

LAPPEENRANTA UNIVERSITY OF TECHNOLOGY

LUT School of Engineering Science

Chemical and Process Engineering

Master's Thesis

**Preparation and Investigation of Bio-coal Mixture
Fuels Used in Large Diesel Engines**

Examiners	Professor, D.Sc. Eeva Jernström (LUT) Professor, D.Sc. Esa K. Vakkilainen (LUT)
Supervisors	Professor, D.Sc. Esa K. Vakkilainen (LUT) D.Sc. Wolfgang Stelte (DTI Denmark) D.Sc. Jussi Heinimö (Miksei Ltd)
Author	Hamid Gilvari

ABSTRACT

LAPPEENRANTA UNIVERSITY OF TECHNOLOGY

LUT School of Engineering Science

Chemical and Process Engineering

Hamid Gilvari

Preparation and Investigation of Bio-coal Mixture Fuels Used in Large Diesel Engines

Master's Thesis

2016

90 Pages, 44 figures, 18 tables, and 1 appendix

Examiners	Professor, D.Sc. Eeva Jernström (LUT)
	Professor, D.Sc. Esa K. Vakkilainen (LUT)
Supervisor	Professor, D.Sc. Esa K. Vakkilainen (LUT)
	D.Sc. Wolfgang Stelte (DTI Denmark)
	D.Sc. Jussi Heinimö (Miksei Ltd)

Keywords: Bio-coal slurry fuel, charcoal, torrefied wood, rapeseed oil, diesel engine

Coal slurry was of vital interest during the last century due to its potential as an alternative fuel where liquid fuels were necessary. Recently, environmental impacts of the traditional fuels, similarities of bio-coal to that of coal, and huge bio-coal supply has attracted the attention to prepare bio-coal slurries as a new fuel.

Rudolf Diesel who invented the diesel engine on 1895 was of the opinion that diesel engines are capable to use different kinds of fuels due to the special design. He tried some kind of vegetable oil to operate on his IC engine. Recently, due to high energy density and more environmentally friendly fuel, researchers believe that bio-coal slurries could act as a new alternative fuel in large diesel engines.

Loads of research on different kinds of bio-coal slurry were done by the other researchers worldwide and a lot of progress to boost slurry's quality were achieved recently.

The present study aims to achieve the ideal condition of different factors affecting on the quality of bio-coal slurry. One charcoal sample and two kinds of torrefied wood were used to investigate and compare the reaction of various factors.

The results show a great gap between the quality of slurries made of different samples and more researches are necessary to fully understand the impact of the different parameter and improving the quality.

ACKNOWLEDGMENTS

This Master's thesis was done at the School of Energy Systems at Lappeenranta University of Technology.

It was my honor to do my Master's thesis under supervision of Professor Esa Vakkilainen who gave me the chance to work on such an interesting topic and also for his valuable comments and kind support during my thesis.

In addition, I would like to thank Professor Eeva Jernström from the Lappeenranta University of Technology, D.Sc. Jussi Heinimö from Mikkeli Development Miksei Ltd, and D.Sc. Wolfgang Stelte from Danish Technological Institute for their worthwhile guides, comments, and helps.

Advice, supports and assists of all the university staffs of the energy department and chemical engineering department of the Lappeenranta University of Technology who always helped me doing this work is kindly appreciated.

I also would like to thank my family who has always supported me in whole my life. I am always proud of them.

Last but not least, I would like to express my deepest thank to my lovely wife, Hengameh, for her patient, support, guide, help, and giving me the confidence to do my best. Thanks for everything my love.

Lappeenranta, January 2016

Hamid Gilvari

Table of content

1	INTRODUCTION	14
1.1	Energy alternatives	14
1.2	Targets of the thesis	15
1.3	Implementation of the study	15
2	BIOMASS AS AN ENERGY SOURCE.....	17
2.1	Woody biomass and its potential.....	17
2.2	Biomass conversion to charcoal	18
2.3	Torrefaction	19
2.4	Bio-coal	20
2.4.1	World production of bio-coal.....	21
2.4.2	Chemical properties of bio-coal	21
2.4.3	Physical properties of bio-coal.....	23
2.4.4	Particle size reduction	24
2.4.5	Ash content.....	26
2.4.6	Heating value.....	30
2.4.7	Volatile matter.....	31
3	BASIC PRINCIPLES OF DIESEL ENGINE.....	35
3.1	Background.....	35
3.2	Slurry fuels in diesel engine	35
3.3	Atomization of fuel.....	37
4	ALTERNATIVE FUELS IN LARGE DIESEL ENGINES	43
4.1	Rapeseed oil.....	43
4.2	Slurry fuels	44
4.2.1	Coal-based slurry.....	44

4.2.2	Bio-coal-based slurry	45
4.2.3	Properties of slurry fuels	46
5	EXPERIMENTS	54
5.1	Material and methods	54
5.1.1	Particle size reduction	54
5.1.2	Slurry preparation and viscosity measurement	56
5.1.3	Proximate and Ultimate analysis.....	57
5.1.4	Measuring of heating values	58
5.1.5	Density	58
5.1.6	Stability measuring method.....	58
5.2	Results and discussion	59
5.2.1	Proximate and ultimate analysis.....	59
5.2.2	Water-based slurries.....	59
5.2.3	Rapeseed oil –based slurries	63
5.2.4	Effect of high temperature.....	66
5.2.5	Heating value.....	68
5.2.6	Density	69
5.2.7	Stability of the slurry.....	70
5.3	Summary.....	70
6	COST ANALYSIS.....	72
6.1	Bio-coal slurry price	72
6.2	Fuel oil price.....	75
6.3	Price of slurry using HFO as the liquid carrier.....	77
6.4	Summary.....	78

7	DIFFERENCES BETWEEN COAL AND BIO-COAL	79
7.1	Possible affecting factors.....	80
7.1.1	More hydrophobicity (less oxygen content) of coal.....	81
7.1.2	More ash and minerals in coal.....	81
7.1.3	More zeta potential of coal.....	82
7.1.4	More apparent density of coal.....	82
8	SUMMARY AND CONCLUSION	85
	REFERENCES.....	88
	APPENDIX	

List of Tables

Table 2-1. Distribution of lignocellulose fraction in softwood and hardwood (Gravelsins, 1998).....	18
Table 2-2. Composition of wood and torrefied wood (van der Stelt et al., 2011)	20
Table 2-3. Bio-coal properties vs coal properties (Meijer, 2011)	21
Table 2-4. Bio-coal composition, yield, and heating value under different final temperatures of charring (Bagramov, 2010)	22
Table 2-5. Density and porosity of charcoal derived from different types of wood (Bagramov, 2010).....	23
Table 2-6. Impurities in coal and wood without bark (% of ash) (Patton et al., 2009).....	28
Table 2-7. Heating values of bio-coal at different temperatures (Bagramov, 2010)	31
Table 2-8. Volatile matters of different wood types (Prins, 2005)	32
Table 2-9. Effect of torrefaction temperature and oxygen content on the volatile matter of Eucalyptus grandis wood (Rousset et al., 2012)	32
Table 2-10. Deashed bio-coal-oil-water mixture solid content as a function of volatile matter (N'kpomin et al., 1995)	34
Table 4-1. Comparative properties of CDF, ULSD, and biodiesel (Kalpesh and Sham, 2012).....	47
Table 4-2. Calorific value of different bio-coal slurries (N'kpomin et al., 1995)	53
Table 5-1. Ultimate and Proximate analysis of the samples	59
Table 5-2. Heating values of samples	69
Table 5-3. Calculated heating values of different slurries	69
Table 5-4. Apparent density of three samples used in this work	69
Table 6-1. Summary of the prices and different properties of different diesel fuels excluding tax	78
Table 7-1. Analysis and slurryability of different coals (Yuchi et al., 2005).....	80

List of Figures

Figure 2-1. Process classification of biomass thermal conversion (Long, 2014)	19
Figure 2-2. Share of bio-coal production in different parts of the world in 2013 (FAO, 2012).....	21
Figure 2-3. Hygroscopicity of 6 mm pellets made from torrefied wood at temperatures from 240-340°C. The control is regular white pellets, tests were done at 30°C and 90% relative humidity (Koppejan et al., 2012)	23
Figure 2-4. Bio-coal structure (Bagramov, 2010).....	24
Figure 2-5. Hardgrove index of different coals, bio-coal, and torrefied pellets (Bagramov, 2010).....	26
Figure 2-6. Normal diesel wear and accelerated wear caused by slurry fuels (Soloiu et al., 2011).....	27
Figure 2-7. Process of ash removal by combination of chemical (Acid) and selective agglomeration treatment (Esnouf, 1991).....	30
Figure 2-8. Maximum solid content vs volatile in bio-coal slurry (N'kpomin et al., 1995).....	33
Figure 3-1. Different types of pressure-swirl atomizers: (a) plain orifice, (b) simplex, (c) dual orifice, and (d) spill return (Lefebvre, 2010).....	38
Figure 3-2. Atomization of two different slurry containing larger coal particles (a) and smaller coal particles (b) (Son and Kihm, 1998)	39
Figure 3-3. Volumetric percentile spectra of droplets of the three tested CWS spray and water spray at 20 psig air jet pressure (Son and Kihm, 1998)	39
Figure 3-4. Droplet size distribution of slurry at 40 MPa and various spray temperature (Soloiu et al., 2011).....	40
Figure 3-5. Sauter mean diameter slurry vs. injection pressure and temperature (Soloiu et al., 2011).....	40
Figure 3-6. Coaxial air-water jets breakup types (Zhao et al., 2012).....	42
Figure 3-7. Droplet size distribution of two suspension spray condition based on water with glass particles with two different mean particle size of 6 μm (left) and 94 μm (right) (Mulhem et al., 2006).....	42

