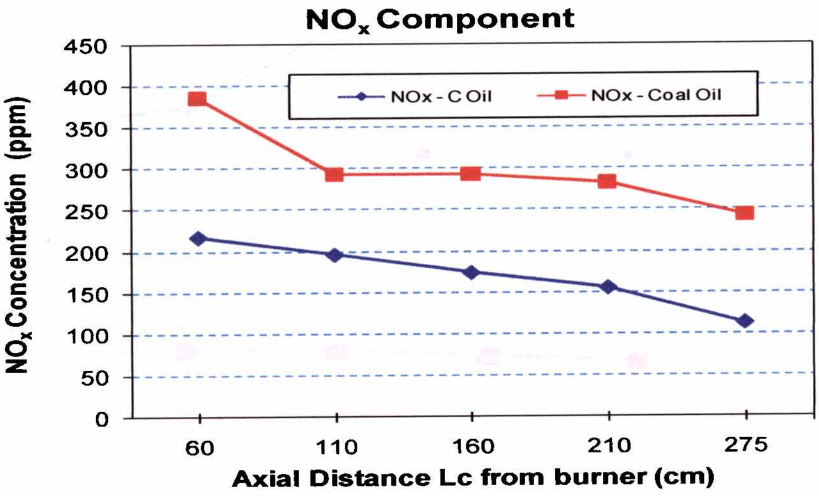
Nitrogen oxides, principally consists of nitric oxide (NO) and nitrogen dioxide (NO_2), are pollutant gases that contribute to the formation of acid rain, ozone and smog. The derivatives of nitrogen component result from the combustion are shown in the fig. 5.8.



(a) *Concentration of nitrogen monoxide*



(b) *Concentration of nitrogen Oxide*



(c) *Concentration of Nitrogen dioxide*

Fig.5.8 *Concentration of derivate nitrogen*

The graphs consists nitrogen of oxide and detail concentration of nitrogen monoxide, and nitrogen dioxide. The average difference of C heavy oil and coal oil; NO (72.208%), NO_2 (63.247%), and NO_x (42.76%) with coal oil is higher respectively. From these graphs there is a summary that the coal oil still produced higher concentration of nitrogen oxide then C heavy oil. Nitrogen oxides formed when oxygen combines with nitrogen in the air or in the fuel. NO is generated first at high flame temperatures, and then oxidizes further to form NO_2 at cooler temperatures in the stack or after being exhausted (fig. 5.8 (a)). The oxidation of NO concentration to NO_2 depends on the available time for the reaction beside its availability of the NO concentration. Less time will produce small concentration of NO_2.

5.6.3 Sulfur Content

Sulfur dioxide makes up about 95% of all of the sulfur oxides that is released during combustion. Sulfur dioxide combines with water vapor in the exhaust to form a sulfuric acid mist. Fig. 5.9 shows the concentration of sulfur dioxide from coal oil is extremely lower then C heavy oil as result of low content of sulfur in coal that is shown in the table 3.1. Sulfur dioxide occurs when the fuel contains sulfur and where the emission levels are directly related to the amount of sulfur in the fuel.

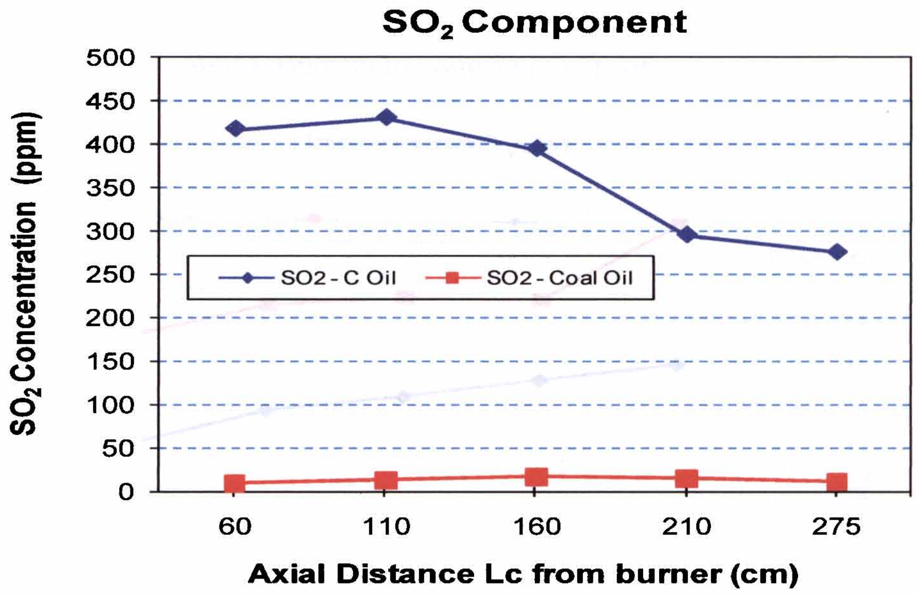


Fig.5.9 *Concentration of sulfur dioxide*

5.7 Summary

An experimental study for the comparison of coal oil and C bunker heavy oil was conducted to characterize the potential of coal oil to be the substitute of C oil for the ships operational. Before the experiment, the tested fuel's combustibility was measured by using TG/DTA. The higher result of combustion from TG/DTA for C heavy oil occurred at 637.08 °C, 17.50 mJ, and coal oil at 585.80 °C, 18.35mJ. While steady combustion was gained, the photograph and parameters of combustion were taken. The incomplete combustion side product that produces pollution was also measured. The results indicated that concentration for all of coal oil combustion side products was higher than C heavy oil. The concentration of oxygen and derivative of oxygen was confirmed as; O_2 (11.59%), CO (30.32%), and CO_2 (20.88%), while the nitrogen derivative concentration as; NO (72.208%), NO_2 (63.247%), and NO_x (42.76%). Temperature of combustion and fuel oil consumption also measured for indicating the heat release energy that transferred from combustion to the cooling media. The result shows that coal oil produced 3526,98 kJ/minutes, and C heavy oil was at 4635.31 kJ/minutes

Chapter 6

Chapter 6

Characterization of the Particulate from the Combustion of Coal oil and C Heavy Oil

Abstract

This study discusses the characteristics of particulate emission for the combustion of coal fuel and heavy fuel oil. Combustion process was set up in a laboratory scale experiment on a 2.75 m horizontal boiler with four annular segment tubes, a water jacket system, and a measurement system for remaining particulate from the combustion. Four sampling points at 60 cm, 110 cm, 160 cm, and 210 cm from the centre of the boiler were used to obtain the data. The particulate was collected by using filtering method with Poly-tetra flour ethylene (PTFE) coated composite filter. The concentration of dry soot and soluble organic fractions are measured based on the data from samplings. The soluble organic fractions that derived from unburned hydrocarbon were identified by using dichloromethane. From this study, the steady combustion of coal oil was achieved and the combustion of coal fuel produced more particulate than the heavy oil. It also concludes that the Application of coal oil as the substitute of the heavy oil still can be a consideration with deeply study the impact to the environment.

6.1 Introduction

There are many research and experiment activities carried out vigorously by many researchers around the world to find the substitute of fossil energy. The condition of uncontrolled-use of fossil energy causes their demands now are in the critical condition. An effective and environmental friendly of the energy substitute are urgently needed to avoid much damage to the environment and to the human being. Moreover, fossil fuel mainly gives an impact from the hazardous of human health such as; respiratory illnesses and cancer to the hazardous for the environment such as acid rain and global warming [23]. Coal that having huge availability and potential of energy source, did not managed for a good to be an alternative energy source. Converting coal into the liquid by a liquefaction process has been achieved, and it is believed as backup energy of the fossil fuel and one of the available alternative energy.

Air pollution comes from many sources; much of it was generated from the processes that related to the energy use, transportation, consumer products, and equipment from industrial. Some of the fuel components were not burned completely that create the pollutants in both gasses and unburned carbonaceous particulates. Gasses pollutants from the combustion appear in the forms of sulphur oxide (SO_x), nitrogen oxide (NO_x), carbon monoxide (CO) and other pollutants material. Thus, the carbonaceous particulate emitted from the combustion is known as particulate matter (PM). It consists an elemental of carbon chain, with several organic compounds, sulphate, metals, acid, fuel vapor, and unburned lubricating oil that also absorbed into its surface [24]. The size and concentration of these particulates are varying depending to the engine load, speed, and fuel composition. The conversion of heavy oil and residual into distillate liquids by employing conventional petroleum catalytic cracking or hydro-cracking technology is not straightforward. Furthermore, this change may significantly affect to the particle emissions as well as the pollutants from the exhaust gas of combustion and heat production. The objective of this research was to create a steady combustion of liquid coal fuel and compare with the C heavy fuel to know its feasibility as the substitute for marine applications.

6.2 Particulate Emission

Particulate emission is defined as tiny particles of solid or liquid suspended in the exhaust gas. These particles mainly formed when the hydrocarbon in the fuel did not completely oxidized during the combustion process, create the semi organic particle that flows together in the exhaust gas stream. The formation of PM depends on the fuel quality, combustion process, as well as the available time for the combustion process [25]. PM consists of two big parts; soluble organic fractions and dry soot. The dry soot formed when the fuel burned not completely, then it changes by a very high temperature from combustion process. Thus, the soluble organic fraction is derived from the unburned hydrocarbon which inside particles are still containing of organic material that needs to be oxidized.

The formation of PM was by two processes; as a product of the combustion in a single particle formation, and it grows from the nuclei or single nano particles [26] as a single particle formation, the nucleation formation step involves the transformation of vapour or liquid after combustion into the cluster formation of nano particle. It remains on the organic material result from the combustion that forms large particles. The formation process is supported by the decrease of temperature in a series of reversible steps. The stability of this process is influenced by the time, and merge of a single particle into the clusters. Another way of cluster formation is by a growing process of a single particle and a chemical reaction after the combustion. Multi steps of chemical reaction from the inorganic oxide produced wider of the agglomerated particle [27].

Table 6.1 *The classification of Particulate size*

Fraction	Size range
PM_1	$\leq 10\ \mu m$
$PM_{2.5}$	$\leq 2.5\ \mu m$
$PM_{2.5} - PM_{10}$	$2.5 - 10\ \mu m$
PM_{10}	$\leq 10\ \mu m$
Ultrafine Particle	$\leq 0.1\ \mu m$

The size of particulate is ranging from a tiny size of single particle formation than merges or oxides into wider size. In the outside part, the compositions of PM are dominated by liquid condensed hydrocarbon particles and the incomplete oxidation of sulphur. Thus, in the inside is composed by solid carbon spheres that covered by absorbed hydrocarbon. There is a classification of the particulate from the combustion process as; PM_{10}, $PM_{2.5}$, Pm_1, $PM_{2.5}$ - PM_{10}, and ultra fine particle [28]. These classifications are based on the size of the formed particle. PM_{10} means that these particulate diameters are in the range of 10 μm, and it is same meaning for $PM_{2.5}$ as well. The ultra fine particle referred to the individual particle less than 100 nanometre. $PM_{2.5}$ - PM_{10} is consisting of varying range particle from 2.4 μm to 10 µm which in the inside was mainly filled by coarse of the merged single particle. Detail of the clustering size particle is shown in table 6.1.

6.3 Experiment process

A stainless steel sampling probe with 6 mm in diameter of sampling hole and 500 mm of length produced by Akano was used for gas sampling. A thermocouple for real temperature measurement was located at the tail of the eyes probe. The high temperature of the exhaust gas was cooled down using a century water cooler before entering the measurement tools. It was followed by a filtering sampling using PG-60 (Produced by Advantec), which the filter it is covered with poly-tetra flour ethylene to measure the particulate concentration. Filter is hydrophobic and low absorption. Flour-polymer is used as the binder and not affected by the air. The properties of used filter are shown in table 3. Principally, PM concentration was calculated by measuring the weight difference of filters before and after an experiment. 20 liters of exhaust gas were taken with 8.5 L min-1 flow rate at the ambient temperature 35-50°C. For measurement of dry soot, the filters from experiment were dissolved in dichloromethane, and then it was heated up until 50°C for two hours. Soluble organic fractions (SOF) are measured by the reduction of the particulate concentration with dry soot one.

6.4. Setting Conditions

The combustion of C heavy fuel and coal oil in the boiler is similar; consisting of mixing of air and fuel, then following by a past of diffusion combustion. The combustion of C heavy fuel oil was characterized by a normal setting for the combustion process, while the coal needs more setting for the stable condition one. The difficult for controlling a proper mixed between air and coal fuel happened when the manual setting is taking a long time. The manual setting was conducted by changing the quantity of fuel and air together. If the fuel was too much supplied and atomized, the exhaust gas turned into black, but when the air is too much supplied the exhaust turned into thin white. Detail of parameters for stable condition for both coal and C heavy oil is shown in table 5.2.

6.5. Cooling Temperature

It is clearly seen from Fig.6.1, that both inlet and outlet water jacket temperature relatively increases in every points from centre of burner. This may be due to the higher turbulent mixing rates, and the combustion taking a complete condition that corresponding to the longer tail of flame lengths. The temperature levels at the end of the afterward zone relatively increase when the furnace length increase. The inlet temperature for second and forward sampling points was already in the heated condition that makes the next heating process faster than in the sorter length of the furnace. The different of temperature from out/in thermometer is also being used as the consideration of the particulate formation. Higher difference of the temperature may lead to higher possibility of particulate formation. The coal oil combustion created lower combustion quality indicated by the heat transferred to the cooling water in the wall.

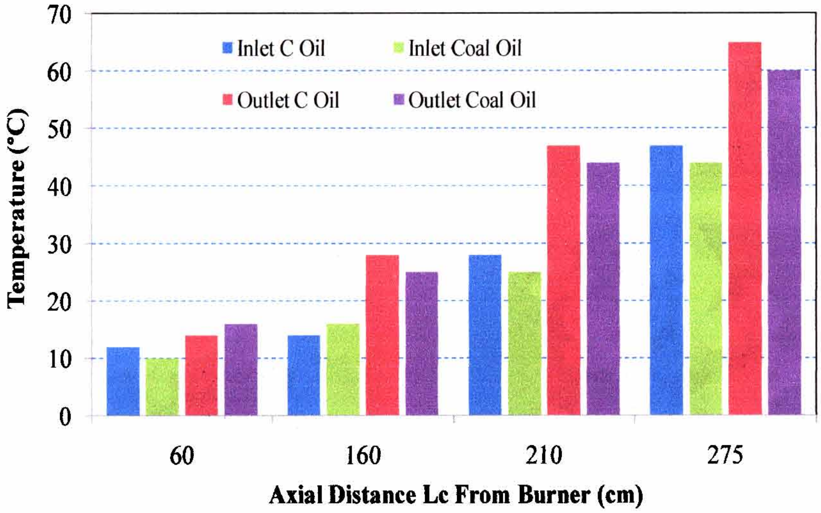
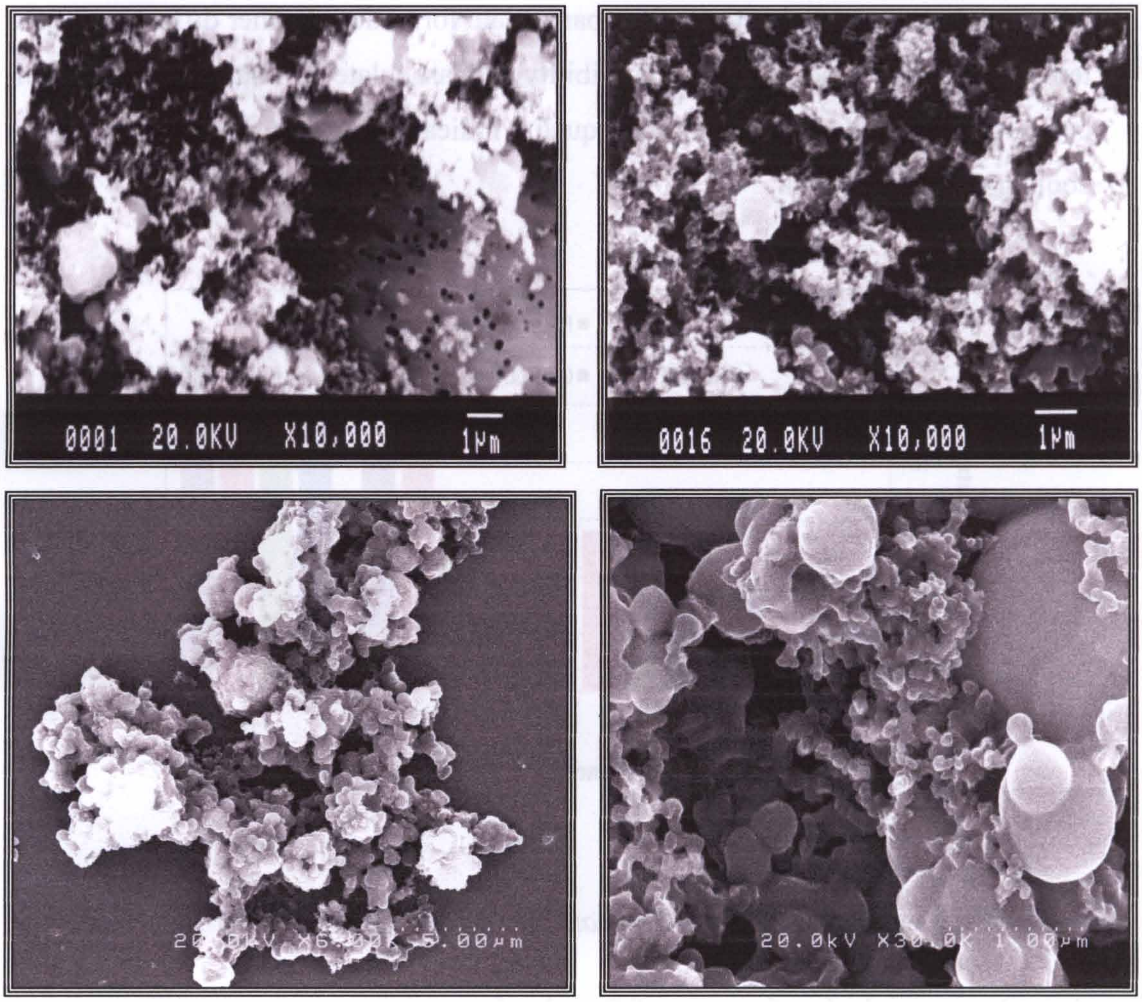


Fig.6.1 *In-out temperature of water cooling system*

6.6 Characteristics Coarse of Particulate

During combustion or gasification, the hydrocarbon component reacted with the available air, producing the heat as energy and also gas CO_2 and others side product of the unburned hydrocarbon and gasses. Furthermore, the inorganic mineral impurities in fuels are converted into solid, liquid and gaseous compounds, which finally leave the system as bottom ashes, fly ashes or vapor. The shape and dimension of the particles have also a direct interaction with the risk assessment for human health. We used Scanning Electron Microscope (SEM) for measuring the dimensional and morphological characterization of PM on filters. This method allows in obtaining dimensional or morphological information, at the same time, crucial for the identification PM formation. These dimensional and morphological results could be related with the characters of the particle, due to the different possible formation pathways (chemical reaction in atmosphere, nucleation, condensation, coagulation and cloud processes).