Figure 4-1. The viscosity of CWS with different PSD at different shear rates (Son and Kihm, 1998)	48
Figure 4-2. PSD for monomodal and bimodal distribution (Lee et al., 2014)	49
Figure 5-1. Appearance of three different solid samples (a) sample 1, (b) sample 2, and (c) sample 3.....	54
Figure 5-2. Laboratory scale hammer mill.....	55
Figure 5-3. Laboratory scale ball mill.....	55
Figure 5-4. High speed homogenizer shaft	56
Figure 5-5. Viscosity of "sample 1"-water slurry at different solid concentrations ($0 < PSD < 38 \mu\text{m}$)	60
Figure 5-6. Viscosity of "sample 1"-water slurry at different solid concentrations ($38 \mu\text{m} < PSD < 50 \mu\text{m}$)	60
Figure 5-7. Viscosity of "sample 1"-water slurry at different solid concentrations ($50 \mu\text{m} < PSD < 63 \mu\text{m}$)	61
Figure 5-8. Viscosity of "sample 1"-water slurry at different solid concentrations ($63 \mu\text{m} < PSD < 100 \mu\text{m}$)	61
Figure 5-9. Viscosity of "sample 1"-water slurries at different PSD and solid concentration at 100RPM.....	62
Figure 5-10. Viscosity of 25 wt. % "sample 2"-water slurry at different particle sizes.....	62
Figure 5-11. Viscosity of "sample 3"-water slurry at different particle size and solid concentration	63
Figure 5-12. Viscosity of "sample 1"-rapeseed oil slurry at different solid concentrations ($0 < PSD < 38 \mu\text{m}$).....	64
Figure 5-13. Viscosity of "sample 1"-rapeseed oil slurry at different solid concentrations ($38 \mu\text{m} < PSD < 50 \mu\text{m}$)	64
Figure 5-14. Viscosity of "sample 1"-rapeseed oil slurry at different solid concentrations ($63 \mu\text{m} < PSD < 100 \mu\text{m}$)	65
Figure 5-15. Viscosity of "sample 1"-rapeseed oil slurry at different PSD and solid concentration at 100RPM.....	65
Figure 5-16. Viscosity 30wt. % "sample 2"-rapeseed oil slurry at different PSD	66

Figure 5-17. Viscosity of "sample 3"- rapeseed oil slurry at different PSD and different solid concentrations.....	66
Figure 5-18. Viscosity of "sample 1"-rapeseed oil slurry at 100RPM vs solid concentration at different temperatures and PSD	67
Figure 5-19. Viscosity of "sample 2"-rapeseed oil slurry at 100RPM vs solid concentration at different temperatures and $0 < PSD < 38 \mu\text{m}$	68
Figure 5-20. Viscosity of "sample 3"-rapeseed oil at different temperatures at 20 wt. % and $0 < PSD < 38 \mu\text{m}$	68
Figure 6-1. Production costs of torrefied wood pellets integrated into a CHP plant in the Baltic area (Wilén et al., 2014)	73
Figure 6-2. Rapeseed oil price from Jan 2005 to present (Fund, 2015).....	74
Figure 6-3. Heavy fuel oil price from Jan 2005 to present (Studies, 2015).....	77
Figure 7-1. Slurryability vs O/C ratio of different coals (Yuchi et al., 2005) and "sample 1" of the present study.....	81
Figure 7-2. Slurryability vs ash content of different coals (Yuchi et al., 2005) and "sample 1" of the present study.....	82
Figure 7-3. Effect of pyrolysis temperature and compression on blackbutt chips porosity. Compression is done at 0.5 MPa (Somerville and Jahanshahi, 2015)	84
Figure 7-4. Effect of pyrolysis temperature and compression on blackbutt chips apparent density. Compression is done at 0.5 MPa (Somerville and Jahanshahi, 2015).....	84

Abbreviations

Al	Aluminum
BTU	British thermal unit
C	Carbon
Ca	Calcium
CDF	Certified Diesel Fuel
CHP	Combined Heat and Power
CI	Compression Ignition
CMF	Coal-Methanol Fuel
CO	Carbon Monoxide
COM	Coal-Oil Mixtures
COW	Coal-Oil-Water Slurry
cP	Centi Poise
CWF	Coal-Water Fuel
CWO	Coal-Water-Oil Slurry
CWS	Coal-Water Slurry
db.	Dry Basis
Fe	Iron
H	Hydrogen
HC	High Hydrocarbon
HFO	Heavy Fuel Oil
HHV	Higher Heating Value

IC	Internal Combustio
ISO	International Standard Organization
J	Joule
K	Potassium
l	Liter
lb.	Pound
LFO	Light Fuel Oil
LHV	Lower Heating Value
M	Molar
Mg	Magnesium
MJ	Mega Joule
Mn	Manganese
MPa	Mega Pascal
MWh	Mega Watt Hour
N	Nitrogen
NO _x	Nitrogen oxides
O	Oxygen
PSD	Particle size distribution
RPM	Round Per Minute
SiO ₂	Silicon Dioxide
SMD	Sauter Mean Diameter
ULSD	Ultra low Sulfur Diesel

Vol. %	Volume Percent
wt. %	Weight Percent
μm	Micro Meter

Symbols

v/v	Volume to Volume ratio
€	Euro Currency
\$	US Dollor

Terms

Hygroscopicity	Readily absorbing moisture, as from the atmosphere
Monomodal PSD	PSD including a continuous size range e.g. from 32 to 45 μm
Bimodal PSD	PSD including at least two different size range e.g. from 32 to 45 μm and from 2 to 10 μm
Peptizing agent	The electrolyte used in the process of converting a precipitate into colloidal sol by shaking it with dispersion medium

1 INTRODUCTION

1.1 Energy alternatives

Today, energy is one of the most challenging issues in the world. It is challenging in terms of cost, security of supply and environmental aspects. Efforts have been made to tackle with these challenges, mostly in recent century, which comprise good results for cheap, renewable, and environmentally friendly energy supply all around the world but still there are some major problems which should be solved in the future such as more clean, the certainty of supply, and cheaper energy.

Biomass and waste are the major energy alternatives today with around 10% share of the world energy production (Kan et al., 2016). The energy produced by wind and solar power is also the other vital renewable energies while biodiesel comprises best replace for diesel fuel (Murugesan et al., 2009). In addition, other kinds of energy sources are growing rapidly, which create solid or liquid forms of fuels as alternatives to fossil fuels. Among these renewable fuels, biomass is a growing energy source mostly in the areas with large forest resources such as Finland, Austria, Russia, Australia, Canada, and USA.

Biomass is a term used for all kinds of wood, agricultural, and forest residues that are renewable, clean, and CO₂ neutral with loads of resources in the nature (Soloiu et al., 2011). Currently around 10% of the global energy production refers to Bioenergy (Council, 2015) However, biomass will have a potential to become a more important source of energy in the future. The European Union target is to increase 20% of the total solid biomass supply by 2020 including biomass from waste, agricultural and fishery, and forestry (Donnelly, 2012). United States also aim to produce 136 billion cubic meters of biofuel by 2022 (Tse et al., 2015).

The possibility of using coal slurry as liquid fuels has been investigated since the 19th century and was commercially used mostly when the oil availability was in doubt such as energy crises in 1970's. Coal slurries had been used in the US, Russia, Japan, China, and Italy in various applications such as boilers, furnaces, and other units (Lee et al., 2014, Frank Rosillo-Calle, 2009).

Bio-coal is the final product of biomass thermal conversion and similarities of bio-coal properties to that of coal and also huge amounts of bio-coal supply had encouraged researchers to study of the feasibility of preparing slurry fuels and investigate their properties in recent years in order to make a cleaner and cheaper fuel.

1.2 Targets of the thesis

The bio-coal slurry must meet the minimum standards of quality in order to apply as a fuel in large diesel engines. These standards refer to viscosity value, heating value, stability and good atomization characteristics. According to the previous studies done by the other researchers, the most important factors affecting the bio-coal slurry features are the raw material of the bio-coal, particle size distribution, liquid carrier, and temperature (Long, 2014, Soloiu et al., 2011).

The first objective of this study is to investigate methods to prepare the bio-coal slurry and to explore the effect of different factors on bio-coal slurry properties. The other goal is to find a way which simultaneously increases the content of bio-coal and improve the quality of the bio-coal slurry.

As one of the main factors to evaluate a new product is the economic potential in the market, the other goal of this work is to estimate the final price of the optimum fuel slurry and compare that with the price of existing fuels in the market.

1.3 Implementation of the study

To obtain the above mentioned aims, the present study will provide theoretical and empirical researches on the topic. A wide literature review on the previous related works done with coal or bio-coal would form the theoretical part. In this part, all the methods for the preparation of a slurry and effect of bio-coal slurry fuel on diesel engine parts will be discussed.

In the experimental part, three different bio-coal samples are divided into four categories of particle size distribution. Water and rapeseed oil are used to make the slurries. Then the viscosity value of all the slurries is measured by the means of a Brookfield Viscometer. The optimum particle size distribution and liquid carrier for each sample is obtained. The next

step is to achieve the effect of rising temperature on the properties of the slurries with the optimum particle size distribution.

2 BIOMASS AS AN ENERGY SOURCE

From the time people discovered fire, biomass was used as a main source of energy. As the years went by, other kinds of energy sources were introduced to the world such as fossil fuel, solar and wind energy, but still biomass count as one of the main sources of energy because of the abundance of plants and lower environmental impact than the other energy sources. Biomass could be found in the form of plants, including trees, vegetable, and food crops (van der Stelt et al., 2011).

2.1 Woody biomass and its potential

According to the U.S. forest service, woody biomass is defined as “the trees and woody plants, including limbs, tops, needles, leaves, and other woody parts, grown in a forest, woodland, or rangeland environment, that are the byproducts of forest management” (Cai et al., 2016). Wood is the major part of existing biomass in the world and currently, 22% of the U.S. renewable energy is derived from woody biomass. (Cai et al., 2016)

The main compositions of wood are cellulose, hemicellulose and lignin (totally called lignocellulose) with more than 90% of the mass ratio of the wood that contain energy because of high contents of carbon (Schorr et al., 2012). Wood also contains high amounts of volatiles and other segments on its composition. Using wood directly as an energy source is done conventionally to produce heat and energy, however, now it is well understood that converting biomass to solid or liquid forms of fuel is easier and economical in terms of storage, shipping, and use. (Esnouf, 1991)

Different wood types contain different portions of cellulose, hemicellulose, and lignin. Table 2-1 shows the approximate portions of lignocellulose in hardwood and softwood.

Patton et al. (2009), reported that 76% of diesel fuel demand in the year 2009 could be replaced by wood supply and it would rise to 123% in the future because of manipulating genetic of tree growth and more accurate management.

Table 2-1. Distribution of lignocellulose fraction in softwood and hardwood (Gravelsins, 1998)

Wood Category (% of dry matter)	Hardwood	Softwood
Cellulose	45-50	40-45
Hemicellulose	25-35	25-30
Lignin	22-30	26-34

2.2 Biomass conversion to charcoal

Charcoal is the solid form of biomass conversion at high temperature conditions (Bagramov, 2010). The use of charcoal as a source of energy goes back to many years ago where people realized charcoal higher burning temperature than wood. This was a worthy achievement in mankind's evolution. Less smoke, easier to ignite and longer burnout time than wood are the other features of charcoal which make it more popular. As the years went by, and by increasing the demand of energy and uncertainty of other sources of energies, renewable energy sources like biomass has attracted the attentions and researchers are trying to use it more effectively and decrease the costs of charcoal production.