C Oil Coal oil

Fig 6.2 *PM image using SEM*

The sample result of SEM photograph that related to the formation and agglomeration process of the PM is shown in figure 6.2. From this SEM photograph, the different formation of the PM from the experimented fuels, C heavy fuel and coal fuel were certified. The combustion of coal fuel derived to the higher production of the PM and also faster in the agglomeration process. The detail size and number of particles for both C heavy oil and coal oil could be analyzed to obtain quantitative results either for the number distribution of the particles or for the morphological, but the high range speed of agglomeration make it difficult to measure it one by one.

6.7 Concentration of the Particulate

Fig 6.3 *Filter for particulate measurement*

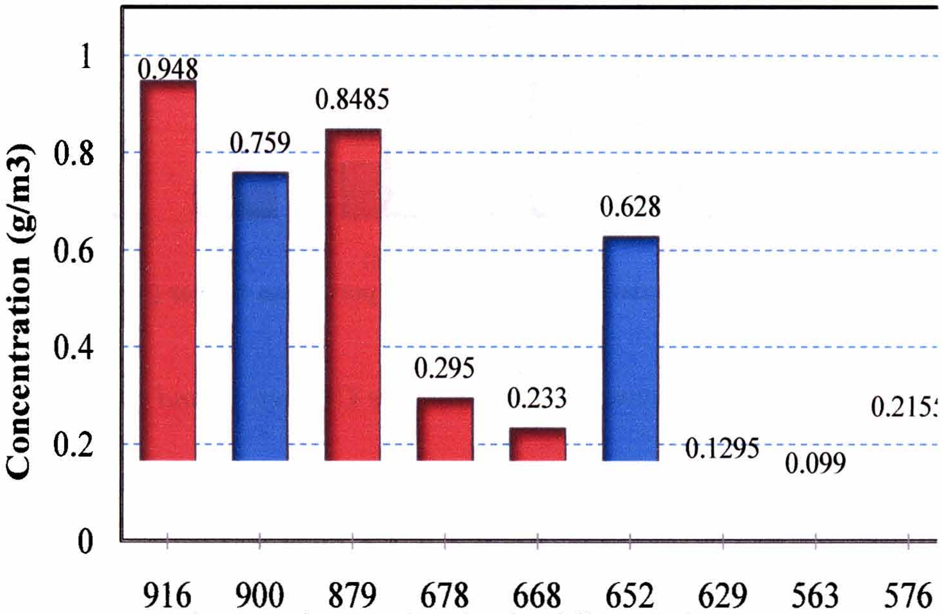


Fig 6.4 *Distribution of particulate by the different of temperature*

The condition of filter for caching the particulate matter for the concentration diameter is shown in the fig. 6.3 and concentration of the PM in the filter is shown in fig.6.4. Due to the condensation and other processes of some vapors solidify the merged particulate pass the system to the atmosphere as the particulate matter. The difference of the color brightness at each of the filters indicated the density of particulate that trapped inside the filter was different. A taken photograph was after diluted in the dichloromethane, so the different degradation of color does not clearly viewed.

The formation and distributions of the PM concentration at the constant mass flow rate of fuel, and the stable of the combustion process related with the decrease of temperature is shown in figure 6.5, it is known that at the beginning of the combustion the difficulty of coal oil for being flame creates higher concentration of the particulate. It means that the quality of combusted fuel gives a big effect to the particulate`s formation.

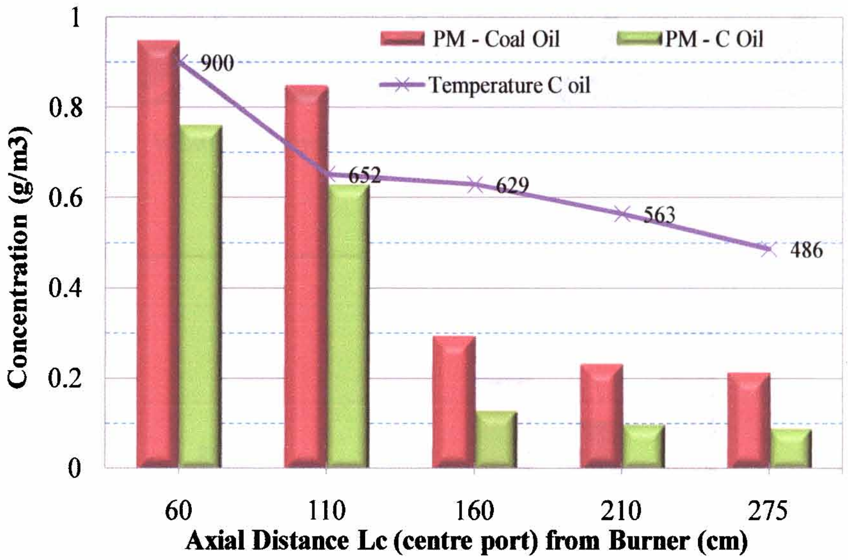


Fig.6.5 *PM concentration from the C heavy oil and coal oil*

General results exhibit that PM concentration values in the forward region soon after the burner centerline resulted in the highest concentration. It decreases rapidly towards the ceiling of the furnace to become very low at the forward flow region. Moving to side against the stream, the PM formation levels in the forward region longer from the burner were influenced by the temperature of the combustion itself.

6.8 Dry Soot

The processes of soot formation are: pyrolysis, nucleation, coalescence, surface growth and the agglomeration. Dry soot from this experiment was calculated from the weight of used filters in the experiment after it diluted in the dichloromethane. The result states that the concentration of dry soot decreases remarkably as the indication of the completion of combustion. In the frontward zone from the burner when the combustion was taking place, because of the limited available time, the possibility of main hydrocarbon inside the fuel was being oxidized to be heat was low. It could be seen also from fig.6.6, that the concentration of dry soot by using of coal oil resulted in higher concentration than C heavy oil.

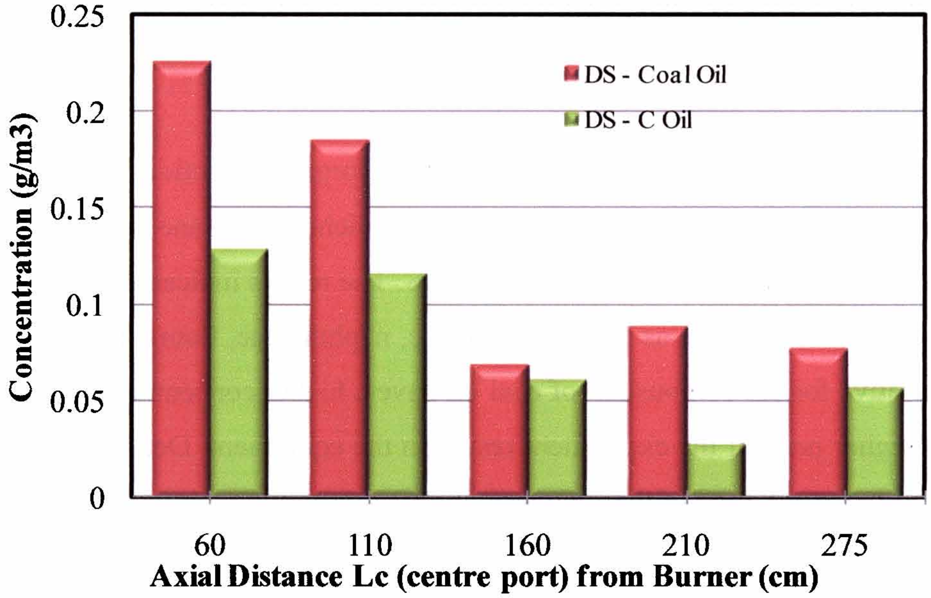


Fig.6.6 *Dry soot concentration of C heavy oil and coal oil*

6.9 Soluble Organic Fractions

The soluble organic fractions were formed as the incomplete oxidation of hydrocarbon, on which the formed object is still having same characteristics as the material before, and it is burnable. A soluble organic fraction from this experiment was measured from the reduction weight of the used filter after an experiment with the weight of filter after diluted in the dichloromethane. All the soluble organic fraction data was shown in fig.6.7. Better combustion is indicating by the small concentration of soluble organic fraction, by meaning that the soluble organic fractions all transforms to the heat and energy.

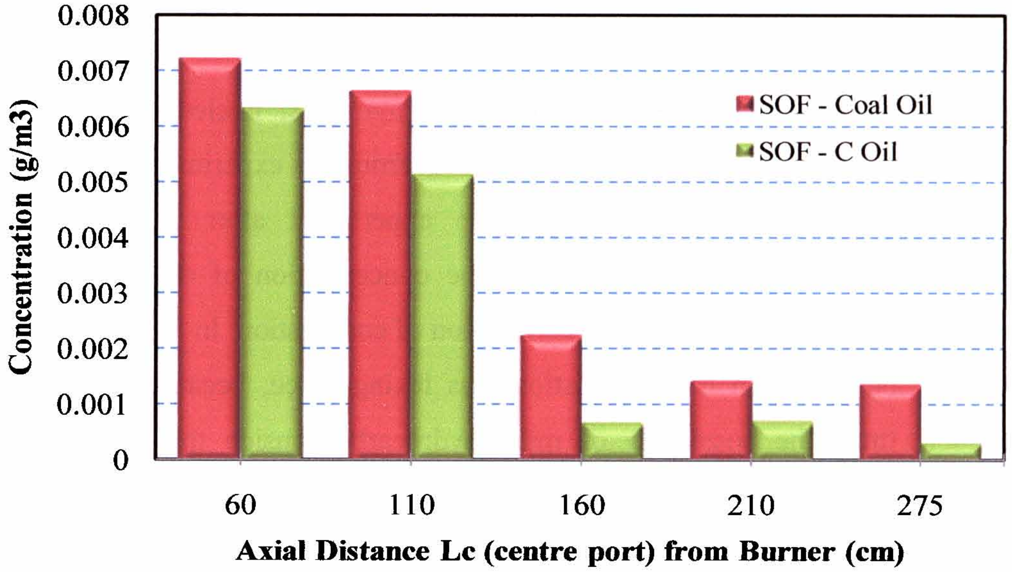


Fig. 6.7 *Soluble organic fractions concentration of C heavy oil and coal oil*

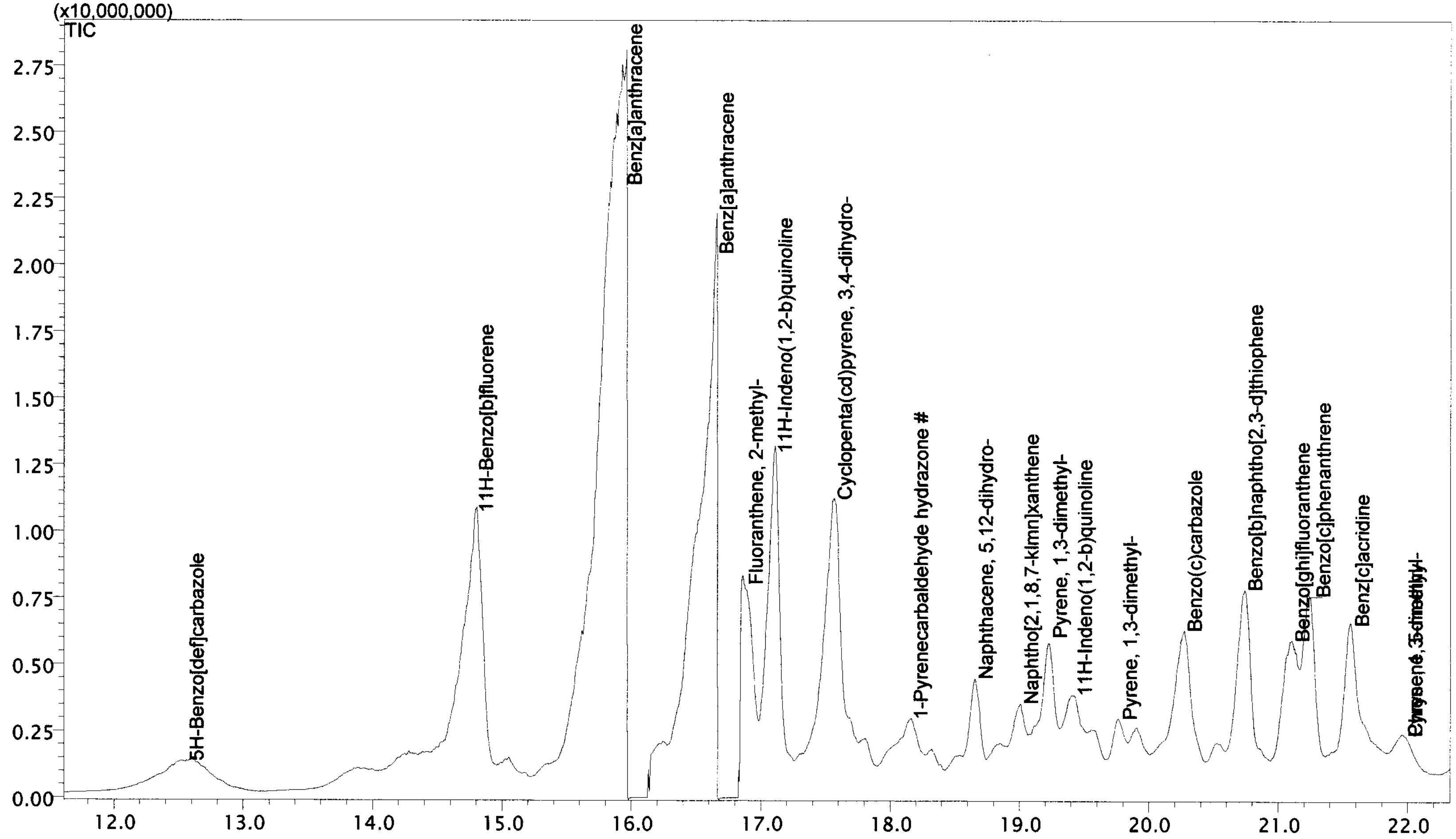
6.10 GC/MS Measurement

In this section, the measurement of soluble organic fractions using GC/MS instruments is shown. The diluted SOF in the dichloromethane was extracted by using small sampling and measured in GC/MS. The results indicated that the soluble organic components such as ; benzene, pyrene, naphthalene, flouranthene, and all of its derivative for the combustion of coal oil have a higher concentration. It is known by the higher peak of the experiment result on the equipment. Detail of data should be found in fig. 6.8 (end of this chapter).

6.11 Summaries

An experiment study was conducted for the steady combustion of liquid coal fuel and C heavy oil at laboratory scale on a 2.75 m horizontal boiler with four annular segment tubes, a water jacket system. The measurement of the particulate matter that emitted from the combustion at several designed sampling points was also investigated. The average result of PM and its component measurement when the steady combustion for both fuels indicated the different of PM formation was about 80.79%. For the PM component; the difference of the soluble organic fraction measurement was 38.96%, thus, the different concentration of dry soot was confirmed at 91.689%. The results of GC/MS measurement indicated that the soluble organic components such as ; benzene, pyrene, naphthalene, flouranthene, and all of its derivative for the combustion of coal oil have a higher concentration. Generally, it is concluded from the laboratory experiment on boiler that there is a possibility of using coal oil, but an after combustion treatment is needed to overcome the particulate problem.

Coal Oil


(x10,000,000)
TIC
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
12.0
13.0
14.0
15.0
16.0
17.0
18.0
19.0
20.0
21.0
22.0
5H-Benzo[def]carbazole
11H-Benzo[b]fluorene
Benz[a]anthracene
Benz[a]anthracene
Fluoranthene, 2-methyl-
11H-Indeno(1,2-b)quinoline
Cyclopenta(cd)pyrene, 3,4-dihydro-
1-Pyrenecarbaldehyde hydrazone #
Naphthacene, 5,12-dihydro-
Naphtho[2,1,8,7-klmn]xanthene
Pyrene, 1,3-dimethyl-
11H-Indeno(1,2-b)quinoline
Pyrene, 1,3-dimethyl-
Benzo(c)carbazole
Benzo[b]naphtho[2,3-d]thiophene
Benzo[ghi]fluoranthene
Benzo[c]phenanthrene
Benz[c]acridine
Chrysene, 3-methyl-
Pyrene, 4,5-dimethyl-