Biomass conversion is done by three main pathways naming biochemical, chemical, and thermal. The biochemical method uses microorganisms to consume biomass and produce a biogas mixture which is used directly as an energy source. In the chemical manner some reactions are done in the absence of microorganisms to produce biofuels, and finally in the third pathway the biomass is converted to bio-coal by means of a thermal decomposition of the raw material (Long, 2014). The thermal conversion done by various processes is shown in Figure 2-1.

In gasification, the biomass are partially oxidized in the temperature of above 800°C to produce a syngas which can be used directly as a fuel for different purposes. (van der Stelt et al., 2011) The main product of hydrothermal method which is done in the temperature range of 300-350°C and high pressure steam (30-50 MPa) is deoxygenized liquid oil (Long, 2014). Fast pyrolysis is a way to convert biomass in a few seconds or less to a liquid

product named pyrolysis oil. In the fast pyrolysis process, the biomass are heated rapidly to a temperature of 450-550°C in the absence of oxygen. Slow pyrolysis is the final pathway of biomass conversion with the solid form of the final product. The biomass are heated slowly from 350 to 800°C with small amounts of oxygen and creates the bio-coal as the source of energy. (Long, 2014)

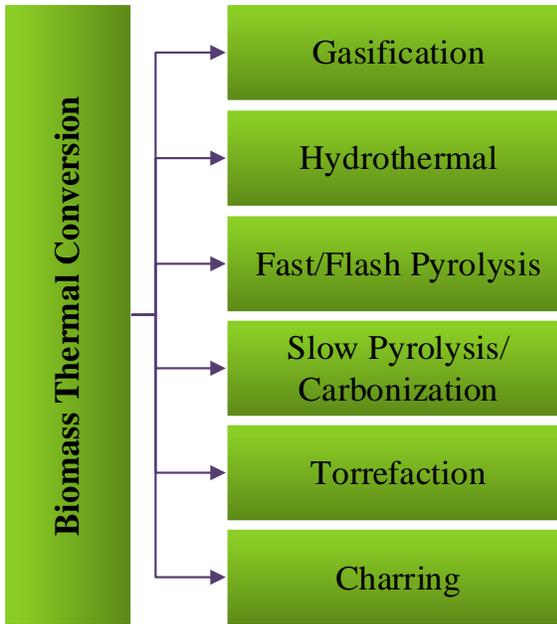


Figure 2-1. Process classification of biomass thermal conversion (Long, 2014)

During thermal decomposition of wood, hemicellulose is the first component decomposed at around 200 to 250°C. Cellulose begins decomposing at a temperature range around 240 to 350°C and lignin is the last component to be decomposed at a temperature range around 280 to 500°C (Schorr et al., 2012).

2.3 Torrefaction

Torrefaction is the mild pyrolysis process in which biomass are placed on the condition of 200-320°C at the atmospheric pressure and low amount of oxygen by higher residence time than the original pyrolysis process and lower heating rate of less than 50°C/min. Residence time of biomass in an ordinary torrefaction process lasts for 30 to 90 min (Schorr et al., 2012).

During torrefaction, around 30% of the raw material mass is driven off as volatiles and moisture, which contain around 10% of total energy of raw material resulting in less mass and higher energy content per unit mass or volume (van der Stelt et al., 2011). Table 2-2 indicates the contents of wood and two kinds of torrefied wood at different condition of torrefaction processes.

Table 2-2. Composition of wood and torrefied wood (van der Stelt et al., 2011)

	Wood	Torrefied Wood	
		250°C - 30 min	300°C - 10 min
Carbone (%)	47.2	51.3	55.8
Hydrogen (%)	6.1	5.9	5.6
Oxygen (%)	45.1	40.9	36.3
Nitrogen (%)	0.3	0.4	0.5
Ash (%)	1.3	1.5	1.9
LHV (MJ/kg)	17.6	19.4	21.0

Currently, 10% of pulverized coal used in the existing coal-fired boilers in Europe are replaced by torrefied wood (Wilén et al., 2014).

2.4 Bio-coal

Bio-coal is a term used for all kinds of biomass thermal conversion products. Recently, similarities of bio-coal properties to that of coal had encouraged researchers to use bio-coal instead of coal in slurry fuels. For example, (Soloiu et al., 2011, Long, 2014, N'kpomin et al., 1995, Awang and May, 2009, Esnouf, 1991) investigated the bio-coal slurry using different kind of liquids including water, vegetable oil ,oil, and a mixture of them. However, there is still a huge gap between properties of the coal slurry and bio-coal slurry, for instance, coal comprises more slurryability than bio-coal therefore coal-water slurry shows more heating value than bio-coal-water slurry, but efforts are being done to decrease these gaps. Table 2-3 displays a glance at the differences of coal and bio-coal properties while

further in the sections 2.4.2 to 2.4.7 there will be more detailed information about the bio-coal properties.

Table 2-3. Bio-coal properties vs coal properties (Meijer, 2011)

	Moisture content	Calorific value	Volatiles	Fixed carbon	Bulk density
	(wt. %)	(MJ/kg)	(%db.)	(%db.)	(kg/l)
Coal	10-15	23-28	15-30	50-55	0.8-0.85
Bio-coal	1-5	30-32	10-12	85-87	0.20

2.4.1 World production of bio-coal

Annual bio-coal production in the world was 51.8 million tons in 2013 while Africa had the most share of that with 60% of the world production and Brazil had the largest amount of production among all the countries by around 12.4% share of bio-coal production. Metallurgy industry is the biggest consumer of bio-coal in Brazil (Bagramov, 2010). The share of the other parts of the world could be found in Figure 2-2 (FAO, 2012).

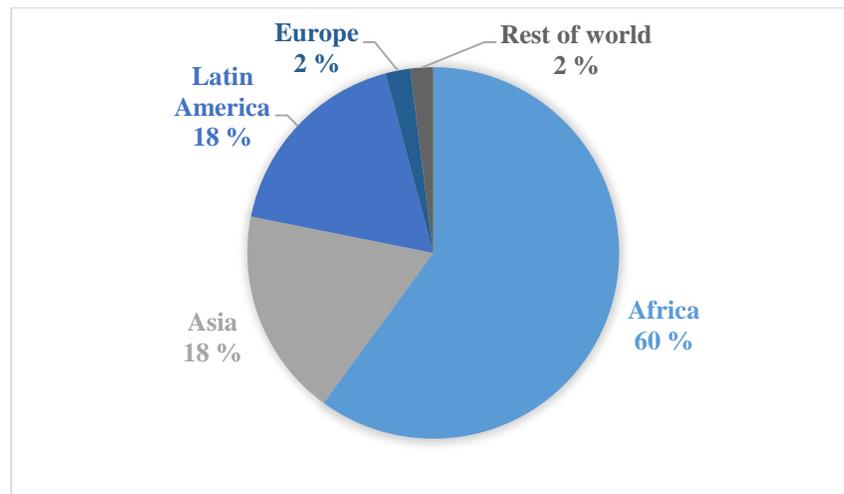


Figure 2-2. Share of bio-coal production in different parts of the world in 2013 (FAO, 2012)

2.4.2 Chemical properties of bio-coal

Yield, heating value, and composition of bio-coal produced by different processes depends on the type of the raw material and conditions of the process such as temperature and

residence time. It is reported the yield of softwood bio-coal is a little bit more than bio-coal from hardwood while hardwood bio-coal has better quality (Bagramov, 2010). Table 2-4 shows an example of bio-coal yield, composition and heating value when the biomass meets different temperatures from 350 to 650°C. It is clear by increasing the temperature, the yield of dry bio-coal decreases, the content of carbon increases, and consequently the heating value rises.

Table 2-4. Bio-coal composition, yield, and heating value under different final temperatures of charring (Bagramov, 2010)

Final Temperature of Charring °C	Yield of dry bio-coal from dry wood wt. %	Bio-coal Composition (wt. %)		
		C	H	O +N
350	45.2	73.3	5.2	22.5
400	39.2	76.1	4.9	19.0
450	35.0	82.2	4.2	13.6
500	33.2	87.7	3.9	8.4
550	29.5	90.1	3.2	6.7
600	28.6	93.8	2.6	3.6
350	45.2	73.3	5.2	22.5
400	39.2	76.1	4.9	19.0

Woody biomass contain hydroxyl groups which make it hydrophilic. During the torrefaction process OH-groups are eliminated mostly as water vapor while remaining product is rich in non-polar unsaturated groups leading to decrease in capacity of water adsorbing. The rate of lowering the moisture or water adsorbing is highly dependent on the conditions of the process. Figure 2-3 illustrate this change in moisture uptake capacity at different temperatures and residence time. As can be seen, increasing the temperature from 240°C to 340°C at the residence times of more than 10 h, decrease the moisture uptake more than two times.

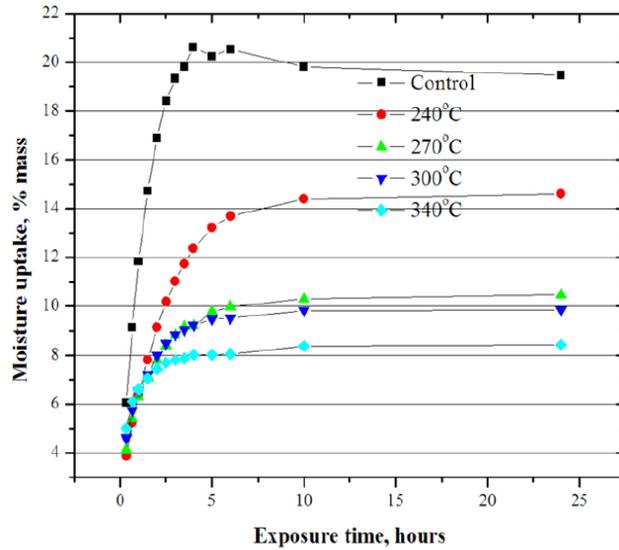


Figure 2-3. Hygroscopicity of 6 mm pellets made from torrefied wood at temperatures from 240-340°C. The control is regular white pellets, tests were done at 30°C and 90% relative humidity (Koppejan et al., 2012)

2.4.3 Physical properties of bio-coal

Bio-coal is a light, porous, and black product of biomass conversion with high surface area. The structure of the bio-coal is similar to honeycomb results in light and porous structure (Figure 2-4) (Bagramov, 2010). Density and porosity of bio-coal depend on the raw material type and also the conditions of the process of conversion. Table 2-5 shows an example of density and porosity of charcoal derived from different wood types.