C Oil

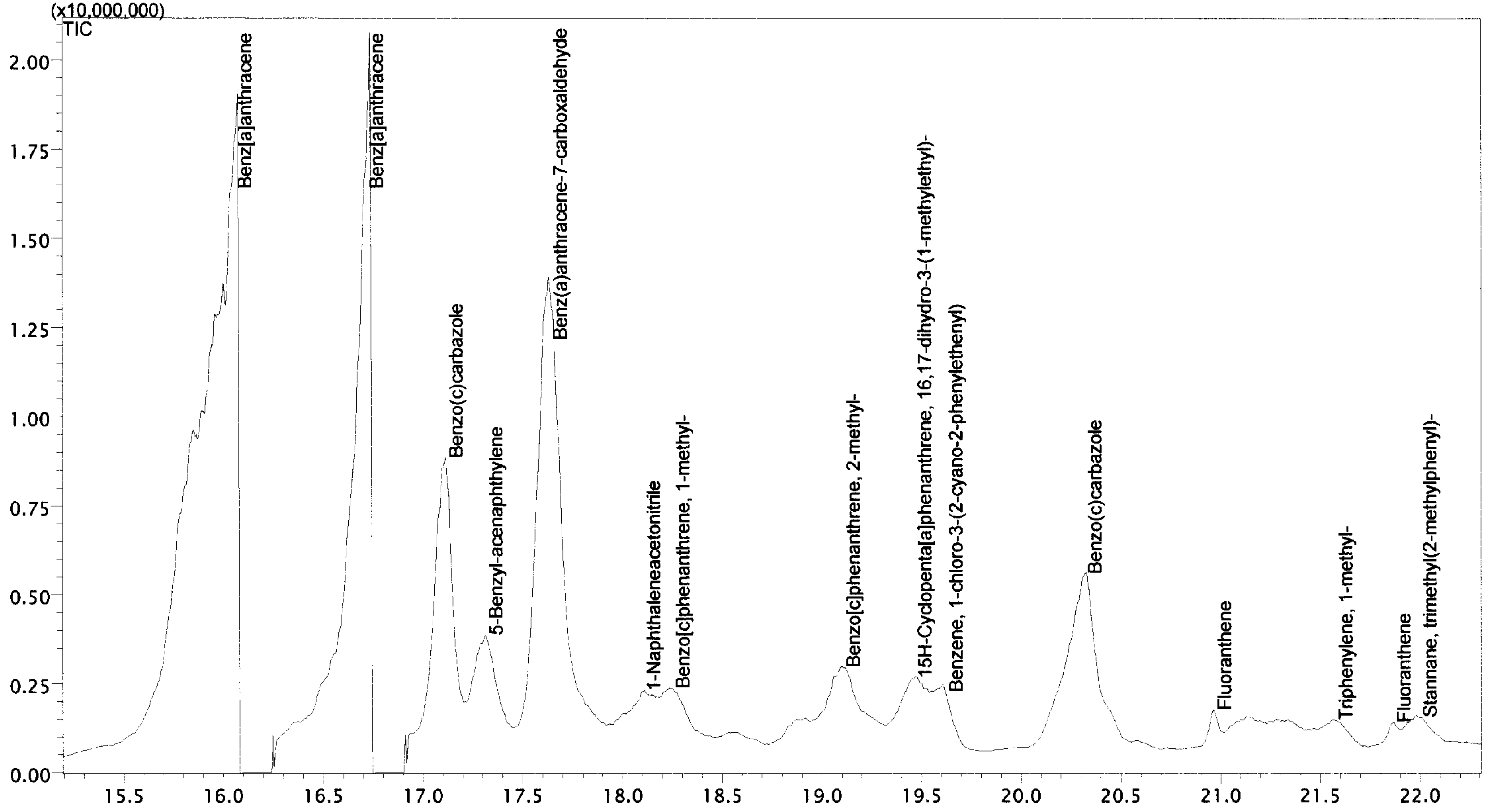


Fig. 6.8 *GC/MS results for the soluble organic fraction in the experimented fuel*

Chapter 7

Chapter 7

Pollution Formation from the Combustion of Coal Fuel and Coal Emulsion Fuel

Abstract

This study was set out to characterize the pollutant's formation such as a derivative of nitrogen, oxygen, carbon monoxide and particulate matter from a steady combustion of liquid coal fuel. Research was aimed to give a bright explanation on preparation, combustion process, and impacts to the environment of exhaust gas formation from a tested fuel; coal fuel and emulsion. A system of horizontal boiler with furnace and water cooling was set up for pursuing a laboratory combustion data. The collection of data is derived from the setting of sampling points from different type emulsion with water content 10%, 20% and 30%. As a result, the steady combustion of experimented fuels reduced particulates and derivative of nitrogen component at the setting of sampling points and concentration of carbon dioxide increased. Physically, the application of emulsion fuel created shorter combustion flame tail, higher temperature and energy transferred to the wall. The micro-explosion as secondary emulsion atomization appears during the droplet disruption process producing the increased of combustion quality and reduced particulate formation. 20% of water contents were also confirmed as optimum blended water for the better combustion.

7.1 Introduction

Due to fuel economic advantages of the application of residual fuel on the ships operational, there are intense research efforts ongoing in the alternative-fuel supply for the conventional engine, and the emission aspects of the treatment. Manufacturers of marine energy system and marine diesel makers have made a significant progress in the attempt to lower fuel consumption. To reduce the operational cost ship owner prefer inexpensive fuel hydrocarbon, which consists of mixtures of distillate fuels and high viscosity of fuel with viscosity of 180-700 cSt. By the increasing of viscosity, the percent of distillate fuel in the blended fuel reduces, which it negatively affects to the fuel quality. In other hands, the availability of coal as alternative energy, which has same characteristics as blended fuel sources, does not manage in a good will.

Many countries have conducted an interactive research for the possibility of using coal as secondary alternative fuel for ships and others long distance sea transportation. It can reduce the operational cost as well as saving for the optimum cost. The use of coal to be a liquid fuel by a liquefaction process was proposed as the alternative of fuel substitute.

There are two types of liquefaction. First one called by direct liquefaction. This liquefaction works by dissolving the coal in a solvent at high temperature and pressure. This process is generally achieved by reacting coal as a slurry in a process-derived solvent. The others one is known as indirect liquefaction. This process was mainly consisting of the complete breakdown of the coal structure by gasification with steam and oxygen. The composition of gasification products is adjusted to filling the required mixture of hydrogen and carbon monoxide, and then it is cleaned to remove the sulfur containing catalyst. Physically, formed coal fuel is high density, black and strong in the smell, and is not easily transported at room temperature.

Main attention of the coal combustion without any treatment to the environment has been focused on gaseous pollutants such as CO, CO_2, NO_x, and SO_2 due to their impacts on the climate change, and acid rain. It is a special effort to make a simultaneous reduction for both NO_x and particulate emission due to the opposite formation condition. Better condition of combustion leads to higher temperature of combustion that gives impact to the higher NO_x formation. While the combustion temperature decreases, it increases the particulate formation drastically. In this paper, an experiment of combustion and measurement of pollutant formation of liquid coal fuel was conducted in a laboratory scale scheme by a treatment of coal oil with adding water as emulsion fuel of 10%, 20% and 30% water content. The measurement of pollutant formation was also performed in order to provide more information about its pollutant formation from different of water contents.

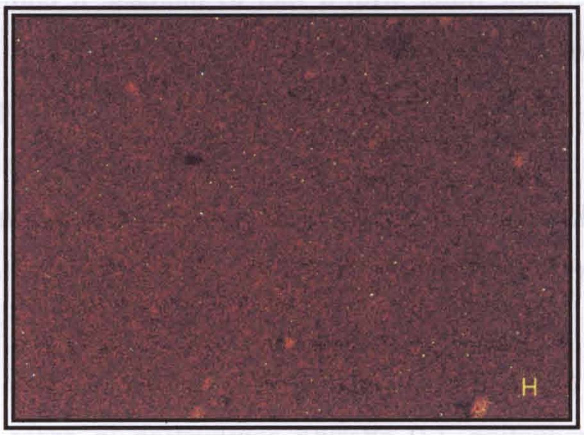
7.2 Additive and Emulsion Condition

Mixing of amount water with a fuel to increase it combustibility with the process of water molecules are enveloped by fuel molecules called by water inside emulsion fuel type. The emulsification technology was developed to increase the completion of combustion by providing enough oxygen from water. Then, it is followed by the reduction of pollutant's formation. The main purposes of emulsion are to convert high viscosity of fuel from semi-solid materials into liquids by mixing process that makes it easier to be handled and transported. The augmentation of water is believed: (1) reducing the combustion temperature, which reduces the nitrogen dioxide production, (2) altering combustion in order to inhibit the soot formation, (3) minimizing the formation of unburned hydrocarbon by providing enough O_2. It is proven scientifically that emulsion fuels significantly lowers emissions such as hydrocarbon, carbon monoxide, carbon dioxide and especially both the hazardous NOx and particulate matters. Keeping the emulsion in a stable condition for its uses was the important point. The difference of water and coal fuel density must be mixed by applying the additive as a binding agent. The function of the surfactant is designed to break the chemical molecules of material inside, and make a bonding for both fuel and water in single molecules. The composition of the additive is as small as possible to reduce its totality amount. The principal ingredient of emulsification agent (additive) is composed by an inorganic material, and it is extremely cheap, about $3 per liter. The total amount of additive is only about 0.3% of totality emulsified fuel volume. Chlorine was included as the additive in order to generate of dioxin. Table 7.1 shows the composition of the additive.

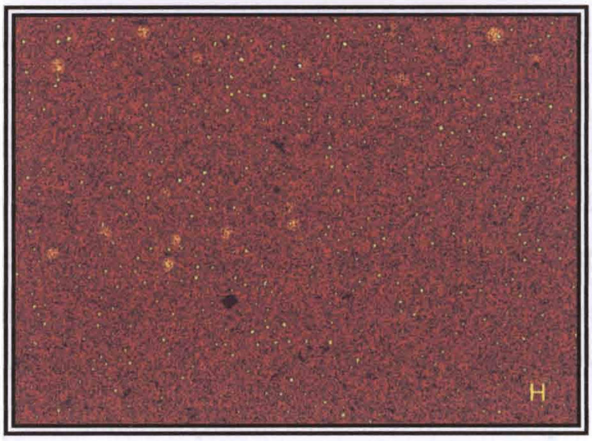
Table 8.1 *Additive Content*

Composition	weight
Natrium (Na)	4.86 wt.%
Calcium (Ca)	0.001 wt.%
Chlorine	4.34 wt.%
Density (at 20°C)	1.101 g/cm^3
PH (at 20°C)	13.5

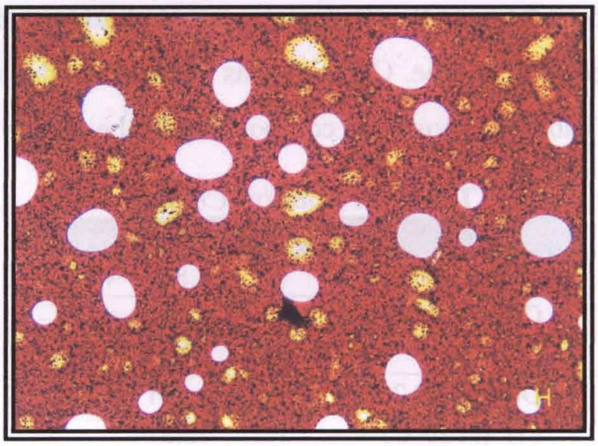
The characteristics of formed emulsion are the stable conditions of combustion in the high-temperature condition, not easily separated between water and fuel, and it can be stored in a longer period with no special treatment. Formed emulsion by applying this agent was characterized with the size of trapped water droplets of 5~10 μm, and it is only 0.2~0.3% of total volume concentration needed for the emulsion.



(a) Emulsion condition at room temperature



(b) Emulsion condition at 50°C



(c)Emulsion condition at 80°C

Fig.7.1 *Emulsion condition in different temperature*

The maximum of good binding of emulsion was gained by 20% of water content. It was also simple in the process of making the additive. The additive is already being patented in both Japan and America. Fig. 7.1 (a), (b), (c) show the condition of emulsion from the scanning electron microscope from room temperature to 80°C. From this figure, the shrink of water molecules by the increase of temperature is appeared. It is also known that the increase of temperature influenced the density for fuel. The water molecule inside the fuel was measured at around 10μm.

7.3 Combustion Condition

The photographs of combustion for both Coal oil and coal emulsion are shown in fig. 7.2 below.

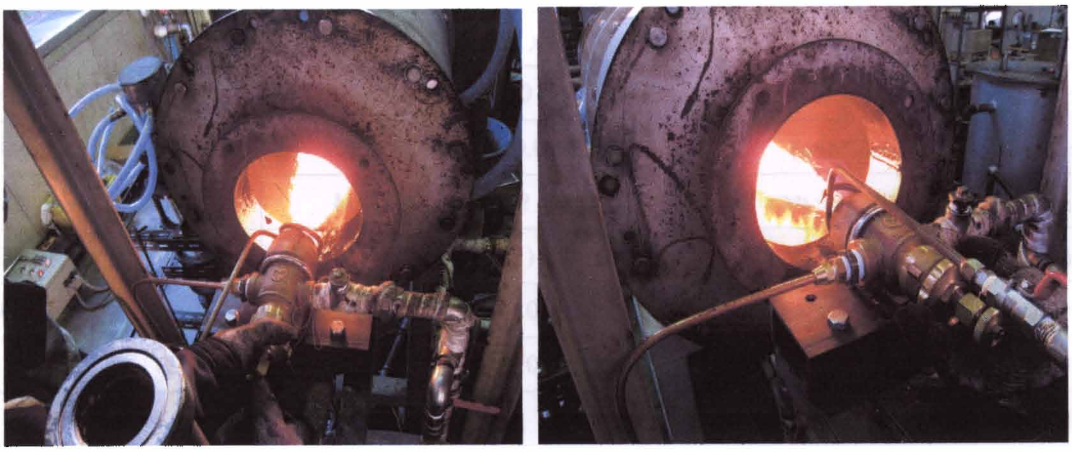


Fig.7.2 *Photograph of coal (left) and emulsion (right) combustion*

Physically, the combustion of emulsion fuel creates a shorter of the combustion tail, and it has a higher of measure's combustion temperature. The emitted exhaust gas color is thin white with small, brown and dark of particles emits. The pollutants emitted was predicted lower than coal combustion based on the physically observation. Visual observation on the flame during the combustion process through small windows at the end of boiler shows the stability of combustion. In the application of 30% water content, the stability of combustion was very difficult to be obtained in a long period. Much water content mixed with low grade coal fuel causes the combustion not run in a better condition. For the application of emulsion fuel, when the air for atomization increases, the flame zone rose being longer, and the temperature of combustion in the flame zone getting higher.

The condition of steady combustion for both experimented fuel are sown in table 7.2 below. The temperature of heating process was set-up at same condition, while the pressures of fuel oil were different; depend on the stable condition on which condition could be gained. Combustion air for supporting combustion was also in same condition at 4500 l/minute.

Table 7.2 *Parameters of combustion condition*

Components	Coal Oil	Emulsion 10%	Emulsion 20%	Emulsion 30%
Water Cooling (**ON** / OFF), Flow rate **(l/min)**	24 ℓ/min	24.80ℓ/min	25.37ℓ/min	25.93ℓ/min
Exhaust Gas Fan (**On** / OFF), Flow rate **(l/min)**	**On**	**On**	**On**	**On**
Tank Heating (ON /**OFF**), Temperature **(°C)**	**On** (80°C)	**On** (90°C)	**On** (90°C)	**On** (90°C)
Fuel line Heating (ON / **OFF**), Temperature **(°C)**	**On** (120°C)	**On** (120°C)	**On** (118°C)	**On** (118°C)
Pressure from Compressor **(MPa)**	0.1	0.1	0.1	0.09
Pressure inlet of Burner **(MPa)**	0.065	0.09	0.035	0.06
Temperature inlet of Burner **(°C)**	90	94	85	81
Heater setting of inlet Burner **(°C)**	On (100°C)	On (108°C)	On (110°C)	On (108°C)
Pressure of Fuel oil **(MPa)**	0.08	0.05	0.08	0.08
Pump flow Rate **(l/min)**	0.25	0.21	0.23	0.19
Water Jacket cooling inlet **(°C)**	8	8	8	8
Water jackets cooling outlet **(°C)**	26	28	28	36
Combustion Air **(l/min)**	4500	4500	4500	4500

7.4 Temperature and Heat Release

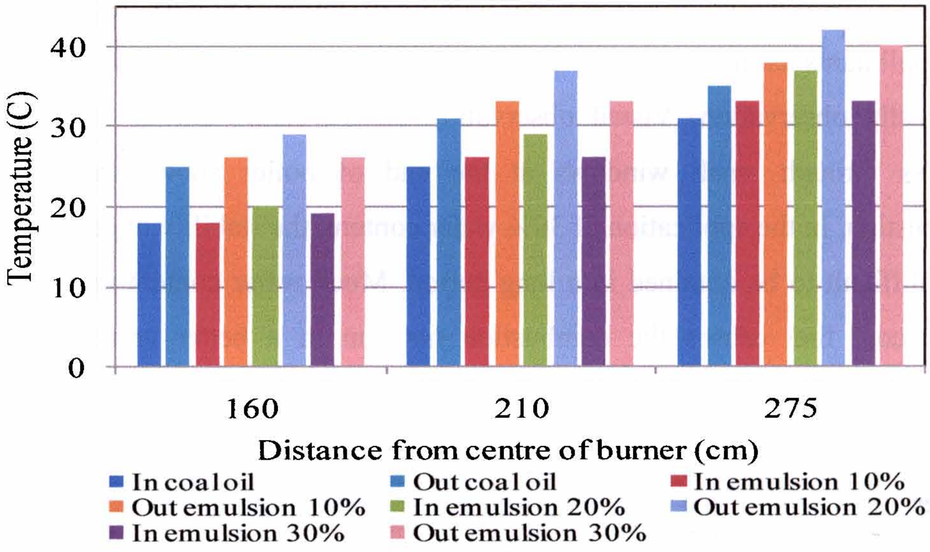


Fig.7.3 *In-out of water cooling jacket*

Temperature of the cooling system with fresh water is shown in figure 7.3. The presence of water raises the temperature suddenly, and then it increases the surface area of combustible air which it leads to the better combustion. From the temperature, the amount of heat transfer from its combustion to the cooling fluid is measured. The heat transfer of coal fuel is 593.79 kJ/minutes, and the application of emulsion with water content 20% resulted in the highest of heat transfer at 768.42 kJ/minutes.