Table 2-5. Density and porosity of charcoal derived from different types of wood (Bagramov, 2010)

Charcoal properties	Raw material wood			
	Spruce	Pine	Birch	Aspen
Density (kg/m ³)	271	347	424	309
Porosity (%)	85	81	77	83

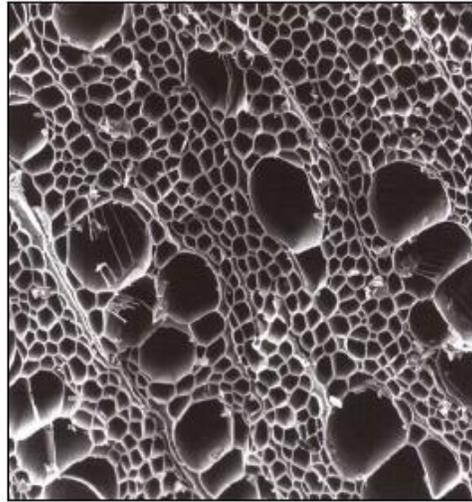


Figure 2-4. Bio-coal structure (Bagramov, 2010)

2.4.4 Particle size reduction

Crushing the solid is one of the initial and significant steps in preparation of slurries. In order to have a better packing of bio-coal particles, homogenous, and stable slurry solids should be in an optimum particle size distribution.

For most of coal slurries 10-80% of the particles have a diameter less than 74 μm . However, for micronized coal-water slurries the particles should be fine having the mean diameter of 15 μm which 98% of them are below 44 μm in diameter. (Lee et al., 2014) Anyway, the precise diameter of particle size depends on the application and type of solid. According to N'kpomin et al. (1995), the smaller particle size of bio-coal, the smaller pore size, thus less absorption of water in the solid leading to a higher concentration of solids. Long (2014), also observed less porous structure of the bio-coal particles less than 50 μm . Chen et al. (2011b), claim that in order to have a slurry fuel, 75-80% of particles should be less than 75 μm .

However, N'kpomin et al. (1995), studied the effect of particle size on deashed bio-coal-oil-water slurry and concluded that too fine particles leads to less concentration of the solid. They suggested the reason lies in the fact that too fine particles (mean diameter around 4 μm) create a network which improves by larger surface forces and trap more liquid and decrease the solid portion of the mixture. They finally concluded that the optimum

diameter of bio-coal particle is between 7 to 11 μm . Soloiu et al. (2011), also reported the same result. They claim that bio-coal particle size around 3 μm results in higher droplet diameter in sprays in a diesel engine and increase the viscosity. In their study, they used the particles with a mean diameter of 10.33 μm because they believed this particle size is enough to pass the nozzle hole and requires smaller residence time for a complete combustion process. For the fuel slurry of Mallee biochar, Shivaram et al. (2013), believed the particle size between 5 to 15 μm for CI engine is required. This value decreases for using in a gas turbine to 4 to 6 μm particle size.

In the other investigation of bio-coal particle size, Ellem and Mulligan (2012), suggested different particle size for different types of diesel engines. They claim particles less than 30 μm are required for slow speed diesel engines. For medium speed diesel engines particles should be finer, less than 10 μm due to controlling engine wear. They also believe that for high speed engines particles less than 2 μm are needed because of smaller cylinder volume and consequently shorter residence time in the cylinder.

Grindability of a bio-coal is depends on the source of raw material, moisture ratio, conditions of the process of charring, milling type, and milling conditions. As mentioned before, one of the advantages of charring is to reduce the moisture content of the biomass, which leads to vaporize most of the volatile matters and give a brittleness structure of the bio-coal (see Figure 2-4). In most of the cases, charring reduces the required energy for grinding up to 80%, depending on the moisture content of the solid (Nordwaeger.M., 2010).

Usually, grindability of a matter is evaluated by the hardgrove index. The smaller hardgrove index, the harder and less grindable matters thus more difficult to micronize. Figure 2-5 shows the hardgrove index for different coals and bio-coal and torrefied pellets against the volatile matters. As shown in this figure, torrefied pellets have less grindability than charcoal while grindability of coals depends on the type of that. According to Figure 2-5 bituminous coal is easier to grind than other kinds of coal.

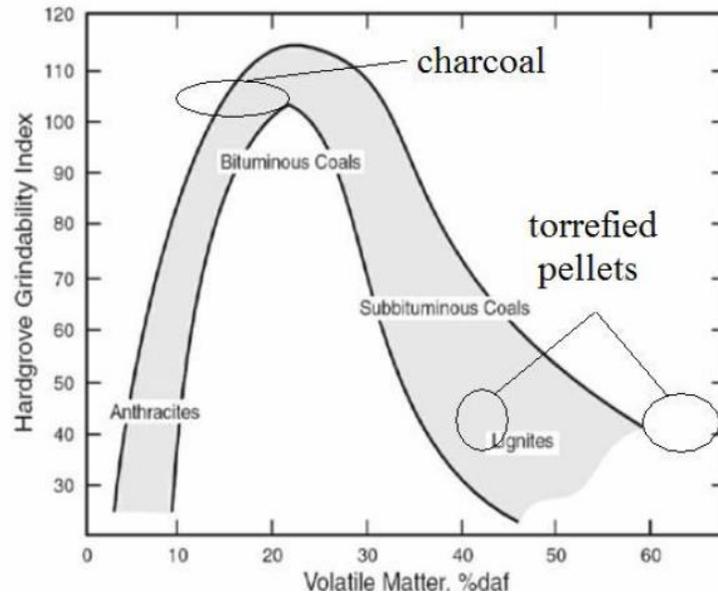


Figure 2-5. Hardgrove index of different coals, bio-coal, and torrefied pellets (Bagramov, 2010)

The process of size reduction is mostly done in several steps. First bio-coal is crushed into small pieces (less than 1cm) by the help of a hammer in very small scale or by the means of an industrial crusher in larger scale. Then grinding is done by means of different devices such as high speed crusher. The final step is micronizing of bio-coal which could be done by the help of micronizing devices (for example, Wiley mill or burr mill or ball mill (Long, 2014)). More detailed information about grinding devices could be found in Papachristodoulou and Trass (1987).

However, some other processes of grinding were tested by some researchers like Atesok et al. (2005), who used wet grinding of coal particles and also investigated the effect of two different dispersant on the grindability of coal and achieved good results. Cui et al. (2008), also investigated a novel process for grinding the coal, utilizing a high pressure water-jet mill and froth flotation. They observed 50 to 70% reduction in energy used for size reduction of coal compare with the traditional mechanical mills.

2.4.5 Ash content

Considering the composition of the solid in slurry fuels results in low amount of impurities exist in both coal and bio-coal. This small amount of components does make big problems

when operating in diesel engines. For instance, ash is responsible for the corrosion in exhaust, piston wear and rings and cylinder wear. According to Ellem and Mulligan (2012), ash components are mostly in the form of oxides such as Silicon (SiO_2), Aluminum (Al_2O_3), Iron (Fe_2O_3), Calcium (CaO), Magnesium (MgO), Sodium (NaO_2), Potassium (K_2O) and Phosphorus (P_2O_5). Silica is the most abrasive component in coal, which is responsible for wear in different parts of the engine (Patton et al., 2009), while other components of ash are not abrasive, they should also be removed because they create some deposits on the engine parts which cause problems (Patton et al., 2009). Silicon dioxides have also the potential of making glass in high temperatures. (Long, 2014) believed that by the addition of calcium oxides and potassium oxides, melting point of silicon dioxide decreases by 75% from 2000°C to around 500°C thus silicon converts to glass sludge when meeting high temperature in the engine and will cause undesired problems in engine parts. The best way he had suggested to tackle this problem is to remove the ash content from the original biomass.

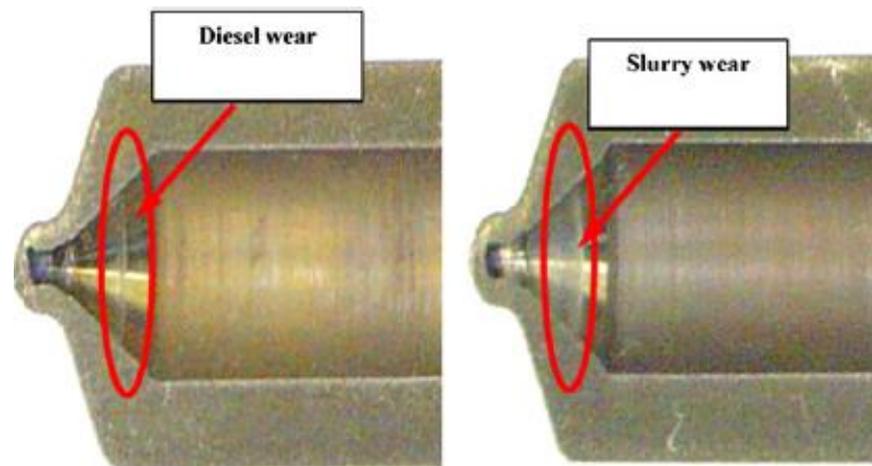


Figure 2-6. Normal diesel wear and accelerated wear caused by slurry fuels (Soloiu et al., 2011)

The major parts of the engine being destroyed by the ash are injector nozzle and orifices (Soloiu et al., 2011). (Soloiu et al., 2011) reported that engine ring wear in coal water slurries is 20 to 100 times higher than ordinary diesel fuel when utilizing the same engine component material. They argue that in order to minimize the wear caused by ash, special high strength material should be used which are too expensive. They used bio-coal slurry

fuel in a diesel engine and observed 4-8 times more wear in the injector's conical seat body shown in Figure 2-6. They also observed corrosion on the injector's needle.

Despite all the above mentioned facts, it should also be highlighted that the particle size of the solids also affects wear in a diesel engine. (Cui et al., 2008) set an investigation of the coal particle size on wear problems and observed double wear in piston ring and cylinder when increasing coal mean particle size from 10.2 to 16.3 μm while the maximum particle size were 32 μm and 47 μm respectively.

Generally, the amount of ash in bio-coal is less than that of coal. However, most of the ash components in bio-coal are water-soluble and easy to remove but silica removing is much harder (Patton et al., 2009). The optimum amount of ash which Soloiu et al. (2011) reported for their coal water slurry in a four-stroke diesel engine was 1 wt. %. They found the major problem of coal slurry fuels in the injector's nozzle erosion.

Table 2-6 indicates the ash content in bituminous coal, hardwood, and softwood. Here, two important issues should be noted. Firstly, the ash content in bio-coal is higher than in wood in term of mass weight since wood losing a major part of its mass during pyrolysis but the ash remains in bio-coal. Therefore, the same amount of ash remains in bio-coal while bio-coal has around 30% mass of the initial wood and secondly, huge amounts of ash in wood, maintain in the bark because most of the ash in wood is the result of transport by wind and they mostly remain on the bark.

Esnouf (1991), had mentioned ash content in poplar wood bio-coal equal to 2.4-3.3% and pine bio-coal 7% while mineral coal contains 10 wt. % ash.

Table 2-6. Impurities in coal and wood without bark (% of ash) (Patton et al., 2009)

	Sio2	Ca	K	Mg	Mn	Fe	Al
Bituminous Coal	20-60	1-20	Trace	0.3-4	Trace	5-35	10-35
Hardwood	5	40	27	7	3	0.8	0.7
Softwood	5	30	13	5	5	0.8	3

More information about the details of the amount of components could be found in (Papachristodoulou and Trass, 1987).

Ash content in bio-coal depends on the biomass resources used to make the bio-coal, but commonly it creates less problems than coal because firstly, in most of the cases it contains less ash and secondly, most of ash in coal is in the form of silica, which is hard to remove while bio-coal has a small amount of silica and more amount of water soluble which are easy to remove (Patton et al., 2009). According to American national standard (ASTM, 1999), the ash content in diesel fuel oil must be lower than 100 ppm and sulfur content should be less than 15 ppm. Patton et al. (2009), set up a lot of experiments to test washability of pine bio-coal by using the distilled water, dilute hydrochloric acid (HCl, 1 wt. %), and acetic acid (10 wt. % AcOH) for wood pretreatment and char treatment. They obtained the best result by combining DW pretreatment of wood followed by DW treatment of bio-coal, which removes ash up to 96% from 1.64% to 0.065%.

In the similar study, Esnouf (1991), examined two separate methods for ash removal process. The first method which is called chemical treatment uses hydrochloric acid (HCl, 0.5 M) to remove ash from fine bio-coal particles with average particle size of 200 μm . The process was done by mixing char with the acid solution for 1 h at ambient temperature. Although they claim this method removes ash content from 20 to 70 wt. % depending on the initial ash content, the result was not satisfying while ash was only reduced from 3.4 to 1.2 wt. %.

The other method was the selective agglomeration treatment which uses large amounts of water-oil slurry and micronized bio-coal. Char is dispersed in water-oil mixture and when the slurry meets stirring vigorously, the hydrophobic parts of the bio-coal remain in the oil phase while hydrophilic minerals go through aqueous phase. The optimum amount of this method removes the ash content from 4.1 to 1.2 wt. %, which do not meet the standard content. Esnouf (1991), suggested a combination of the chemical and selective agglomeration treatment and claims ash reduction to 0.8 wt. % by this method. Schematic of the process is shown in Figure 2-7.

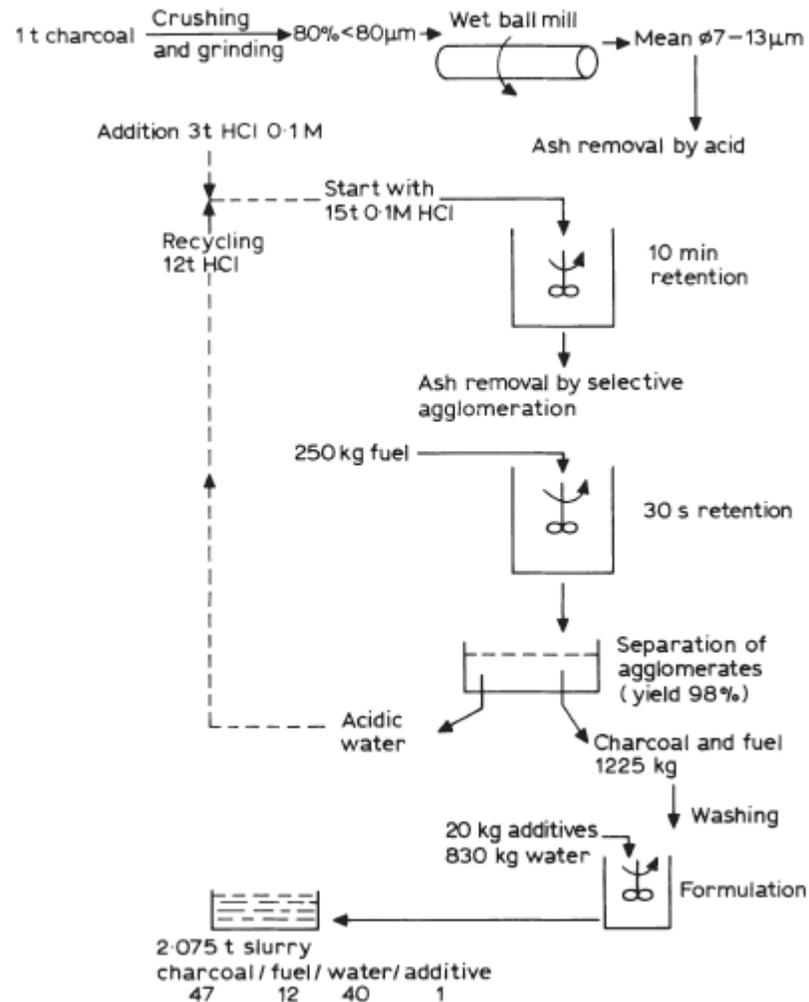


Figure 2-7. Process of ash removal by combination of chemical (Acid) and selective agglomeration treatment (Esnouf, 1991)

2.4.6 Heating value

Different types of fuels vary in the amount of releasing energy during combustion. The amount of releasing energy of a specific mass or volume of a fuel is called heating value. There are two kinds of heating values named higher heating value (HHV or gross energy) and lower heating value (LHV or net calorific value). The difference between HHV and LHV lies in the stored energy in vapor water. Basically, combustion of hydrocarbon fuels produces a special amount of water depending on the hydrogen content. Because of high temperature of the combustion the produced water stores a part of the energy and vaporize. The total energy produced by the fuel is called HHV but LHV is subtracting vaporized

energy of water from HHV. In fact, LHV is the available amount of heat of a fuel after vaporizing water. The most used units for heating values are Btu/lb., J/g, KJ/kg, and MJ/kg.

Bagramov (2010), determined the heating value of different bio-coals produced at different temperatures. Bio-coal with a processing temperature of 350°C has 31.56 MJ/kg heating value and as the temperature of the process increases, the heating value also increases (because of rising carbon content) so that charring at 700°C leads to heating value of 34.88 MJ/kg. It should be highlighted that increase in heating value is slightly with the temperatures above 500°C as shown in Table 2-7.

Table 2-7. Heating values of bio-coal at different temperatures (Bagramov, 2010)

Charring Temperature (°C)	350	400	450	500	550	600	650	700
Heating Value (MJ/kg)	31.6	32.7	33.1	34.2	34.4	34.5	34.7	34.9

Soloiu et al. (2011), also reported heating value of cedar bio-coal at a temperature around 400°C equal to 29.21 MJ/kg and Long (2014), reported heating value of 35.08 MJ/kg for yellow poplar charcoal at a charring temperature of 700°C.

2.4.7 Volatile matter

The products other than moisture, which, given off as gas or liquid at high temperature in the absence of air called volatile matter (Speight, 2012). In charring process, liquids and tars which do not drive off completely, form volatiles. Usually, volatiles are a mixture of short and long-chain hydrocarbons or aromatic hydrocarbons and some sulfur. (Corresionpedia, 2015)

Generally, volatiles are divided to combustible and incombustible gases. Hydrogen, carbon monoxide, and methane are some examples of combustible and carbon dioxide is an example of incombustible matter in coal (Speight, 2012). In lignocellulosic biomass around 80% of dry basis mass is volatile (Koppejan et al., 2012). For example, volatile matter of Mallee wood is reported to be 77.9 wt. % (Ellem and Mulligan, 2012). Volatiles of other different types of wood could be found in Table 2-8.

Table 2-8. Volatile matters of different wood types (Prins, 2005)

Wood Type	Ash	Volatile
	wt. % of dry material	
Beech	1.2	82.7
Willow	1.6	81.4
Larch	0.1	82.8
Straw	7.1	79.0

The amount of volatiles in charcoal depends on the conditions of charring process specially the temperature. The more process temperature, the less volatile in the final product. For instance, at the temperature of 300°C about 50% of the volatiles remain, but at 1000°C there will remain no volatile (FAO, 1985). However, in the other literatures, this value was reported more or less such as only 20% reduction of volatiles that Koppejan et al. (2012) reported in their study in the temperature range of 250-350°C.

Table 2-9. Effect of torrefaction temperature and oxygen content on the volatile matter of *Eucalyptus grandis* wood (Rousset et al., 2012)

Torrefaction treatments		Proximate analysis (%)	
Temperature (°C)	O (%)	Volatile matter	Fixed carbon
240	2	79.56	20.37
240	6	79.36	20.58
240	10	77.46	22.44
240	21	80.59	19.40
280	2	75.60	24.13
280	6	71.20	28.70
280	10	73.10	26.80
280	21	73.14	26.70

In the other study, Rousset et al. (2012), studied the effect of temperature and oxygen content in the torrefaction process in the final volatile matter of *Eucalyptus grandis* wood exhibited in Table 2-9. It is obvious by increasing the temperature, the amount of volatiles decrease while the effect of oxygen is complicated.

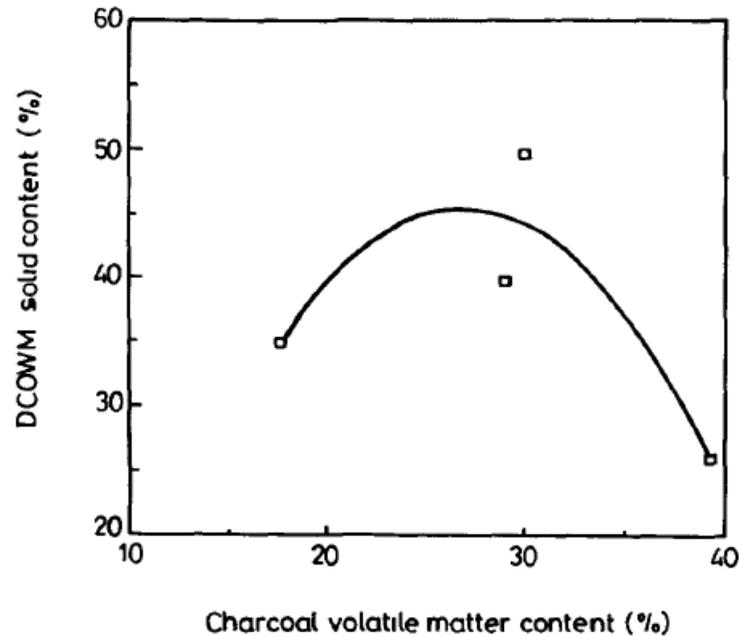


Figure 2-8. Maximum solid content vs volatile in bio-coal slurry (N'kpomin et al., 1995)

N'kpomin et al. (1995), investigated the effect of volatiles on the maximum concentration of solid in bio-coal slurry and observed that as the amount of volatiles increases, the solid concentration also increases up to an optimal point as shown in Figure 2-8. The measured value of this optimum is reported to be near 30%. Table 2-10 also shows the effects of volatile amount on the bio-coal concentration.