7.5 Carbon Dioxide and Oxygen

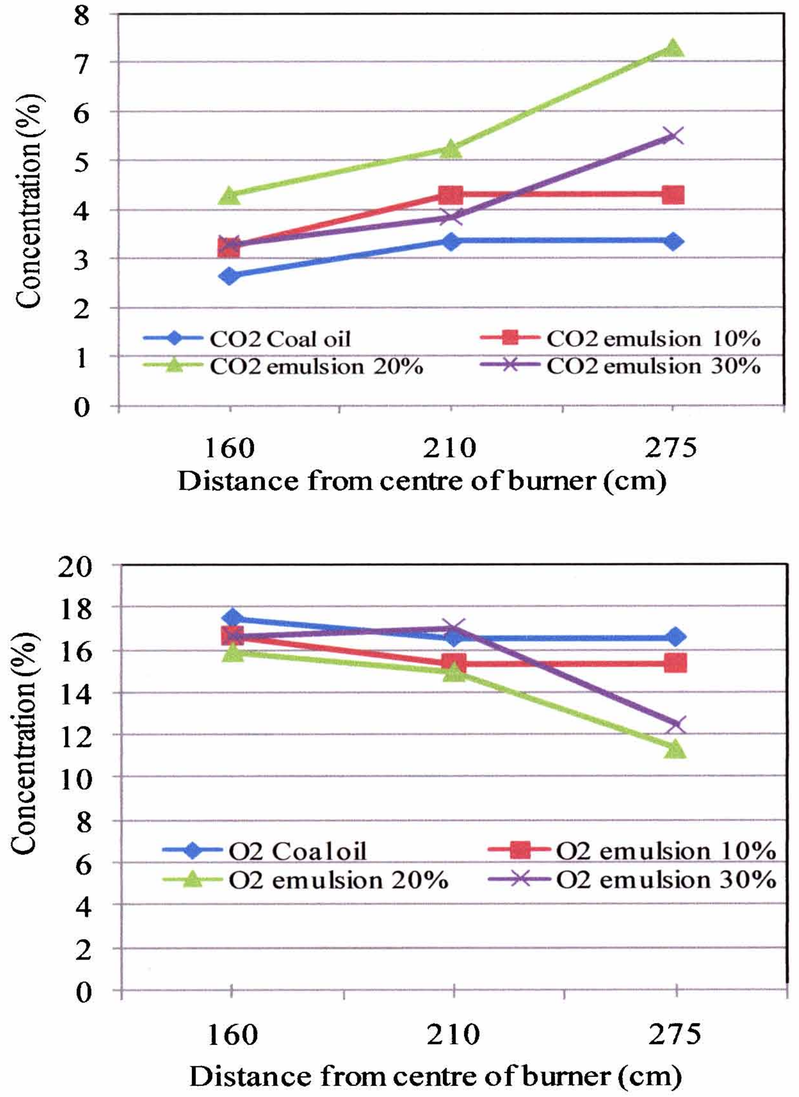


Fig. 7.4 *Concentration of carbon dioxide and oxygen*

Combustion is an exothermic oxidation of fuel with the sufficient amount of oxygen an air with the objective of producing energy, heat, and light. The combining of oxygen in the air and carbon in the fuel forms carbon dioxide that requiring the right mixing turbulence, sufficient activation temperature and enough time for the reactants to come into contact and combine. The amount of remaining oxygen and the formation of carbon dioxide can be one of the parameters for the quality of combustion. Figure 7.4 shows the concentration of carbon dioxide and the remains of oxygen. The presence of water with micro-explosions of water droplet is believed as the causes of increasing concentration of carbon dioxide. These processes also affect to the decrease of remaining oxygen. The application of 20% water content emulsion gives the best result of carbon dioxide and oxygen remain with 7.65% of the decrease of carbon dioxide.

7.6 Carbon Monoxide

Carbon monoxide, CO is a highly toxic gas, formed along incomplete of the combustion process. During the combustion, most of the carbon burned and reacts with oxygen. However, some of the carbon component stays in the intermediary stage as the result of limited time and it turned to carbon monoxide. The concentration of CO in the flue gas is less in a normal condition, but it rises abruptly as soon as fuel combustion starts to be incomplete. Figure 7.5 shows concentration of CO in the experiment. The application of water as emulsion fuel clearly created less formation of CO up to 45% reduction. 20% amount of water for the emulsion resulted in the effective treatment for reducing of CO.

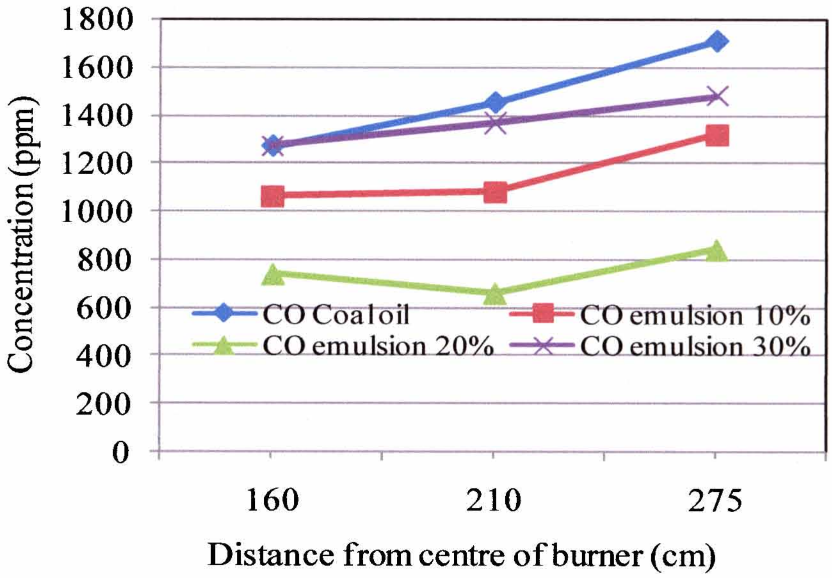
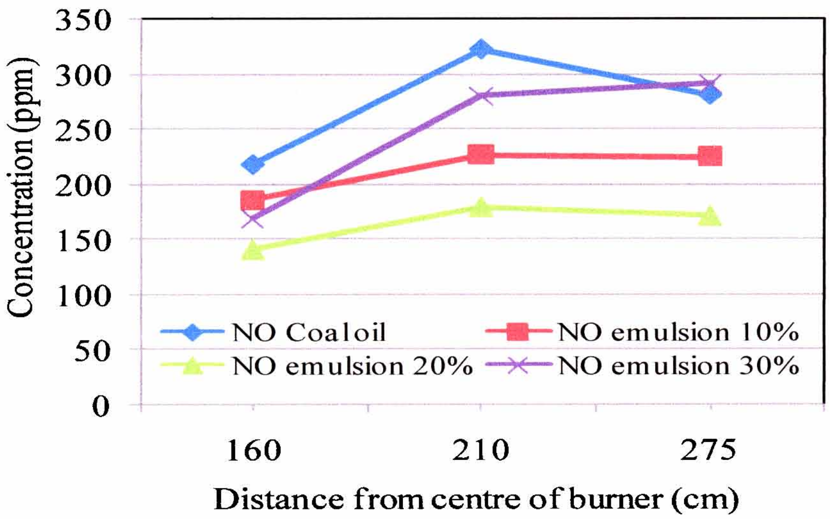
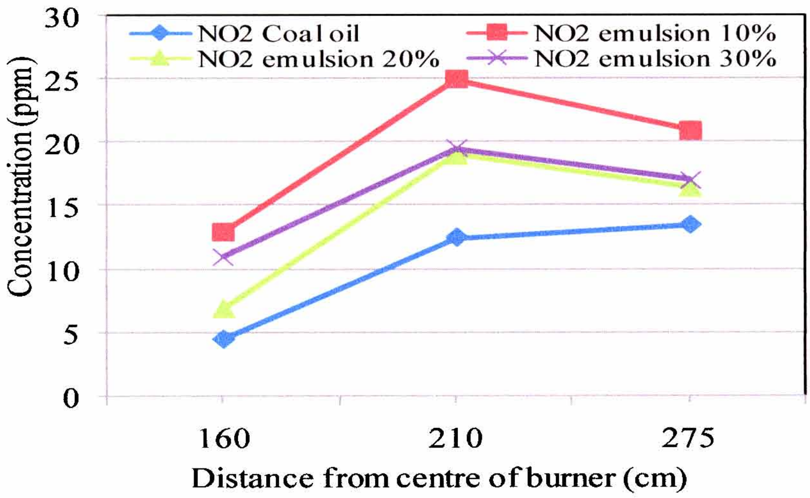


Fig.7.5 *Concentration of carbon monoxide*

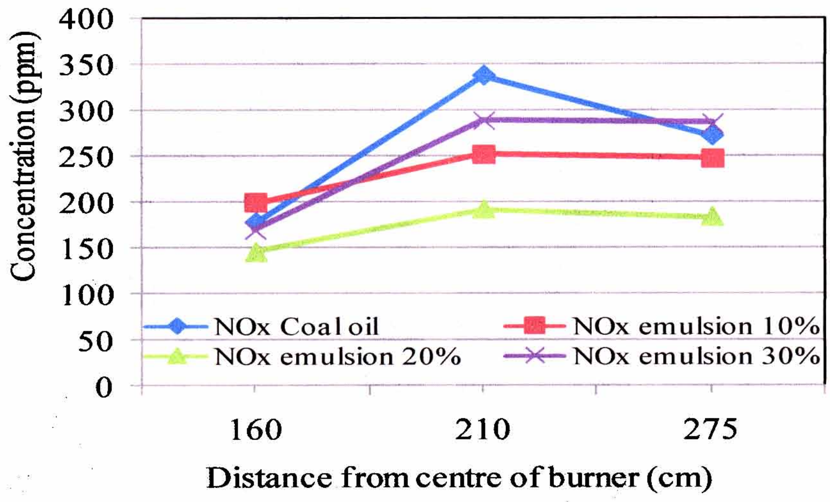
7.7 Derivative of Nitrogen



(a) Concentration of Nitrogen oxide



(b) Concentration of Nitrogen dioxide



(c) Concentration of derivative nitrogen

Fig.7.6 *Various concentration of derivative nitrogen*

The component of nitrogen in the fuel is the main source of the derivative nitrogen pollutants known as NO_x. This pollutant is a group of highly reactive gases, which contain nitrogen and oxygen in various amounts and chemical configuration. The presence of water droplet's micro-explosions in the fuel that provide secondary combustion is the causes of combustion temperature decreases. It revealed that the presence of water vapor in the reactants influences the physical and chemical kinetics of combustion and has the beneficial effect on rate of heat release and reduction in pollutant emission. During combustion vaporized water reduces the flame temperature and changes in chemical composition of reactants, resulting higher OH radical's concentration controlling NO formation rate and soot oxidation.

Figure 7.6 (a), (b), and (c) show the concentration of NO, NO_2, and NO_x. From the sampling point 160 cm, concentration of NO and NO_x components increase as the effect of the increase combustion temperature, then it decreased drastically. It affects to the breaking of a nitrogen atom in N_2, then react with oxygen forms NO as chain reaction. It initiated by a nitrogen molecule and an oxygen atom. The application of emulsion increases the combustion temperature, and it decreases of the concentration for all of nitrogen oxide while it compared with the coal oil without any treatment. The decrease of concentration was measured around 32% - 40% for all of experimented sampling point.

7.8 Particulate Emission

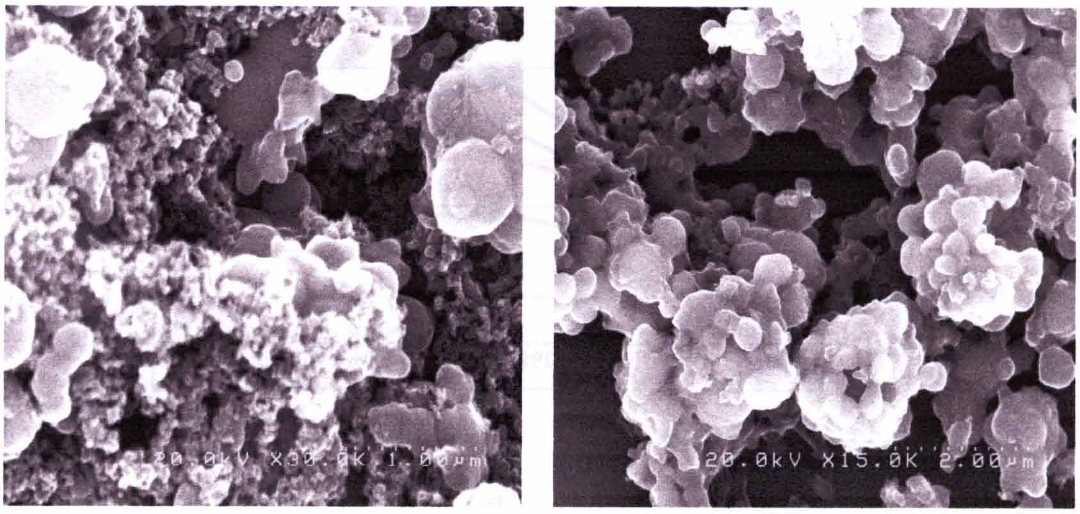


Fig.7.7 *Photographs of particulate coal (left) and Emulsion (right)*

The Particulate matter (PM) is one of the products from the incomplete of the combustion process. Carbon and hydrogen inside the hydrocarbon chain not all was combusted a long combustion, and it transformed from a liquid to particle and gases. Due to condensation and other chemical reactions, it may merge and forms a solid particle. Fig. 7.7 shows results of observation using the scanning electron microscope.

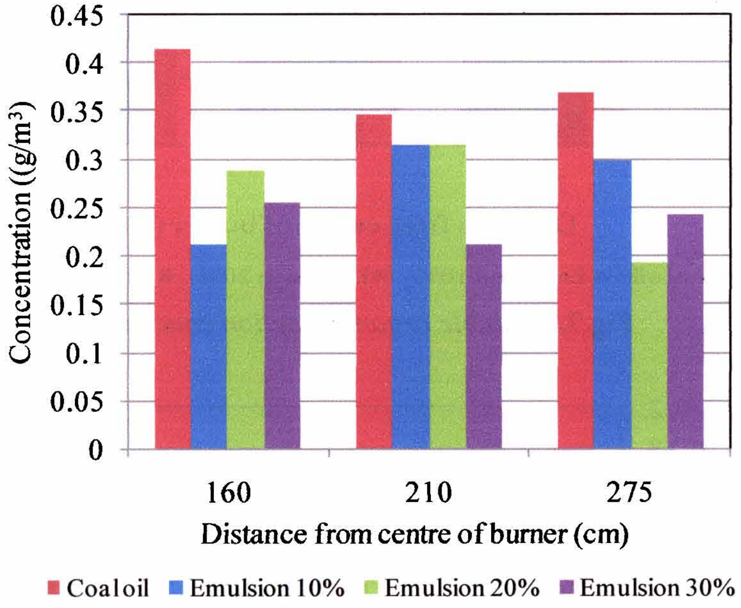


Fig.7.8 *Particulate matter emitted from the combustion*

Figure 7.8 shows the concentration of PM from the sampling point in the experiment. The higher combustion temperature creates combustion run more completely and the formation time of particle will lead to be more limited. This condition is giving an impact to the formation of PM, which mainly happened in a low temperature of combustion. At sampling point 160 cm, the particulate concentration of coal fuel combustion reached almost 16.31% in average, while at the end of sampling point, 275 cm, about 47.4%.

7.8.1 Dry Soot and Soluble Organic Fraction

The component of PM consists of two main part; dry soot and soluble organic fractions (SOF). SOF is derived from incomplete combustion of hydrocarbon with incomplete oxidation that formed soluble liquid, and it has same characteristics as hydrocarbon. While dry soot is the hydrocarbon that already combusted for more than 80%, and it has different characteristics.

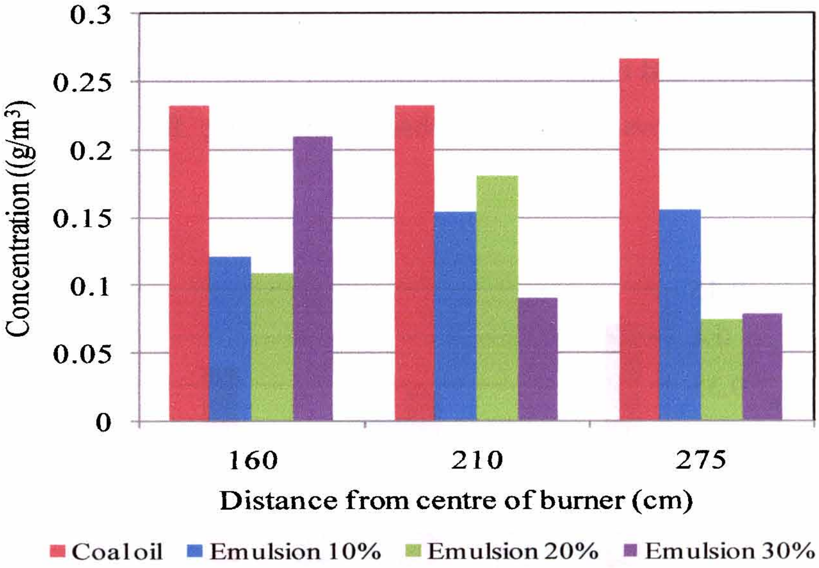


Fig.7.9 *Soluble organic fraction concentration*

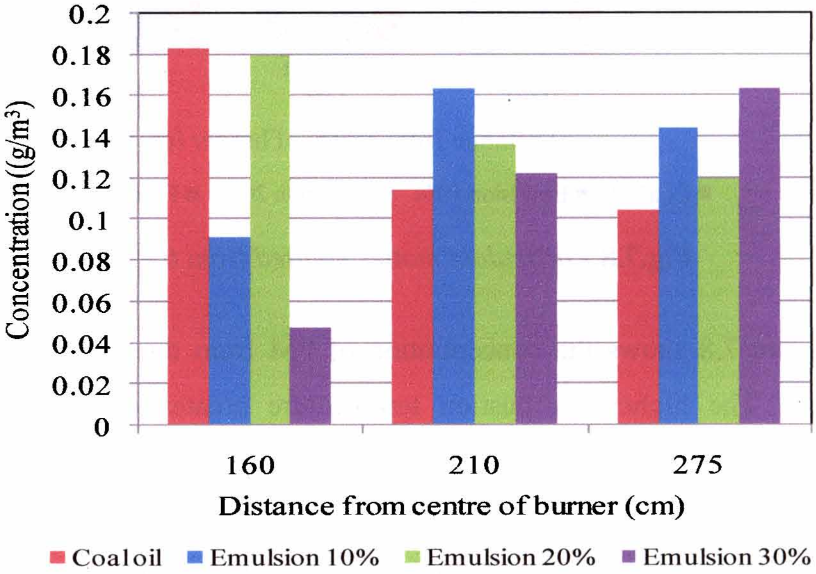


Fig.7.10 *Dry soot concentration*

Figure 7.9 shows the concentration of SOF. When the combustion runs in a better condition, the concentration of SOF will decrease, and it leads to the higher of dry soot formation. The highest concentration of SOF was shown in the sampling point 275 cm, and the average of the decrease of SOF by the application of coal emulsion fuel is up to 60% for emulsion of 20% water content. Figure 7.10 shows the concentration of dry soot. For the dry soot components, the application of emulsion leads to the increase concentration about 36.5%.

7.8.2 Poly Aromatic Hydrocarbon

The acidic and basic portions of the SOF are isolated by liquid-liquid extraction techniques with aqueous base and aqueous acid, respectively. In order to known component's inside dichloromethane which consists of dissolved organic compounds, GC-MS is operated. The result is shown in Fig. 7.10 and 7.11. The GC-MS results will not be explained in detail. General result shows that contents of organic compounds inside are dominated with Benzene, Anthracite, Methane, Pentane, Floranthene, Thyophene, and its entire derivatives. Material inside are growths then proceeds with hydrocarbons, polymerized and coagulate with others forming soot. It also certified that by using emulsified coal fuel, intensity of all soluble organic fractions decreases by 0.15 of organic compounds.