Table 2-10. Deashed bio-coal-oil-water mixture solid content as a function of volatile matter (N'kpomin et al., 1995)

Volatile matter	solid content	domestic oil content	surfactant + water content
(%)	(%)	(%)	(%)
17.7	35	10	56.5
29	40	12	48
30	50	15	35
39.3	26.5	8	65.5

3 BASIC PRINCIPLES OF DIESEL ENGINE

3.1 Background

Rudolf Diesel, a German scientist had invented his first IC engine in 1895 (Murugesan et al., 2009). The working procedure of his engine was increasing the temperature of air by compression and then introducing the fuel as very small particles which ignite in the hot air. The released energy during combustion, forces the piston downwards and turns the crankshaft which produce power.

The main difference between a diesel engine and gasoline engine is that the gasoline engine operates with spark ignition but a diesel engine uses compression ignition.

Nowadays, different kinds of diesel engines are used depending on their application. In one classification they are divided into two-stroke and four-stroke engines and in the other classification they are distinguished as high speed (around 1200 RPM), medium speed (around 300 to 1200 RPM), and low speed (around 60 to 120 RPM) diesel engines. The high speed engines are used in transportation section including cars, buses, trucks, and etc. medium speeds have loads of applications in mechanical drives such as compressors, generators, and pumps. Low speed diesel engines has been used mostly to power large ships and electricity production in the range of 40-100MW. (National Energy Technology Laboratory, 2007, Ellem and Mulligan, 2012)

Since diesel engines are used commercially all around the world, there is a vital concern on the engine's emission such as nitrogen oxides (NO_x), carbon dioxide (CO_2), and particulate matters (PM) (Tse et al., 2015).

3.2 Slurry fuels in diesel engine

When Rudolf Diesel designed his first engine, he believed that the engine could run over a wide range of fuels. He tested the engine with groundnut oil and obtained very good results (Long, 2014). After some decades, researchers tried to test CWS as a new fuel for the diesel engine (Wamankar and Murugan, 2015).

Using coal as a diesel engine fuel was one of the area of interest by an overwhelming number of researchers and recently after loads of studies become more successful (Patton

et al., 2009). US Department of Energy (DOE) had done much research on the feasibility of using the CWS on diesel engines during the last 40 years. They have reported when using CWS on a medium speed diesel engine, the thermal efficiency is the same as the efficiency of combined cycle gas turbine running on natural gas (Wamankar and Murugan, 2015).

Other researchers also have studied the use of the CWS on diesel engines and almost all of them observed the same and significant known problems in the moving parts of the engine called wear. Almost all the moving parts which are either in direct contact with CWS fuel or combustion product are being affected by the wear (National Energy Technology Laboratory, 2007). Soloiu et al. (2011), studied CWS in a four-stroke diesel engine and realized that the main part being destroyed by the CWS is the injector's nozzle. They also observed some problems on the rings and nozzle tip created by the ash in the CWS.

In the other study, some researchers studied the effect of particle size on the engine performance and reported that slurry containing 75 μm particle size leads to engine operation failure because of agglomeration of coal dust in the cylinder. They observed better working of engine when using 40 μm solid particles but still there were some problems with the engine such as late combustion. (Soloiu et al., 2011)

Effect of 25 wt. % bio-coal-oil mixture on a four-stroke one cylinder diesel engine was studied in the other investigation and it was observed 4-8 times faster wear in the needle's seat compared with the normal diesel fuel. The authors believed that this high wear acceleration will not be effective for a long operational cycle. (Soloiu et al., 2011)

According to Flynn et al. (1989), fuel injection nozzle operates at high pressures of 70-140 MPa in order to make a good atomization of the fuel in the allowed time. Therefore, it has the highest load and shortest life span among a diesel engine's part. The pressure of the nozzle is higher than 140 MPa in CWS in order to give a better atomization. The fluid velocity in this situation exceeds 250 m/s for a CWS fuel. Flynn et al. (1989), suggested super hard material like cubic boron nitride or diamond compact could be used in order to increase the life span of the nozzle. Other engine parts realized to be destroyed in this study

were piston ring and cylinder wear which authors proposed tungsten carbide coatings to rise durability and less wear of these parts.

3.3 Atomization of fuel

Atomization is the process in which fuel bulk is converted into small droplets. Generally, liquid surface tension tends to keep the liquid surface to have the least surface energy and achieve this by keeping the liquid shape spherical. When the fuel meets internal and external forces it begins disruption and creates smaller droplets. Final droplet diameter depends on the amount of forces (Lefebvre, 2010). The combustion efficiency and combustion products are drastically dependent on the breakup and separation of solid-liquid (Mulhem et al., 2006).

There are different types of atomizers which are currently used the in vast majority of applications such as diesel engines. The most known atomizers are pressure atomizers which convert pressure to the kinetic energy and create high relative velocity between fuel and surrounding air or gas. Four kinds of different pressure atomizers are shown in Figure 3-1. Plain orifice atomizer is mostly used for low-viscosity fuels while in low velocity does not show a good quality atomization. The simplest atomizer is the simplex type. Fuel is fed into the swirl chamber and creates an air-cored vortex which increase the angular velocity of the fuel, resulting in a high speed and good quality atomization. Dual orifice which is created from two simplex atomizer is used mostly in aircrafts and gas turbines. In this type of atomizer, two nozzles coalesce and share their energy within a short distance from the atomizer. Finally, spill return atomizer is the simplex type of pressure atomizers. The main benefit of this nozzle is that fuel-injection pressure is always high, thus even in low fuel rates the atomization quality is high. (Lefebvre, 2010)

One of the main factors affecting the atomization is viscosity (Son and Kihm, 1998). The viscosity of the fuel has an inverse effect on the atomization since it prevents any change in system geometry (Lefebvre, 2010, Mulhem et al., 2006). According to Son and Kihm (1998), increasing the viscosity by 22 times results in an increase of 30% in the most probable droplet size.

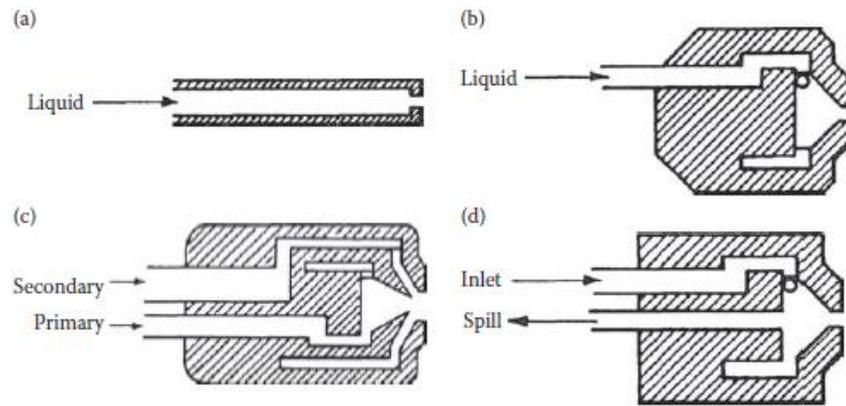


Figure 3-1. Different types of pressure-swirl atomizers: (a) plain orifice, (b) simplex, (c) dual orifice, and (d) spill return (Lefebvre, 2010)

In the atomization process, the most significant mean particle diameter is the Sauter mean diameter (SMD), which is defined as the diameter of a drop in spray whose ratio of volume to surface area is the same as that of the whole spray.

As mentioned before, PSD has a significant effect on the viscosity, thus PSD has a direct influence on the droplet size. Son and Kihm (1998), studied the effect of particle size on atomization of a CWS and realized that when smaller particles ($32\text{-}45\mu\text{m}$) in water meets high pressure jet blasting atomization, capillary bonding forces between coal particles and also between particles and water result in preventing water to strip off and more particles remain in a droplet which makes the droplet bigger. The capillary bonding forces are a result of high surface area of fine coal particles and high particle number density.

On the other hand, when there are bigger particles ($63\text{-}90\mu\text{m}$) in the CWS, their capillary bonding forces are weak, which allows large particle to separate easily from each other and from water when meeting high pressure. Figure 3-2 illustrates these explanations.

Son and Kihm (1998), also set some experiments to investigate these explanations empirically. They have measured SMD of different slurries of different particle size distribution of $32\text{-}45\mu\text{m}$, $45\text{-}63\mu\text{m}$, and $63\text{-}90\mu\text{m}$ and compared the results with pure water SMD. As shown in Figure 3-3, the more particle size of CWS, the more similar SMD to pure water, which confirms the findings in Figure 3-2

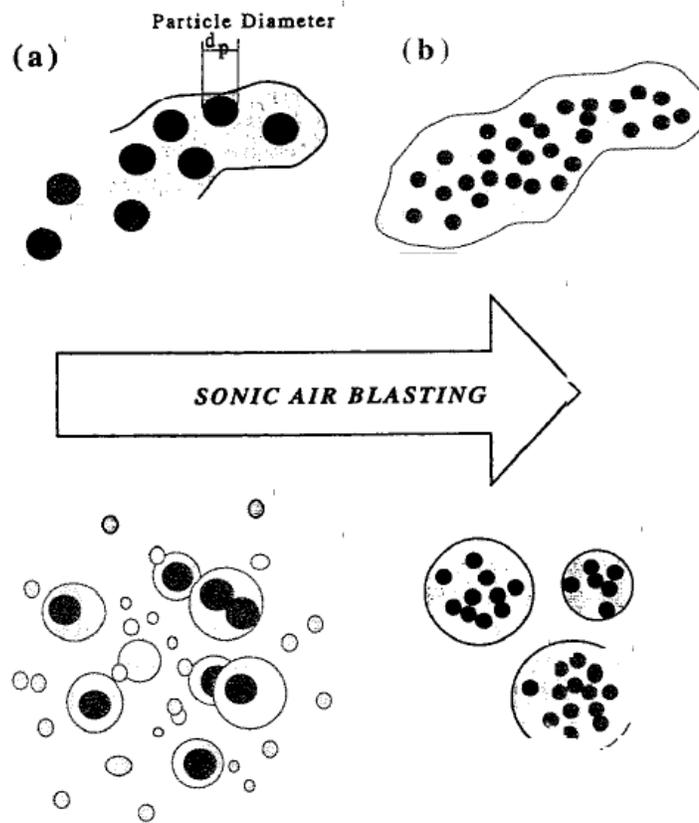


Figure 3-2. Atomization of two different slurry containing larger coal particles (a) and smaller coal particles (b) (Son and Kihm, 1998)