7.9 Summaries

The experiment of steady combustion of coal fuel and the application of emulsion with water content 10%, 20%, and 30% were successfully experimented in the laboratory scale of a horizontal boiler. Physically, the combustion of emulsion fuels creates a shorter of flame length and higher of combustion temperature in a flame zone. Using emulsion also increases the temperature of cooling media and also increases the quantity of heat that transferred to water jacket cooling. Optimum of water content for emulsion was at 20% that indicated by the best result of exhaust gas formation as well as particulate matter generated from the unburned hydrocarbon. The analysis presented in this study revealed that emulsion treatment has an impact to the formation of pollutant sources; CO_2, CO, NO_x, as well as particulate formation. The reduction of pollutant's concentration was believed as the effects of the decrease of the combustion temperature, and it was as the result of the micro-explosion of water droplets. The application of emulsion causes the decreases of pollutants; CO up to 46.42%, NO_x up to 33.52% and PM up to 16.21% as well.

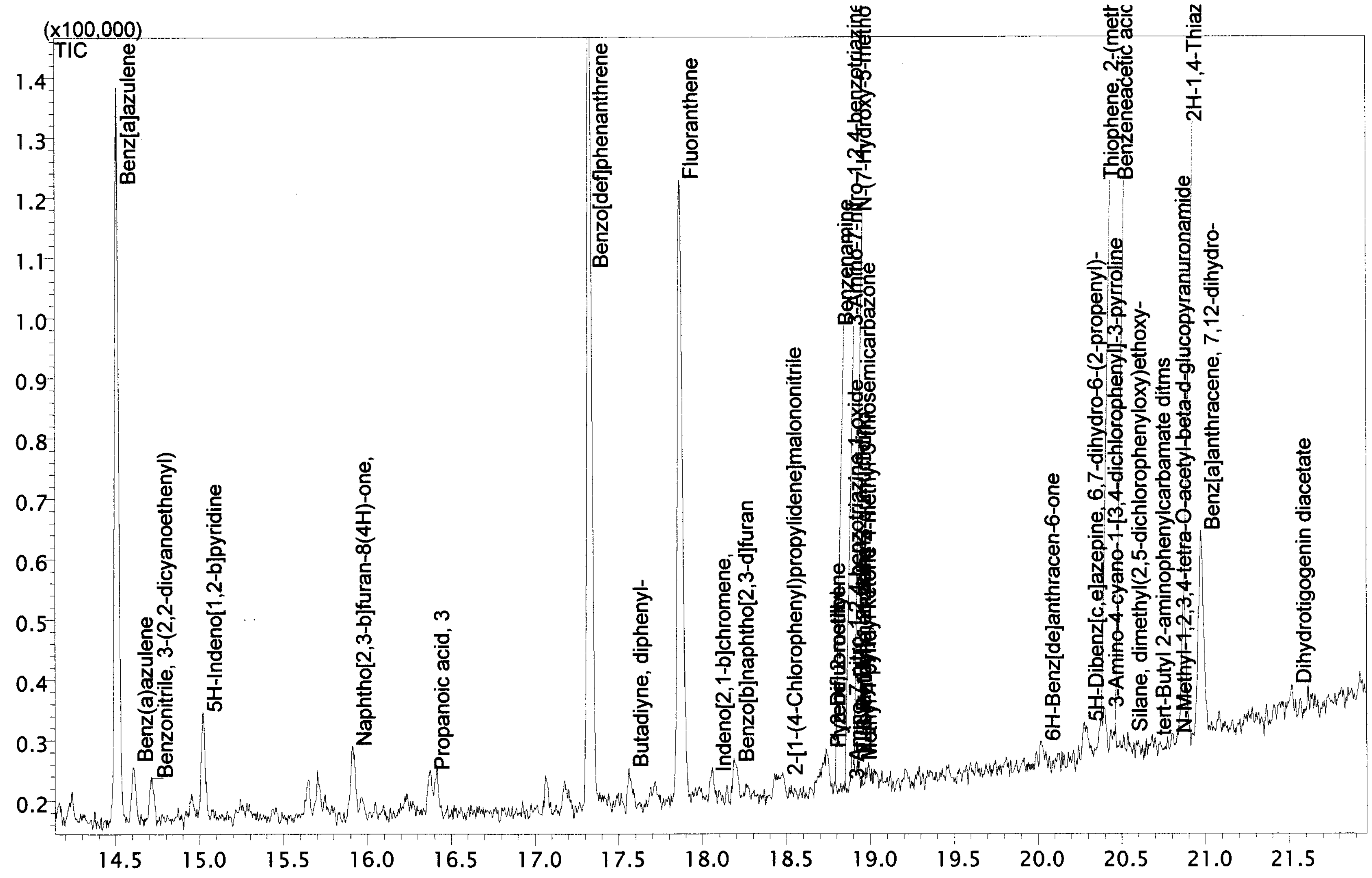


Fig.7.10 *GC-MS result for SOF of coal*

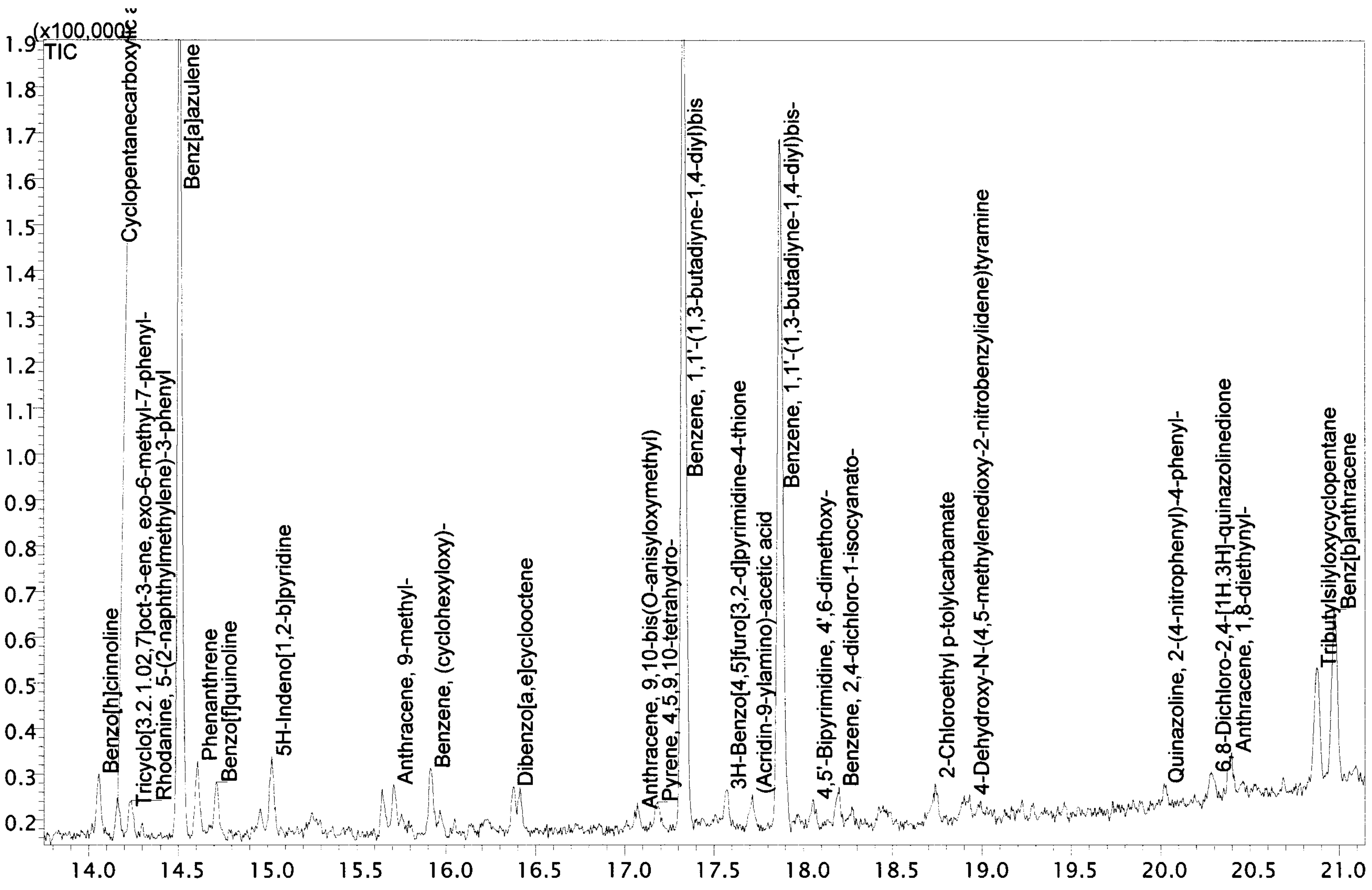


Fig.7.11 *GC-MS result for SOF of coal emulsion 20%*

Chapter 8

Chapter 8

Particulate Reduction from the Combustion of Coal Emulsion Oil

-Effect of 2nd Stage Combustion-

Abstract

The steady combustion of coal fuel was successfully conducted in a lab-scale boiler with burner to investigate the formation of particulate matter. A result of combustion indicates that the concentration of particulate component is high, and it needs to be treated. Further research is designed to overcome the problem of high concentration of particulate by a special treatment. Secondary combustion was proposed to decrease PM concentration. Circle pipe from stainless steel ø330 mm, 50 holes for burning support diameter ø1.5 Mm was inserted in the second blocks of boiler from the burner. The collection data gains from three points of sampling, after a secondary combustion set up. For its consistency, supply gas from daily use's gas in town was supplied to the secondary system. It also assumes that all gas from town gas is combusted, and its combustion was neglected. The experimented fuel was coal emulsion fuel with 20% of water content. Secondary combustion gives an impact for both combustion and the formation of particulate and its component. The result state that by applying secondary combustion process, the concentration of particulate in the exhaust gas was decreasing.

8.1 Introduction

In the last century, much of the world's energy needs have been fulfilled by hydrocarbon fuels, which provided a convenient, plentiful, and inexpensive energy source. The current rising costs of such fuels and concerns over the adequacy of their supply in the future have made them a less desirable energy source and has led to an intense investigation of alternative sources of energy. The ideal alternative energy source is a fuel which is renewable, inexpensive, and plentiful, with examples of such fuels being the byproducts of wood, pulp, and paper mills, and household and commercial refuse.

The use of alternative energy sources is not problem-free. However, since there is a concern over the contents of the emissions from the combustion of such fuels as well as the environmental ramifications of acquiring and transporting the fuel and disposing of the residue of combustion. One promising prior art device for using such alternative energy sources, while maintaining a high degree of environmental quality, after burner combustor wherein the secondary combustion apparatus is provided for combustion in order to control temperature conditions, provide a combustion for unburned hydrocarbon, and the rates of combustion are controlled to consume the fuel entirely. After burner combustors are capable of burning various types of fuel and producing significant amounts of heat, which can be employed for decreasing the composition of pollutant's formation emitted together with exhaust gas.

After burner that provides secondary combustion operates on the principle which is thermally promoting an oxidation reaction between the pollutant compounds in the exhaust gas, unburned hydrocarbon with the available oxygen. Afterburner is the simplest type of thermal oxidizer. This type of thermal oxidizer does not include any type of heat recovery system to recover a portion of the waste heat generated by the combustion process.

Several researches regarding to the application of coal to be a new source of energy was conducted in a small lab scale of experiments. The experiments were conducted from the preparation of combustion, composing a steady combustion, and some treatment to increase its combustion ability and exhaust gas components formation. The main proposes of this research to know its possibility of coal fuel to be the substitute of C heavy oil, with a friendly environmental protection. The treatment that suggested can overcome the problem of high concentration of particulate emitted from the coal fuel combustion is after the burner system that known as secondary combustion. This treatment was operated and the particulate emission was measured.

8.2 After Burner Position and Apparatus

Secondary combustion apparatus made from stainless steel, and it mounted to the furnace between the second tubes to the third tube, as it is illustrated in the fig.8.1. The window for the observation of secondary combustion is located at the side of the burner. Total length of the apparatus was 100 mm with the inner length is 54 mm. In order to mount the apparatus with tubes, the wall bold joins was set. Inside the combustor, small circle of copper pipe with diameter 350 mm outlet and 310 mm, and thickness 40 mm are prepared for the support of secondary combustion. At the copper pipe 50 small hole of Ø2.5 Mm diameter with same direction of a hole to the centre of the furnace is used for combustor. City gas that consists of; methane (CH_4) 88.9%, Ethane (C_2H_6) 6.8 %, propane (C_3H_8) 3.1%, and butane (C_4H_{10}) 1.2%, is used, and it is assumed that all of these gases were completely combusted along the secondary combustion process. Details of design for the secondary combustor are illustrated in fig.8.2. below.

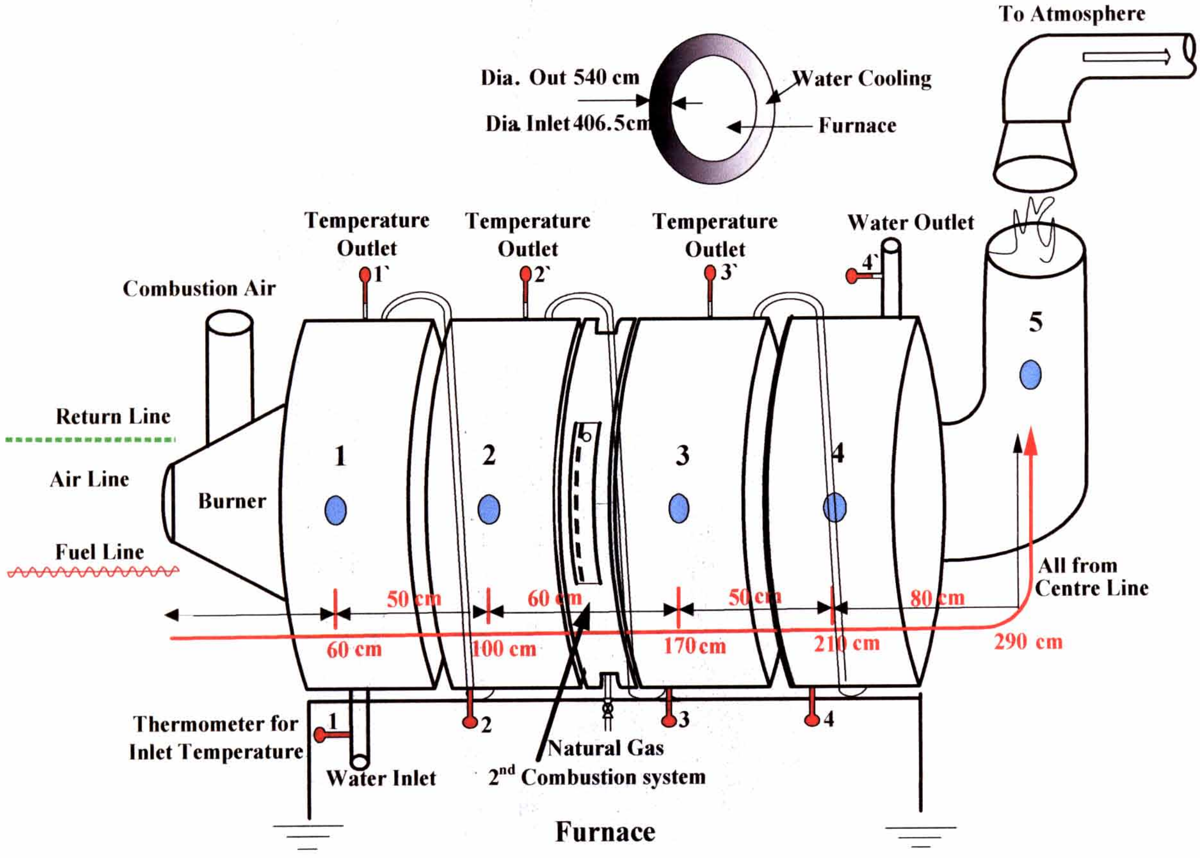


Fig.8.1 *Secondary combustion apparatus at the boiler*

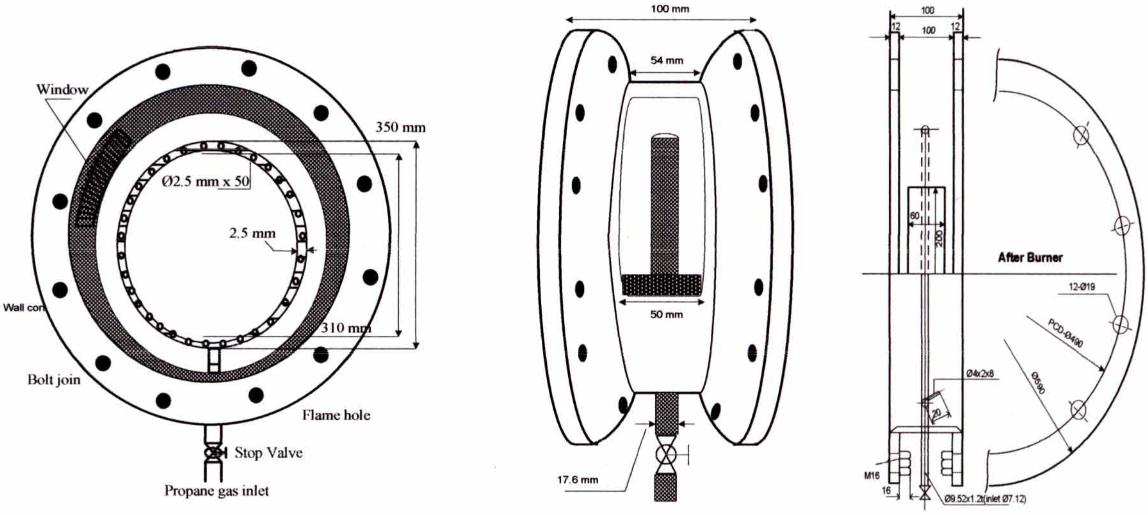


Fig.8.2 *Design of secondary combustor*

The photographs of the combustor and also the photographs of the combustion process in after burner system are shown in fig. 8.3.