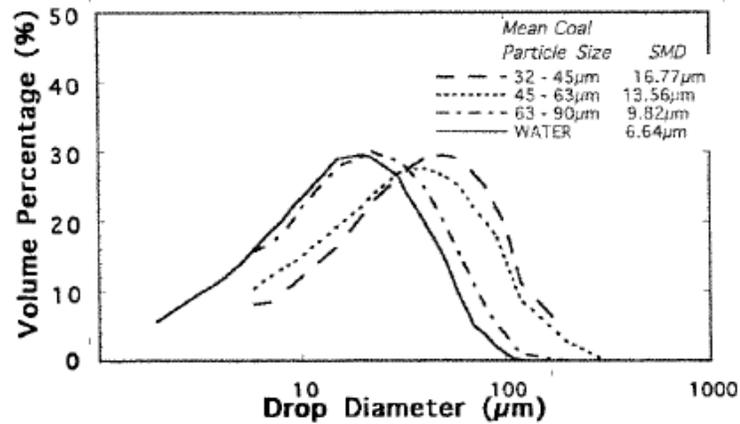


Figure 3-3. Volumetric percentile spectra of droplets of the three tested CWS spray and water spray at 20 psig air jet pressure (Son and Kihm, 1998)

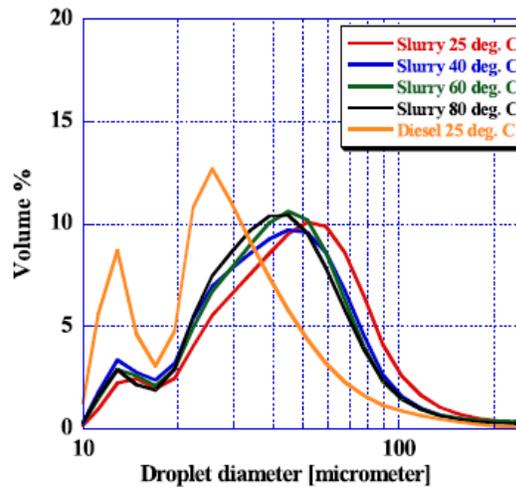


Figure 3-4. Droplet size distribution of slurry at 40 MPa and various spray temperature (Soloiu et al., 2011)

Soloiu et al. (2011), had done some experiments on the bio-coal slurry fuels containing 25 wt. % cedar chips bio-coal, 72 wt. % diesel fuel, and 2.5 wt. % water slurry. They have studied the effect of temperature and pressure on the atomization of the slurry and compared it to the atomization results for diesel fuel. The results could be found in Figure 3-4 and Figure 3-5. It is clearly seen that change in temperature has negligible effect on the slurry atomization and the authors proposed considering the temperature effect may complicate the engine operations.

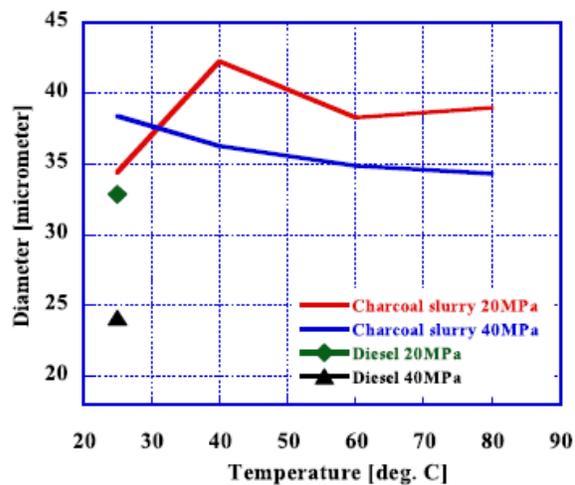


Figure 3-5. Sauter mean diameter slurry vs. injection pressure and temperature (Soloiu et al., 2011)

Changing the pressure of atomization had more influence on the atomization of slurry and authors concluded that 40 MPa pressure is an optimal and easy to achieve pressure to be used in atomization of their slurry.

Zhao et al. (2012), researched different patterns of the atomization regime of CWS and believed that atomization is a very complex process as involves highly turbulent and convoluted interfaces and breakup and coalescence of liquid masses. They proposed the Rayleigh-type breakup as the main regime of atomization for highly viscous CWS. For low viscosity value slurries, the atomization regime is also Rayleigh-type for low air velocities, Fiber-type for high air velocities and the atomization regime for very high air velocities. Schematic of different atomization pattern are shown in Figure 3-6.

Mulhem et al. (2006), believed that when the suspended solid particles exceed a critical value, solids and liquids separate more. In this study, they used a twin-fluid nozzle atomization and concluded that when the mean particle size of the solids are bigger than 50 μm the final droplet size distribution have two peaks. The first peak corresponds to the solid particle diameter in suspension and second one goes back to either pure liquid or suspension-drops in the spray. The less solid particle size, the smaller is the diameter peak. For the mean particle size of less than 50 μm the droplet size distribution is monomodal. Here the droplet size is equal to the pure liquid droplet diameter. Figure 3-7 illustrate their findings.

Tsai and Vu (1987), investigated the effect of unimodal and bimodal particle size on the atomization of a CWS. For unimodal particle size distribution they set two experiments with different particle size distributions of less than 44 μm and less than 75 μm . For bimodal particle size they have used two different particle size distribution of 75 wt. % particles less than 75 μm and 25 wt. % particles less than 8 μm .

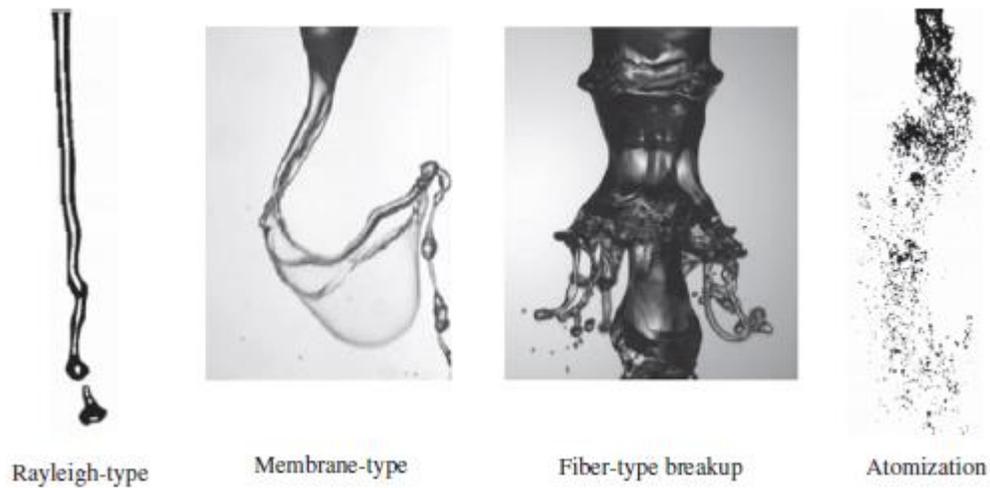


Figure 3-6. Coaxial air-water jets breakup types (Zhao et al., 2012)

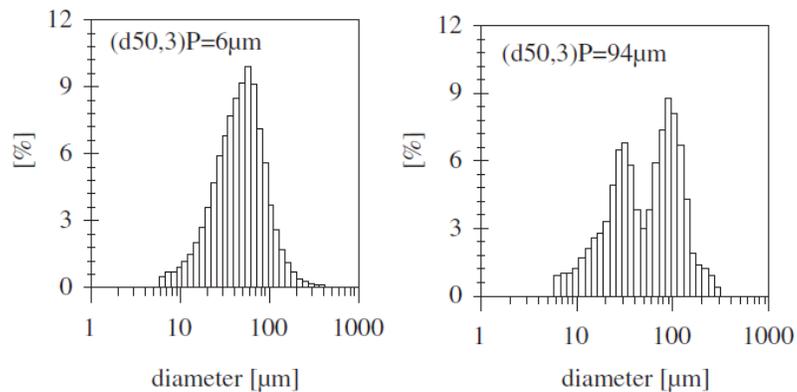


Figure 3-7. Droplet size distribution of two suspension spray condition based on water with glass particles with two different mean particle size of 6 μ m (left) and 94 μ m (right) (Mulhem et al., 2006)

They have used a twin-fluid jet atomizer and observed that droplet diameter of two unimodal CWS are smaller than bimodal CWS droplet size. They were of the opinion that particle size and PSD does not only change the viscosity which result in poor atomization quality. They believed low atomization quality is also because of packed system in which particles are tightly bound together.

4 ALTERNATIVE FUELS IN LARGE DIESEL ENGINES

4.1 Rapeseed oil

Rudolf Diesel who invented diesel engine in 1895 suggested using of vegetable oils in diesel engines and he believed that in future vegetable oils could be a very interesting fuel. Rudolf diesel run his engine with groundnut oil in 1900 but cheap price and also more efficiency of the fossil fuels had stopped researches on using vegetable oils (Murugesan et al., 2009). As the years went by, using vegetable oils became more real and vegetable oils are being used these days as they have less effect on the environment than fossil fuels.

There are many different kinds of vegetable oils with high heating values which could be used as a good substitute of water in coal or bio-coal slurries. The benefit of vegetable oil is the high heating value which elaborates the fuel quality. On the other hand, vegetable oil are more expensive than water leading to increase the price of final slurry fuel. Rapeseed oil is one which produced worldwide with huge amounts yearly. Rapeseed-oil is derived from rapeseed. A huge number of rapeseed oil producer countries are countries which do not produce rapeseed, but produce rapeseed oil by the rapeseed they import from the other countries. The main region by producing rapeseed oil are Europe, China, India, and Canada. Only 10% of the produced rapeseed oil is exported worldwide. (Frank Rosillo-Calle, 2009)

There have been bunches of researches on using rapeseed oil as fuel in many applications. For example, Altın et al. (2001), studied physical and chemical properties of rapeseed oil and reported that they are very similar to that of diesel fuel and in the future it could be substituted as a diesel fuel. Altın et al. (2001), believed that it is possible to use them in diesel engines by some modifications to the raw vegetable oils.

However, as reported by the other researchers, merit of vegetable oil as a diesel fuel is the lower NO_x emission while demerits of that are decreasing engine performance, increase CO and HC emission (Altın et al., 2001).

By knowing the above mentioned facts, it could be said that rapeseed oil is one of the options to be used as the liquid phase in bio-coal slurries aiming to produce a valuable and clean fuel. The viscosity of the rapeseed oil is reported to be around 79 cP at the room

temperature. For high temperatures of 60 to 70°C the viscosity value decreases to 21 and 15 cP, respectively (Noureddini et al., 1992).