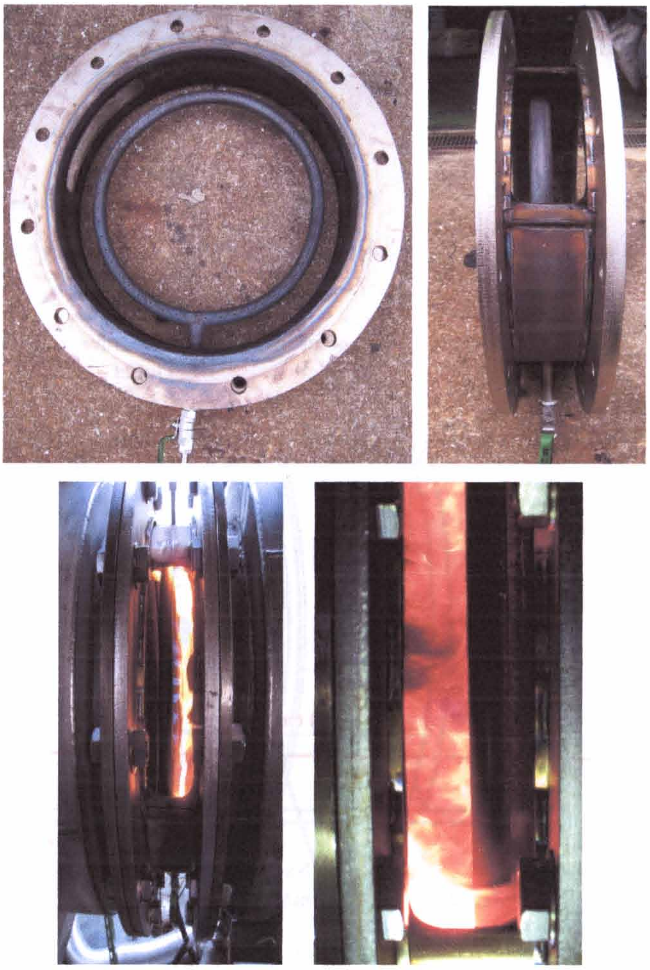


Fig.8.3 *Combustion condition in different temperature*

8.3 Temperature and Heat Transfer

From the experiments, the composition of temperature for the inlet and outlet of tube`s boiler are shown in table 8.1. From this table, it is know that there is not a big different for the temperature before the use of after burner. It assumed that the sampling point 1 and 2 give the same results, and it was neglected. When after burner was operated, the temperature drastically increases, and the increasing rate was almost double. The different temperature at in-outlet of points 3 increases for 5°C, from 7°C to 12°C, that creates a higher of heat transfer from 705.38 kJ/min to 1209.23 kJ/min. While in the sampling point 4, the increase was observed up to 6°C, from 5°C to 11°C which it is also resulted in higher of heat transfer from 507.84 kJ/min to 1108.45 kJ/min. the overall average of heat transfer was measured increases from 2418.44 kJ/min to 3627 kJ/min. table 8.1 record the all of the sampling data from the experiment.

Table 8.1. *Temperature of in/out tube in sampling points*

Components	Secondary combustion			primeraly combustion		
	Inlet	Outlet	Difference	Inlet	Outlet	Difference
Point 1	18	26	8	18	27	9
Point 2	26	31	5	25	29	4
Point 3	31	43	12	30	37	7
Point 4	43	54	11	37	42	5
Overall Temperature	18	54	36	18	42	24

8.4 Particulate Matter

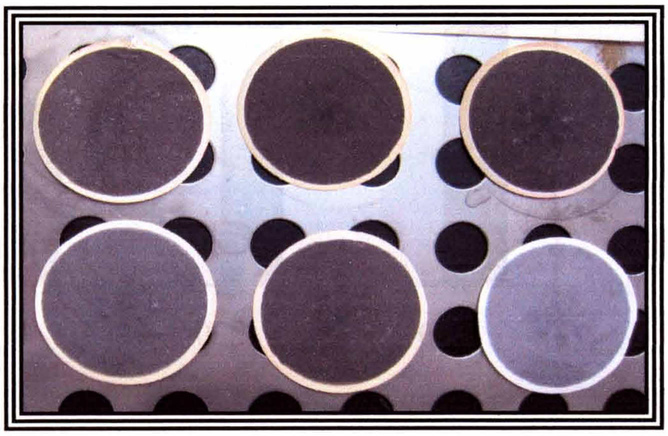


Fig.8.4 *Filter condition for particulate concentration*

The concentration of particulate from unburned hydrocarbon of fuel along the combustion process is the main objective of the system for secondary combustion. The absorption and heterogeneous nucleation of vapour phase pollutants onto existing particles can create toxic particulate and create severity of adverse health effects. This is happened due to the ability of small particles to more effectively penetrate through the upper respiratory tract, which serves as the body's first line of defense. That way, it is important to lessen the concentration of particulate from the combustion process, especially from the low grade of fuel quality that contributed higher of particulate formation. After burner is one of the treatments for this problem. Fig.8.5 It shows the concentration of particulate from the experiment with and without after burner treatment. It is clearly seen that the application of secondary combustion with after burner giving a big impact to the decrease of particulate formation. The concentration of particulate was measured at the level of Oxygen 6% since the rule for inland coal application of industry is set out at that point. At the sampling point 3 (170 cm from the main burner), the concentration of different of particulate concentration up to 1.340 g/m^3 and in follows to the sampling point 5 that resulted of different concentration up to 1.386 g/m^3.

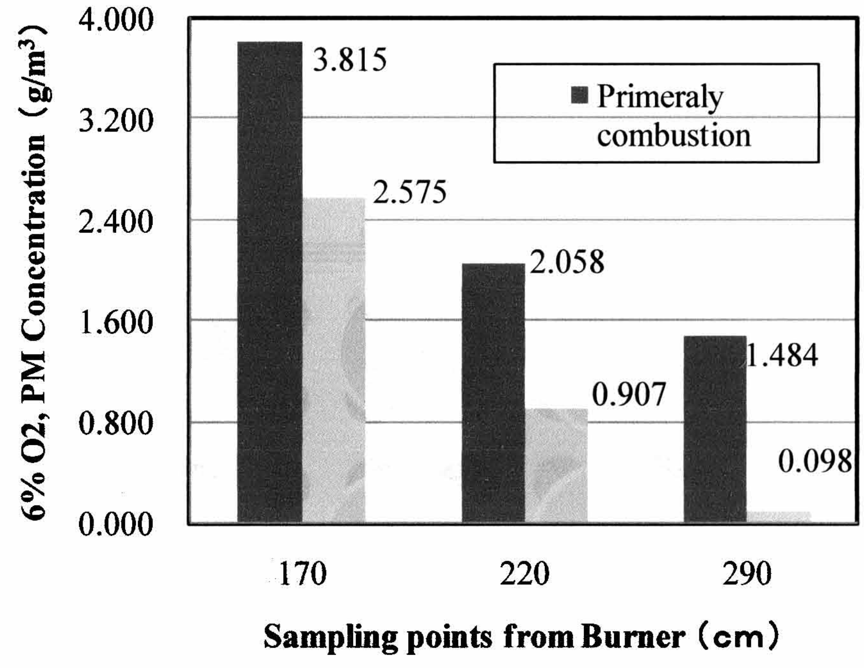


Fig.8.5 *Particulate Concentration at rate of 6% O_2*

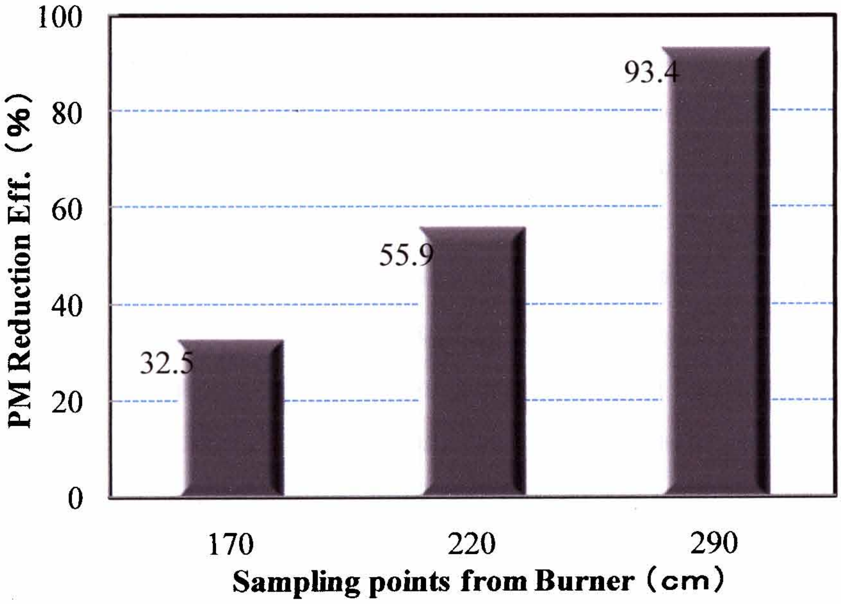


Fig.8.6 *Reduction efficiency of PM by secondary combustion*

The reduction efficiencies of particulate formation with after burner treatment are shown in fig. 8.6 below. The highest reduction was gaining at the end point of sampling with the reduction is confirmed up to 93.4%.

8.5 Soluble Organic Fraction

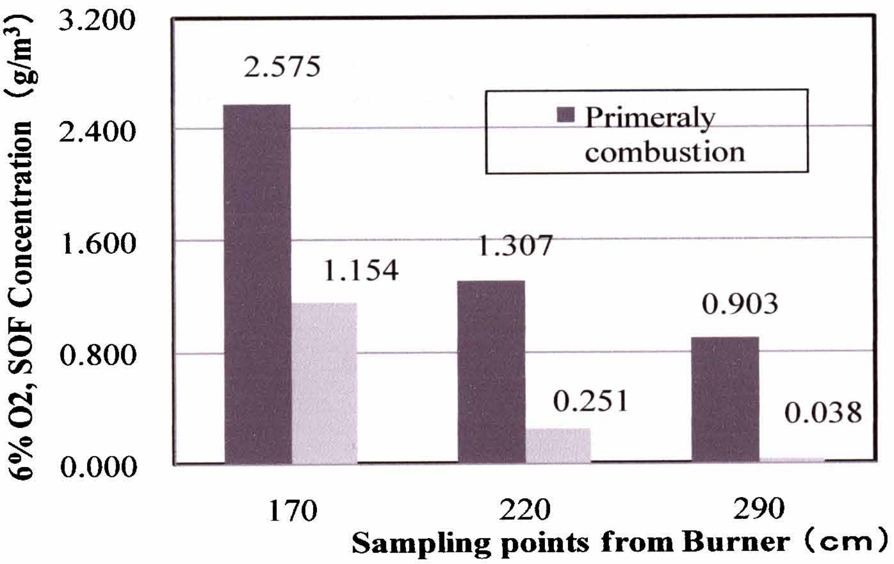


Fig.8.7 *SOF condition at rate of 6% oxygen*

The soluble organic fractions were formed as the incomplete oxidation of hydrocarbon, on which they formed object is still having same characteristics as the material before, and it is burnable. The remaining of the soluble organic fractions among the sampling points for the secondary combustion is shown in fig. 8.7. The secondary combustion which provides a burning system effectively decreases the concentration of the soluble organic fractions on which at the inside still have a hydrocarbon compounds as the product of the incomplete combustion process. The reduction of SOF is increasing by the longer length of sampling points. This is happened because nearer sampling point from after burner believed still content the combustion process that resulted in lower reduction concentration. Comparative of the secondary combustion treatment with there is no treatment is shown graphically at fig. 8.8. The sampling points 290 cm from the burner resulted in the highest reduction with up to 89.7% reduction.

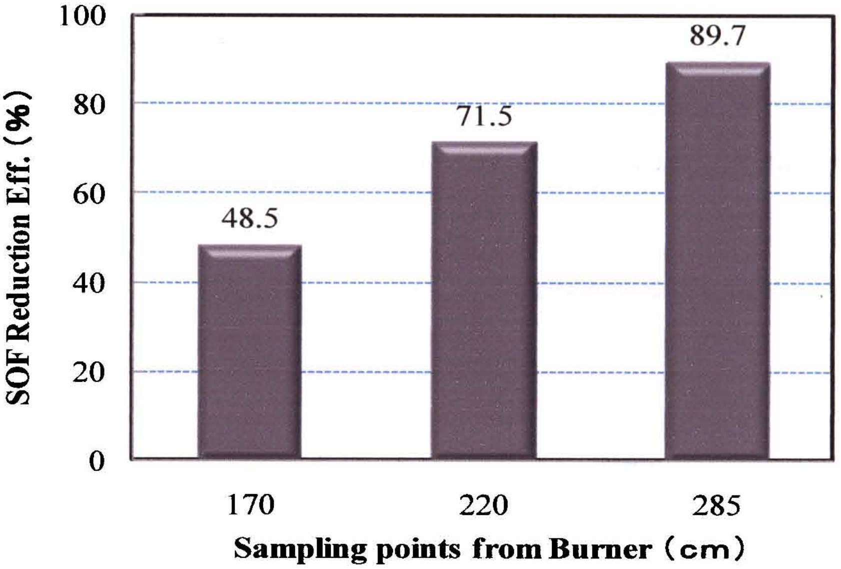


Fig.8.8 *Reduction efficiency of SOF by secondary combustion*

8.6 Dry Soot

Dry soot is a component inside the particulate emission that characterized by the formation of particulate was more enough to be said as a complete process. Dry soot does not have any similarity from the unburned hydrocarbon which it exists inside the soluble organic fractions. The application of secondary combustion clearly resulted in the decreases of the dry soot component; since the whole particulate components were drastically decreased.

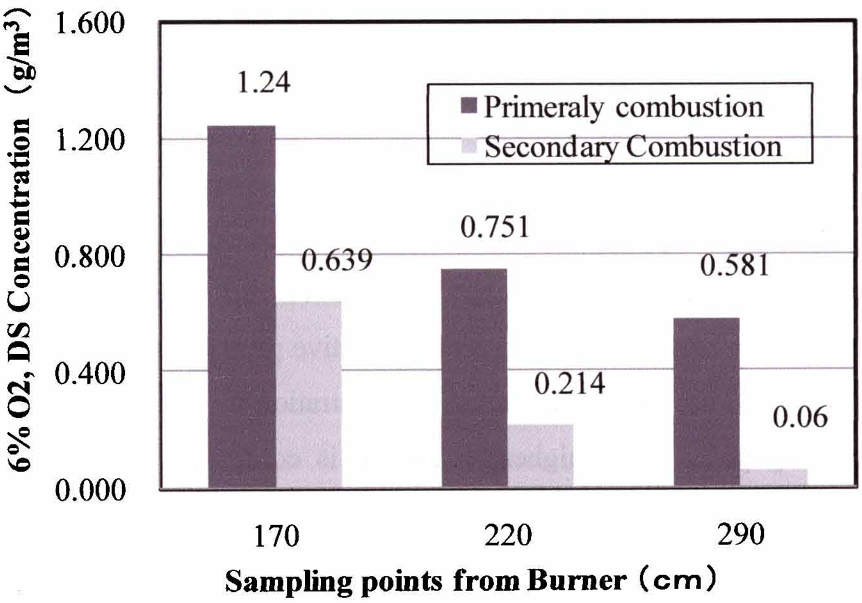


Fig.8.9 *Dry soot condition at rate of 6% oxygen*

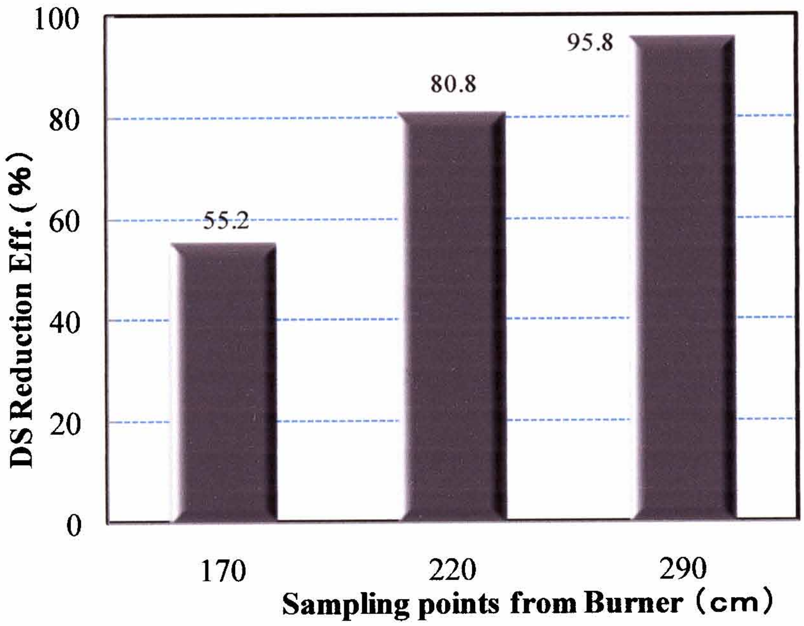


Fig.8.10 *Reduction efficiency of DS by secondary combustion*

At the sampling point 170 cm, the use of after burner makes a different of dry soot formation almost 0.601 g/m^3, while at the sampling point 290 cm, the drastically decreasing of dry soot confirmed for more than 0.581 g/m^3. All of dry soot data is shown in fig.8.9. below. Average of a result confirms that after burner giving a big impact to the reduction of dry soot. Comparative of the secondary combustion treatment with there is no treatment is shown graphically at fig. 8.8. The sampling points 290 cm from the burner resulted in the highest reduction with up to 89.7% reduction.

8.7 Summaries

The application of after burner as secondary combustion for treating the particulate emission from the combustion of coal emulsion with 20% of water content have successfully conducted at the laboratory scale of an experiment. Secondary combustion apparatus was made from stainless steel at the outer and inner the round pipe to provide a secondary combustion with the gas supply from the city. The application of after burner gives an effective performance for reduction of the particulate. The different of particulate concentration up to 1.340 g/m^3 to 1.386 g/m^3 at sampling points. The highest reduction is confirmed up to 93.4%. The particulate components; soluble organic fractions resulted the reduction up to 89.7% while the dry soot reduction 89.7%.

Chapter 9

Chapter 9

Particulate Matter and NO$_x$ Removal by Combination of Electrostatic Water Spraying Scrubber and Emulsion Fuel

Abstract

In this study, experiments were performed with the combination of using emulsion oil with 10% of water content and an electrostatic water-spraying scrubber to evaluate effectiveness for the simultaneous removal of particulate emission and NO$_x$ emission. The combustion of coal oil and its emulsions was investigated in a three-meter horizontal boiler with a fresh water cooling system. Two comparisons between coal and oil water emulsion flames are presented that, due to the different initial conditions of the spray, provides complementary combustion information. The combustion efficiency is improved when water is emulsified with coal oil. The distribution of NO$_x$ indicates that a significant reduction is obtained in the final part of the flame, as the attributed to a decrease in the rate of thermal NO formation because of lower gas temperature. The electrostatic water spraying scrubber mechanisms and combines with electrostatic precipitator and inertial wet scrubber removes particulate matter combustion and emitted exhaust gas. The effects of several parameters such as; corona power, gas flow rate, on the contaminant removals have been investigated intensively. The present study shows that at the setting flow rate, the removals of PM are enhanced with the increase of applied voltage. The overall removal efficiency was higher than 99% by electrostatic water spraying scrubber.

9.1 Introduction

The main pollution pollutant from the internal-combustion engine was identified as oxides of nitrogen (NO_x), and the particulate matter (PM) that has to be reduced. The formulation of NO_x and PM in the combustion chamber are contradictory and the simultaneous reduction of both is normally possible. Lowering the combustion flame temperature in order to reduce NO_x causes balance between soot formation and burnout to tilt towards increased PM emission. On the other hand, PM emission can be reduced by inhibiting their formation by better mixing of the fuel and improving their oxidation by increasing the combustion temperature, which. Consequently, causes an increase of NO_x emission. Thus, a trade-off is needed if both are to be reduced at the same time. One way to get around this dilemma is to replace or makes a treatment at the fuel, by replacing the coal fuel with coal oil emulsion (also known as coal oil/water emulsion) as an alternative fuel. Coal oil emulsions have evolved from earlier attempts to reduce combustion temperature for the NO_x reduction purposes. From all the methods to reduce combustion that proposes to introduce water into the combustion chamber, emulsions appear to be the most appropriate because they require no equipment retrofitting. This type of delivery may also provide advantages due to enhanced droplet's evaporation caused by the droplet micro-explosion from rapid gasification of the suspended water in the atomized droplets. A reduction in soot formation may e the result of different mechanisms.

The removal of PMs smaller than a few micrometers from exhaust gas presents a serious problem. The sizes of PMs, such as; smoke, fine powders, or oil mist, which is usually hazardous to human health, are not easily to remove by conventional methods. Therefore, an effective control of the PM, especially at the size range from 0.1 to 2 μm is still a great change for the engineers. To solve these problems, we are introducing electrostatic precipitators, and conventional inertial scrubbers as one of the solutions. In the electrostatic water spraying scrubber, PMs and scrubbing droplets are electrically charged to opposite polarities. The charged droplets capture the oppositely charged PMs due to coulomb attraction forces. Hereinafter in chapter the scrubber using electrostatic forces will be referred to as Electrostatic water spraying scrubber and the precipitation process as electro scrubbing. The major objective of this study was to evaluate the potential of electrostatic water spray in controlling pollutant and improve the PM removal efficiency. The other aim of the present work was also to investigate the effectiveness effect of the additional water in the form of an emulsion on the combustion of heavy oil. Coal oil without any treatment and in an emulsion with 10% water was burnt in a large scale of the laboratory furnace.

9.2 Experiment Procedure and Setup

9.2.1 Experimental Setup

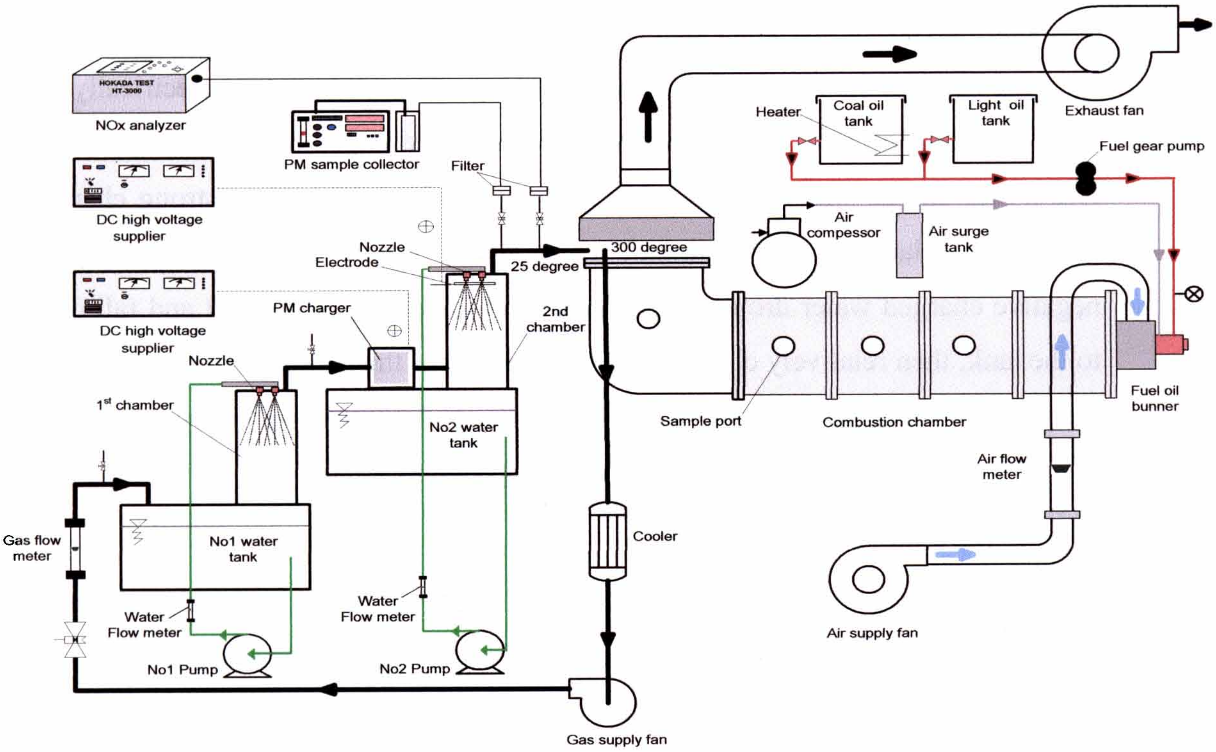


Fig.9.1 *Schematic diagram of experimental setup*

The system that used in supporting the experiments still have the same system as it was explained in the chapter 2; the experiment process. The main mechanisms that we want to introduce in this chapter are the electrostatic precipitator process and water scrubber system. An electrostatic water spraying scrubber used to collect mainly PM in the exhaust gas, and it had shown systematically in fig.9.1. The scrubber consists of two chambers. In the first chamber, the water from the tank no. 1 was pumped through two nozzles (orifice diameter one mm) with flow rate 3.4 ℓ/min. A mount of larger course PM is removed in this chamber. Ultrafine and condensable PM which could not be collected by water area grown to a few tenths of a micron in preparation for removal, and then remain PM were charge by a PM charger. The charger was made of stainless steel saws (four pcs) as positive electrodes that connect to the high-voltage suppliers adjusted to various voltages range from 1 kV to 10 kV to charge PM positive. These saws were mounted between 5 steel plates, which connected to the earth. In the second chamber, the water was pumped from thank no. 2 by the centrifugal pump and discharged through two nozzles (orifice diameter 0.5 mm) with flow rate 0.8 ℓ/min. They created droplets with 190 – 198 μm in diameter measured by Phase Doppler Particle Analyzer Aerometric. A stainless electrode (induction electrode) of inner diameter 15 mm is placed around the upper edge of spraying head of the nozzle. The induction electrode was connected electrically to a high DC voltage power supply adjusted to various voltages range from one kV to five kV to charge water droplets. This arrangement can provide a strong charging field with relatively low voltages. Thus, under stable operating conditions, a negative charged water droplet cloud is formed to collect charge PM and fall down to the tank, then relatively clean water from the top of the tank is re-circulated by the pump to the charging electrode, where it is recharged, completing the cycle.

9.2.2 Measurement of PM Mass Concentration

The raw and after treated PM was directly sampled by PG-60 composite filter paper as the properties are shown in table 3.2, and the PM mass on each filter was determined gravimetrically by the difference in mass before and after each test PM mass concentration in treated or untreated exhaust gas were determined by isokinetic sampling using EPA method 5 “sampling method for stationary sources." The scrubbing process for the experiment was divided into; no spray water (NS), after first chamber (1st), neutral droplet-neutral PM (ND-NP), charged droplet-neutral PM (CD-NP), charged PM neutral droplet (CP-ND), charged PM charged droplet (CP-CD). In these methods, the PM was collected on a 60 mm glass microfiber. The total PM mass was determined by the gravimetric method.

9.3 Result and Discussion

9.3.1 Reduction of NOx and PM by Using Emulsion Oil

Fig.9.2 and 9.3 show the measured NO and NO_x concentration for coal oil and emulsion along the axial length of the combustion chamber. The No and NO_x

emissions display a remarkable difference between the coal oil and emulsion combustion tests. The addition of 10% of water has a dramatic effect on the flame. The presence of water in coal oil brings a considerable reduction on NO_x emission. The results indicated that 10% water in the coal can give a reduction in NO and NO_x emission of up to 28-48% and 18-42% respectively. As a result from the coal oil combustion process about 90% of the NO_x is NO. The No is primarily formed by the oxidation process of the atmospheric nitrogen (N_2). Water added to the fuel lowers the combustion temperature due to water evaporation. When the water in the coal-water

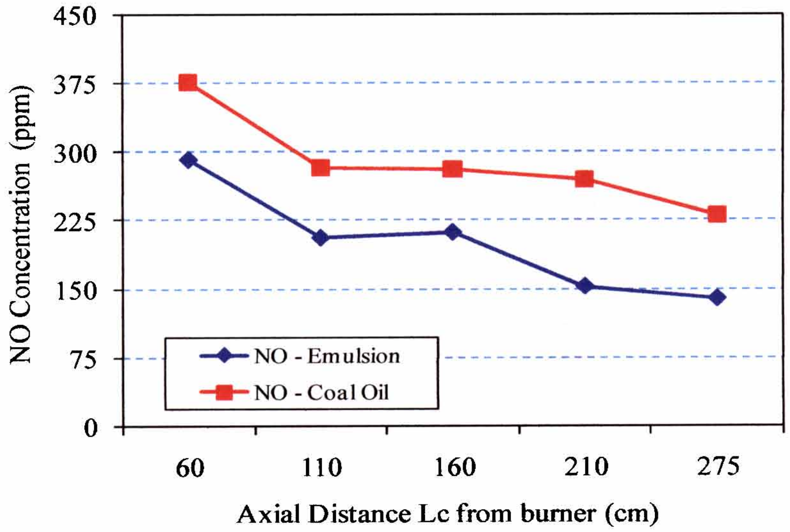


Fig.9.2 *NO concentration at different positions of furnace*

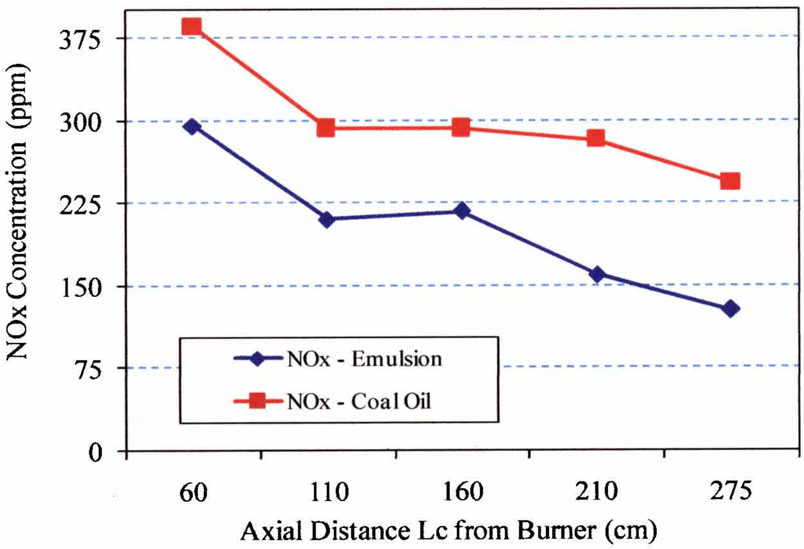


Fig.9.3 *NOx concentration at different positions of furnace*

Emulsion evaporates; the surrounding fuel is vaporized too. This process increases the surface area of the coal oil that contact for the combustion process/. The lower temperature and the better coal oil distribution are leading to a lover formation of NO and NOx. The flame temperature is reduced by 90°C. The heat absorbed by the water injected in the emulsion and enhanced radiative heat transfer due to the higher particle's number density. The distribution of NOx indicates that a significant reduction is obtained in the final part of the experimented sampling points. This may be attributed to a decrease in the rate of thermal NO formation as a consequence of lower gas temperature.

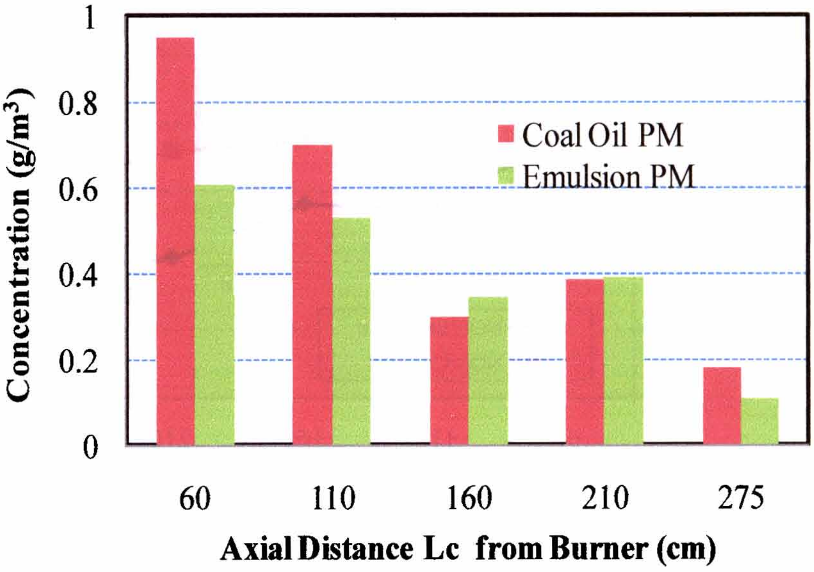


Fig.9.4 *PM mass concentration at different positions of furnace*

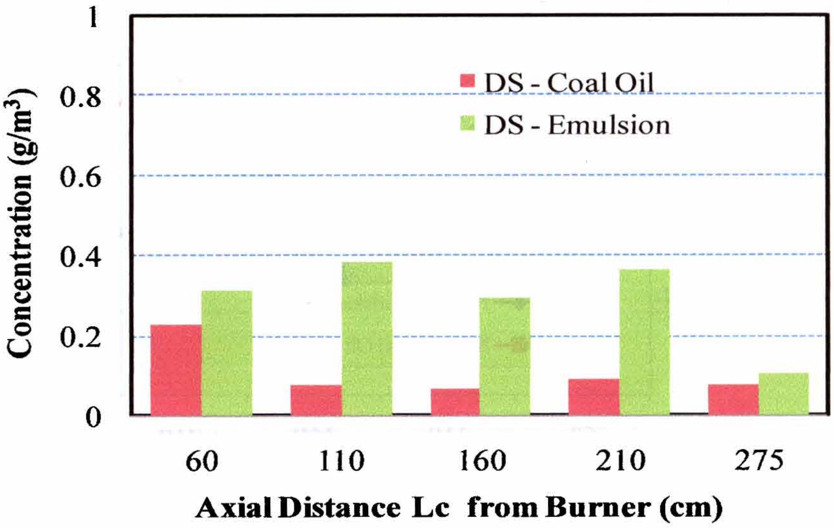


Fig.9.5 *Dry soot mass concentration at different positions of furnace*

In fig. 9.4 indicated PM mass concentrations for burning coal oil and emulsion at axial position of the furnace. Particulate matter includes of three main components; dry soot formed during combustion, heavy hydrocarbon condensed or absorbed on the soot (soluble organic fractions), and sulfate. In the combustion of coal oil, there is one more component called by chenosphere. The concentrations of PM in emulsion oil were all smaller than that by coal only. The decrease n soot concentration as a ringing from more uniform oxygen distribution as a consequence of the improved mixing caused by the secondary atomization, which improves atomization resulting in lower emission concentrations of PM from 5-36% at various positions of the furnace as shown in fig. 9.5 and 9.6.

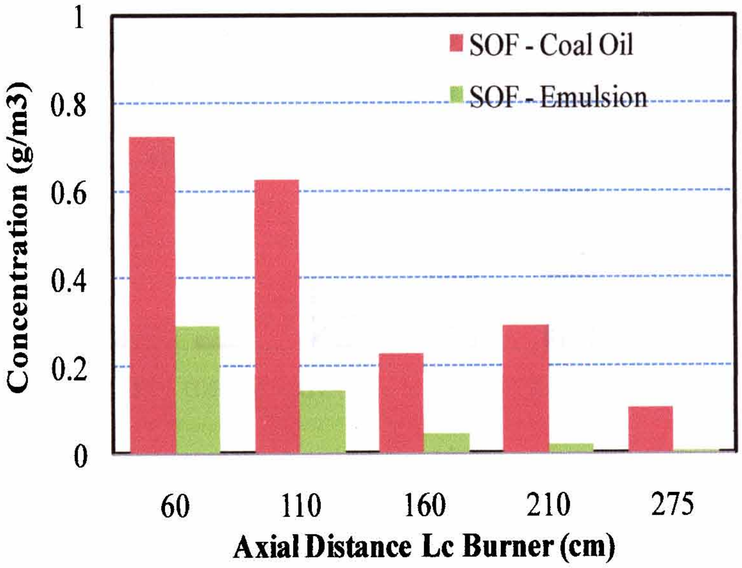


Fig.9.6 *SOF mass concentration at different positions of furnace*

9.3.2 Reduction of PM by Using Electrostatic Water Spraying Scrubber

Fig. 9.7 show shows the PM mass concentrations under various water performances, corresponding to a constant flow rate of the exhaust gas 1800 ℓ/h fed into the scrubber. Pm mass concentration for the un-treatment condition of exhaust gas is in the range from 0.52 g/m^3. PM mass concentration was removed in the exhaust gas from 0.39% to 0.5 g/m^3 in the scrubber depending on the PM scrubbing performances.

In fig. 9.8, it shows PM collection efficiency of the scrubber. Comparison with the results of water performances such as no spray water, neutral water and neutral OM, charged water and neutral water, spray neutral water and charged PM, and both of charged PM and water droplets. When the scrubber is used at neutral water to remove neutral PM, it only collects coarse PM by the single impaction mechanism as conventionally. However, these are not affected on the fine particulate matter, because of their very lightweight, fine PMs are pushed out of the part of the water droplets and are forced to follow the streamlines. Therefore, PM was removed with low efficiency. The highest of PM efficiency only reached to 72% at the sampling point nearest to burner and 80% for both chambers.

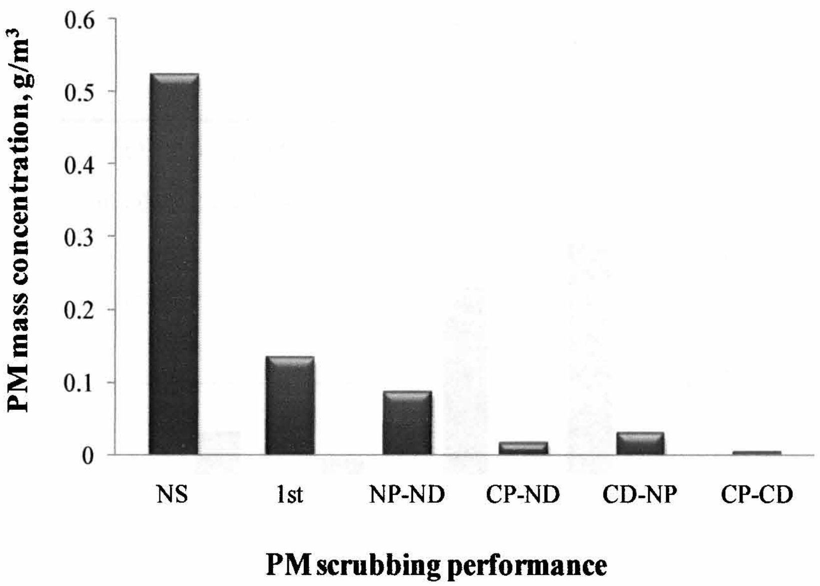


Fig.9.7 *PM mass concentration at various scrubbing performance of the scrubber*

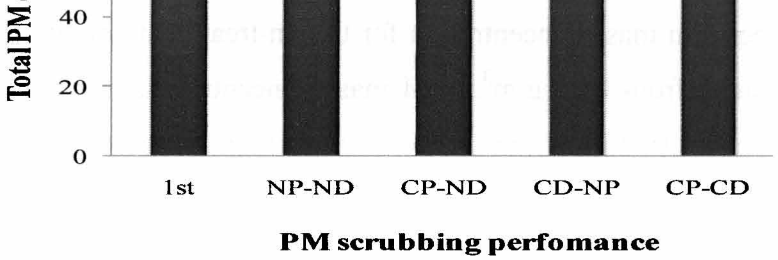


Fig.9.8 *PM mass efficiency at various scrubbing performance of the scrubber*

It is a note that the same amount of spraying water, in the case of using charged droplet neutral PM or neutral droplet charged PM results in the more effective collection of PM than using the neutral droplet neutral PM. It is because of an image charge of opposite sign is induced on neutral objects, generating a force of attraction. These forces lead to the PM water droplet attracted each other that stronger than the impaction and interception mechanism causing an increase in the efficiency of PM collection up to 97%.

The better results were obtained when both PM and water droplets were oppositely charged. The collection efficiency was gained as high as 99% corresponding to positive PM and negative droplets more may time upper than using neutral droplets neutral PM 20%/ the collection efficiency was highly increased due to there is coulomb force between charged droplets and charge PM, that causes forces from a strong mechanism to drive charge PM to the charged droplet. It was demonstrated experimentally that the electrical charging of droplets and PM allows an increase of the collection efficiency of PM that compared to the conventional scrubber at the same amount of water using.

9.3.3 Effect of Corona Power on PM Collection Efficiency

Fig. 9.9 present the total PM collection efficiency as a function of corona power normalized to the exhaust gas flow rate of 1800 ℓ/h. it is seen that the increase collection efficiency from 95% to 99% in the secondary chamber requires an increase of corona power from 0.05 W/h to 11.3 W/h. at the same exhaust gas ratio and corona power a strong linear relationship was established between the PM collection efficiency is as the impact of strong effect of the charging voltages on collection efficiency. At increasing voltage, the corona current increased, which led to the increasing of ion density, thus enhancing the PM charging and collection processes inside the scrubber. For induction charging water, in principle, there is no electrical energy consumption. In a practical system, the only current flowing through the power supply is the leakage current and the current due to deposition of droplets on the induction electrode. There for an amount of small energy for charging water is eliminable. The total PM collection could gain more than 99% in the scrubber with 11.3 W/h of power consumption.

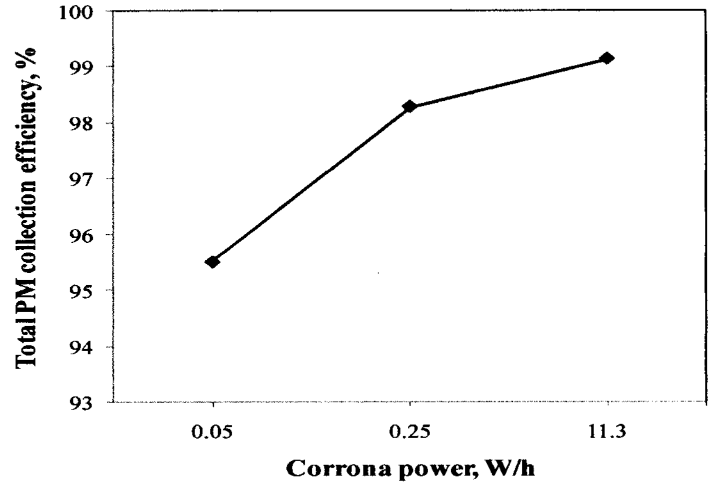


Fig.9.9 *Correlation between PM collection efficiency and corona power*

9.3 Summaries

The partial distribution of NOx inside the combustion chamber indicates that the generation of NOx over the final part of the flame is reduced by the addition of water. The main source of NOx in that region is considered to be the thermal machisms, and the observed reduction NOx formation is in accord with the decrease in flame temperature. Reduction in NO and NOx emission were gained up to 48% and 42%, respectively.

The additional of water to coal oil in emulsion formation can significantly accelerate the evaporation and combustion processes in the flame. This is very important in the residual fuel application such as coal fuel and other heavy fuel with low quality of fuel, while the water amount can weaker the fine atomization of the coal oil and coal emulsion fuel. Among the possible effects of water addition, the micro-explosion phenomenon is considered responsible for the significant changes in the flame process. The effects are high burnout of the cenospheres initially generated in the flame and the reducing of unburned hydrocarbon by up to 26% of emulsion application.

The application of water spraying combined with electrostatic precipitator is shown in the reduction for both NOx and particulate emission. The removal of PM mass was gained over 99% at gas flow rate of 1800 ℓ/h. Further improvement of removal efficiency was gained by charging sprays utilizing electrical forces an effectively operate for small sizes.

Chapter 10

Chapter 10

Conclusions and Recommendations

10.1 Conclusions

The development application of low grade quality of coal for the coal as fuel by the liquefaction technology has been conducted in laboratory scale of experiments with industrial support of liquefaction technology. In line with the purposes of the project to utilize low grade of coal by converting to liquid as fuel, the experiments were successfully conducted. The experiment process was began from the preparation process, designing a combustion system, and ended by the treatments for environmental friendly propose. The objects of the research are the combustion performance, exhaust gases contents measurement, and particulate emission. From all of experiment`s results, some conclusions are taken as follows:

1. By providing a good support system for the combustion process, the steady combustion of low grade liquid could be performed. There is a possibility of the application its fuel to be the substitute of C bunker heavy oil. NOx formation in the exhaust gas was measured at 242 – 396 ppm while the particulate emission as the effect of unburned hydrocarbon reached up to 0.170 g/m^3.
2. Comparison the exhaust gas from the combustion of C heavy oil with coal fuel indicated that coal fuel producted higher of exhaust gas components as; O_2 (12%), CO (31%), and CO_2 (21%), while the nitrogen derivative concentration as; NO (72%), NO_2 (63%), and NO_x (42%). The energy transfer to the cooling media was recorded at 3527 kJ/minutes, and C heavy oil was at 4635 kJ/minutes. Before the experiment, fuel's combustibility was measured by using TG/DTA. The higher result of combustion from TG/DTA for C heavy oil occurred at 637°C, 17.5 mJ, and coal oil at 586 °C, 18 mJ.

3. Particulate Matter (PM) measurement from all sampling points shows that average of PM emitted from coal fuel is 80% higher than C heavy oil, while in detail; Soluble organic fraction higher 39%, and dry soot lower more than 92%.
4. The application of emulsion fuel with water contents from 10, 20, and 30% shows that at 20% water content, the combustion was in the condition of most steady. Reduction of exhaust gas components was gained as; CO up to 46%, NO_x up to 34% and PM up to 16%, respectively.
5. The application of after burner (secondary combustion) gives an effective performance for reduction of the particulate. The highest reduction is confirmed up to 94% for all of PM, with soluble organic fractions resulted up to 90% and dry soot 89%.
6. Application of the combination between coal emulsion, water spraying scrubber and electrostatic precipitator indicated successful decreasing of exhaust gas components and particulate emission with 48% and 42% for NO and NO_x, 26% of unburned hydrocarbon (PM). The removal of PM mass with the application of spraying scrubber and electrostatic precipitator was gained over 99% at gas flow rate of 1800 ℓ/h.

From overall of the experiments results, it is concluded that there is a possibility of the application of coal liquid fuel for transportation fuel together with the special treatment for the combustibility and the exhaust gas components.

10.2 Recommendations

In order to carry out the next steps of experiment by application of coal oil as fuel for diesel engine, there are some considerations have to be carefully thinking and find the answers before the experiments:

1. Determine the optimum heating temperature of coal fuel that make it's easily being transported to the support system in the fuel line.
2. The sludge of particles inside coal fuel has to be removed from the fuel. It can be bottleneck the burner.
3. Economic aspect of treatment for the coal oil must be measured, while it will be produced for industrial purposes. Low grade of coal is quite cheap, but to

build up the system for the conversion of coal to liquid needs a good financial support.

4. The smell of coal oil and emitted of exhaust gas must also being treated in more environmental friendly manner.
5. Many aspects of the combustion and utilization of the coal oil have to be experimented in order to have enough information and knowledge about the characteristics of coal fuel.

References

References

[1] Speight, J. G. 1994. The Chemistry and Technology of Coal, 2nd ed. Marcel Dekker, New York.

[2] Van Krevelen, D.W., Coal: Typology–Physics–Chemistry–Constitution, Third ed. (Elsevier Science, Amsterdam, 1993).

[3] EIA, International Energy Outlook 2002 (U.S. Department of Energy, Energy Information Administration, Washington, D.C., March 2002), p. 72.

[4] Elliot, T. C. (editor), Standard Handbook of Power plant engineering (McGraw-Hill, New York, 1989).

[5] Tang, J. T. and F. Engstrom, Technical Assessment on the Ahlstrom Pyroflow Circulating and Conventional Bubbling Fluidized-Bed Combustion Systems, in Proc. of the International Conference on Fluidized-Bed Combustion,p.37, 1987.

[6] Anon., Boilers and Auxiliary Equipment, Power, Special Edition, June 1988.

[7] Berkowitz, N., An Introduction to Coal Technology (Academic Press, New York, 1979).

[8] Schobert, H. H., Coal: The Energy Source of the Past and Future (American Chemical Society, Washington, D.C., 1987).

[9] Elliot, M. A. (editor), Chemistry of Coal Utilization, Secondary Suppl. Vol.2 (John Wiley & Sons, New York, 1981).

[10] J.B. Heywood, 1988, "Internal Combustion Engine Fundamental, Mc Graw-Hill.

[11] Miller, B. G., S. Falcone Miller, and A. W. Scaroni, Utilizing Agricultural By-Products in Industrial Boilers: Penn State's Experience and Coal's Role in Providing Security for our Nation's Food Supply, paper presented at the Nineteenth Annual International Pittsburgh Coal Conference (University of Pittsburgh, September 23–27, 2002).

[12] Davis,W. T. (editor), Air Pollution Engineering Manual, Second edition, (JohnWiley & Sons, New York, 2000)

[13] Wark, K., C. F.Warner, andW. T. Davis, Air Pollution: Its Origin and Control, Third ed. (Addison-Wesley Longman, Menlo Park, CA, 1998).

[14] Mine Safety and Health Administration (MSHA), www.msha.gov, 2003.

[15] EPA, Latest Findings on National Air Quality: 1997 Status and Trends (U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Washington, D.C., 1998)

[16] Davis,W. T. (editor), Air Pollution Engineering Manual, Second ed. (JohnWiley & Sons, New York, 2000).

[17] Jackson, L. J., Surface Coal Mines: Restoration and Rehabilitation (IEA Coal Research, London, 1991).

[18] EPA, Mercury Study Report to Congress (U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, U.S. Government Printing Office,

Washington, D.C., December 1997).

[19] Clarke, L. E. and L. L. Sloss, Trace Elements: Emissions from Coal Combustion and Gasification (IEA Coal Research, London, 1992).

[20] EPA, Greenhouse Gases and Global Warming Potential Values (U.S. Green-house Gas Inventory Program Office of Atmospheric Programs, U.S. Environmental Protection Agency, U.S. Government Printing Office, Washington,

D.C., April 2002).

[21] Masaharu, N.: Effect of Peroxides during Pretreatment for Coal Liquefaction, (Energy Fuel, Vol.17, 2003, pp. 506-510)

[22] Jeong, I.C., H. Lee, K.: Auto Ignition and Micro-Explosion Behaviors of Droplet Arrays of Water in Fuel Emulsion (Int. J. Automobile Technology, Vol.9 No.6, pp.735-740.

[23] Coda Zabetta, E., Hupa, M., Niemi, S.: Bio-derived fuels may ease the regeneration of diesel particulate traps, Fuel, Vol.85, 2006, pp.2666-2670

[24] D`anna, A., Violi. A., D`alessio, A., Sarofim A.F.: A Reaction Pathway for Nanoparticle Formation in Rich Premixed Flame, Combustion and Flame,Vol. 127, 2001, pp.1995-2003.

[25] Apple J, Bockhom, H., Fenklach, M. : Kinetic modeling of soot formation with detailed chemistry and physics: laminar premixed flame of C_2 hydrocarbon, Combust. Flame, 121, 2000, pp.122-136.

[26] Frenklach, M., Wang, H. : Detailed mechanism and modeling of soot particle formation. in Soot Formation in Combustion: Mechanisms and Models of Soot Formation, (Bockhorn, H., ed.), Berlin,Springer-Verlag Springer Series in Chemical Physics, Vol.59, 1994, , pp.162-190.

[27] Helble, J. J., Sarofim A.F.: Factors determining the primary particle size of flame-generated inorganic aerosol", Journal of Colloid and Interface Sci., Vol.128, No.2, 1988, pp.348-364.

[28] Seinfeld, JH., Pandis, SN.: Atmospheric chemistry and physics: From air pollution to climate change, New York: John Wiley&Sons, Inc, 1998.

[29] Osami Nishida, et.al,; "Test Result of Practical Engines for Reduction of Marine Air Pollution by Emulsion Fuel Oil", Journal of the JIME, vol.43, No.15, 2008 pp.122-129.

[30] H.S.Kim,T.Murakami, O.Nishida, H.Fujita, W.Harano."Formation Characteristics of PM and SOF by Spray Combustion of Marine Heavy Fuel Oil", Journal of the Korean Society of Marine Engineers vol.28, No.2, January, 2004, pp.292-299.

[31] W.Bartok, AF. Sarofin, "Fossil Fuel Combustion", New York, Wiley.1991.

[32] K.J., Baumgrad, Johnson J.H., "The Effect of Fuel and Engine Design on Diesel Exhaust Gas Particle Size Distributions", SAE Technical Paper 960131, 1996.

[33] Bedford F., Rutland C., Dittrich P., Raab A., and Wirbeleit F., "Effects of Direct Water Injection on DI Diesel Combustion", SAE Paper: 2000-01-2938, 2000.

[34] Bowman CT., "Control of Combustion-Generated Nitrogen Oxide Emissions: Technology Driven by Regulation", Proceeding of Combustion Institute, Vol.24, pp.859, 1993.

[35] Chippett S. and Gray WA., "The Size and Optical Properties of Soot Particles",

Journal of Combustion and Flame, Vol.31, pp.149-186, 1978.

[36] Choi MY., Hamins A., Mulhilland GW., Kashiwagi T., "Simultaneous Optical Measurement of Soot Volume Fraction and Temperature in Premixed Flames", Journal of Combustion and Flame, Vol.99, pp.174-186, 1994.

[37] Lin C.Y., and Pan J.Y., "The Effect of Sodium Sulfate on the Emissions Characteristics of an Emulsified Marine Diesel Oil-fired Furnace", journal of Ocean Engineering, Vol.28, pp.347-360, 2001.

[38] Doug W., "Pounder`s Marine Diesel Engines and Gas Turbines", 8th edition, Elsevier Butterworth-Heinemann, 2004.

[39] Galssman I., "Combustion", San Diego, Academic Press, 1996.

[40] Glassman I., "Soot Formation in Combustion Processes", in: Proceeding of the 22nd International Symposium on Combustion, The Combustion Institute, pp.295-311, 1989.

[41] Haynes BSaHGGW, "Soot Formation", Prog. Energy Combust. Sci., Vol.7, pp.229-273, 1981.

[42] Lee R., Pedley J., Hobbs C., "Fuel Quality Impact on Heavy Duty Diesel Emission-Literature Review", SAE Paper 982649.

[43] Medalia A.I., and Heckman F.A., "Morphology of Aggregates: 2. Size and Shape Factors of Carbon Black Aggregates from Electron Microscopy", Carbon 7, pp.567-582, 1969

[44] A.G.Bailey,; "Electrostatic Spraying of Liquids", Wiley, New York, 1988.

[45] G.W/Penney, "Electrical Liquid Spray Dust Precipitator", U.S. Patent 2, pp.357-354, 1944.

[46] H.J.White, "Industrial Electrostatic Precipitator", Addison Wisley, Reading, Mass, 1963.

[47] C.Eyraud, J.Joubert, R.Morel, C.Henry, and B.Roumesy, "Study of a New Dust Collector Using Electro statically Sprayed Water", Proc. Part I, Inter, Clean Air Congr, London, pp 129-130, 1966

[48] S.Calvert, S.C.Young, H.Barbarika, and R.G.Patterson, "Evaluation of Four Novel Fine Particle Collection Devices", US Environmental Protection Agency Report EPA/600/2-78-062, 1978.

[49] B.RajMohana, R.K.Jain, B.C.Meikapa, " Comprehensive analysis for prediction of dust removal efficiency using twin-fluid atomization in a spray scrubber", Separation and Purification Technology 63, pp.269-277, 2008

[50] J.B.Joshi, V.V.Mahajani, V.A. Juvekar, "Absorption of NO dissolved in gases", Chem. Eng. Commun, Vol.33, pp.1-92, 1985.

[51] S.Chang, D.LitteJohn, S.Lynn, "Effect of metal chelates on wet flue gas scrubbing chemistry", Environ. Sci. Technol, 17, pp.649-653, 1983.

[52] H.S.Kim, et.al., "Development of diesel engine emission control system on NO_x and SO_x by seawater electrolysis", 24th CIMAC, 2004.