4.2 Slurry fuels

Slurry fuel is a term used for the mixture of micronized solids (coal or bio-coal) with a lot of liquids such as water, oil, or alcohol resulting in a stable liquid fuel (Chen et al., 2011b, Esnouf, 1991). The use of coal slurries as a fuel dates back to 1879 where coal was mixed with oil to be used in industrial boilers. Later on, in 1950, works on coal-water slurries have been increased in the USSR. However, researches were stopped in 1970 due to lack of economic incentives (Chen et al., 2011b) (Papachristodoulou and Trass, 1987).

In the recent century, the quantity of researches on slurry fuels was contingent upon the price of fossil oil. Whenever the fossil oil price decreased, attentions went to the use of fossil oil therefore less research remains on the slurry fuels (Esnouf, 1991, Chen et al., 2011b). Today, not only the fossil oil price, but also the environmental impacts of fossil fuels leads to more attention to the environmentally friendly fuels that also could meet the fuel consumer requirements simultaneously. Therefore, slurry fuels have attracted attention in this era again.

Not only some of the industrial units and equipment, e.g. IC diesel engines accept just the liquid fuels, but also liquid fuels have more advantages over than solid fuels. Cheap and easy transportation, ease of maintaining and storage, and finally low emission of pollutants of their combustion are the points should be considered when comparing solid and liquid fuels (Esnouf, 1991, N'kpomin et al., 1995).

4.2.1 Coal-based slurry

As mentioned before, coal-oil slurries were used as fuel from 1879. The cheap price of fossil fuels had been always an obstacle for using coal slurries commercially. However, the United States used these slurries during two world wars (Papachristodoulou and Trass, 1987).

Coal-based slurries have been used as fuel for industrial steam boilers, utility boilers, and blast furnaces. Coal slurries are black in color and have the appearance similar to that of

crude oil with complex flow and combustion characteristics. According to Papachristodoulou and Trass (1987), there are bunches of coal slurry types mentioned briefly in the following.

- Coal-oil mixtures (COM): Also known as coal-oil dispersion (COD) is a suspension of coal in fuel oil. Normally 40-50 wt. % of the solid is mixed with 50-60 wt. % oil. The US patent 4201552 had made this mixture and claimed their prepared COM is stable and shows good efficiency of combustion, easy to handle and economical to store.
- Coal-oil-water (COW): is a mixture of coal and oil with less than 10 wt. % water in the mixture. It is reported that small amount of water could improve the effectiveness of the stabilizer and the combustion efficiency increases.
- Coal-water-oil (CWO): a suspension of coal in water (as the main ingredient) and oil which has more than 10 wt. % water in its content.
- Coal-water fuels (CWF): is a suspension of micronized coal in water mostly in proportion of 70-75 wt. % coal, 25-30 wt. % water and approximately 1wt. % of additives.
- Coal-Methanol fuel (CMF): is a suspension of coal in methanol. Sometimes water is added to the mixture in order to enhance the fuel properties and is known as CMW.

The properties of coal slurries depend on the coal type or rank, particle size, particle size distribution, particle shape, volume fraction of coal in the slurry and additive's amount and type. For instance, (National Energy Technology Laboratory, 2007), had suggested particle size of 3-20 μm with the maximum particle size of 85 μm for coal water fuels.

4.2.2 Bio-coal-based slurry

The idea of making bio-coal slurry comes after coal slurry due to similarities of bio-coal to coal. Bio-coal slurries are not produced commercially yet, but the number of researches about that is increasing rapidly. The main problem of bio-coal slurry is the low amount of solid concentration near of 30-40 wt. % (Chen et al., 2011b, Soloiu et al., 2011, Long, 2014) because it leads to a low heating value of the water slurry and high price of slurries

not having water as the liquid carrier. Moreover, in case of bio-coal-oil slurry the viscosity of the slurry increases as oils are more viscous than water. Using additives was reported to decrease the viscosity value (Soloiu et al., 2011), while increase the final price.

Bio-coal slurry represents bunches of benefits over coal slurry. For example, as reported in the literatures, the sulfur content in bio-coal is smaller than that of coal, thus bio-coal slurry decreases engine abrasion compare to coal slurry fuels (Wamankar and Murugan, 2015, Patton et al., 2009). In addition, bio-coal is a kind of clean and renewable energy which recently had attracted attention as an environmentally friendly energy source.

4.2.3 Properties of slurry fuels

The object of making slurry fuel is the combustion of slurries to produce energy while in the majority of cases the properties of fuel such as particle size distribution, viscosity, stability, and heating value had some influences on the combustion efficiency. For instance, big particles or high viscosity causes inappropriate atomization and pumping in a combustion unit.

Below some of the most significant factors affecting combustion efficiency are listed and a review of the previous related works is explained briefly.

4.2.3.1 Viscosity

Basically, when thinking about the feasibility of slurry fuel production regardless of overall costs and heating values of the final product, the physical properties of the fuel are the most significant factors which should be taken into account. The viscosity of a fluid is the most important property of a fuel pumping into a combustion chamber as it directly affects pumping efficiency and atomization quality of the slurry fuel.

The industrially accepted value for a fuel is a Brookfield viscosity of 1000 cP at 100 RPM (Boylu et al., 2004). However, this value is the minimum acceptable viscosity value in order to enable the devices dealing with the fuel work properly such as pumps. Generally, to be able to use a fuel in a diesel engine, the viscosity value should be less to have a better atomization quality.

In case of diesel engines, due to pumping of fuel and atomization by the injection nozzle, the viscosity should be low enough to increase atomization efficiency and prevent wearing of different parts of the engine. Although the slurry viscosity increases by increasing the solid ratio in the mixture, efforts are being made to improve the concentration of solid, heating value of the final slurry, and viscosity of slurry. UFA (2015), claim a fuel with the viscosity of below 5.5 cP at 40°C is suitable for diesel engines, however, this value may change by considering diesel engine design and size, temperature of the slurry, and the characteristics of the injection system. For instance, Wärtsilä Company, which is one of the leaders in producing large diesel engines, claims their commercial diesel engine model 46F operating in the range of 7.2 to 19.2 MW power, works on the fuels with the viscosity range of 2 to 730 cP @ 50°C (Wärtsilä, 2010). Table 4-1 shows different properties and the accepted viscosities for CDF, ULSD, and biodiesel.

Table 4-1. Comparative properties of CDF, ULSD, and biodiesel (Kalpesh and Sham, 2012)

Properties	CDF	ULSD	Biodiesel
Density @ 15-20°C (kg/m ³)	840	840	871
Viscosity @ 40 °C (cP)	2.2-5.3	2.4	4.6
Sulphur	462 (ppm)	<10 (wt. %)	<10 (wt. %)
Water (vol. %)	-	ND*	ND
Diesel fuel (vol. %)	100	ND	ND
Surfactant (vol. %)	-	ND	ND
Ash (wt. %)	<0.01	ND	ND
LHV (MJ/kg)	45.6	42.5	37.5

*ND: Not Determined

There are ample of factors affecting the viscosity of a slurry such as volume fraction, the viscosity of the liquid phase, particle size, particle size distribution, particle shape, additives, zeta potential, and etc. (Mishra and Kanungo, 2000).

As coal-based slurries have been investigated from long time ago, there are an overwhelming number of studies about coal slurries. Here, some of the investigations on coal slurries followed by studies about the bio-coal slurries are mentioned.

Dinçer et al. (2003), investigated the effect of three different dispersant on the viscosity of coal-water slurry and they reached good results in lowering the viscosity of a 63% solid concentration slurry from 3050 cP to 1000 cP by adding 0.14 wt. % additive. Boylu et al. (2004), studied the effect of particle size distribution on the viscosity of three different types of coal and water slurry at solid volume fractions between 0.59 to 0.74 and results showed that by decreasing mean diameter of the particles from 50 μm to 19 μm , the viscosity increases by the order of 2 to 3 times from around 700-900 cP to 2100-2900 cP. Cui et al. (2008), showed more than five times increase in viscosity for the increase in the solid ratio of coal-oil mixture from 45 to 55 wt. %. The mean particle size in this study was 2.71 μm .

In the other study, Son and Kihm (1998), investigated the effect of particle size on the viscosity of a CWS. They had made three different particle size distribution of 32 μm <PSD< 45 μm , 45 μm <PSD< 63 μm , and 63 μm <PSD< 90 μm of the same coal sample and made the slurries with the same solid concentration and measured the viscosities in different shear rates. Displaying the results in Figure 4-1 shows that by decreasing the PSD from 63-90 μm to 32-45 μm , the viscosity increases around 8-9 times at the higher shear rates.

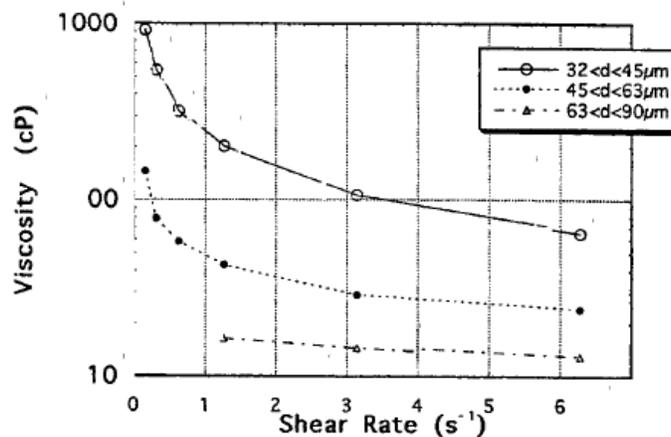


Figure 4-1. The viscosity of CWS with different PSD at different shear rates (Son and Kihm, 1998)

Soloiu et al. (2005), investigated the rheological behavior of a mixture of bio-coal-HFO-water and a small amount of surfactants. They observed a non-Newtonian behavior of the

fluid while the lowest viscosity they obtained was 27 cP at 60 rpm viscometer spindle's speed by 25 wt. % bio-coal, 72 wt. % HFO, 2.5 wt. % water and 0.5 wt. % surfactant. N'kpomin et al. (1995), studied the properties of deashed bio-coal-oil-water and measured the viscosities of different mixtures vary in oil to bio-coal ratio. They also used a surfactant to improve the viscosity of the mixture and reached good results. The lowest viscosity in their report is obtained at 45 wt. % solid, 25 wt. % HFO and 30 wt. % water with the value of 1253 cP. They believed the viscosity reduction is due to the lower interaction between particles when adding surfactant. Awang and May (2009), measured viscosities for slurries containing 5, 10, and 15 wt. % bio-coal and observed increase in viscosity from 6.9 to 14.5 cP. In the other study, Chen et al. (2011a), uses Mallee char as the solid in slurry fuel and observed high viscosities in 35 wt. % char concentration without addition of additives. Long (2014), used 25% (v/v) waste wood bio-coal to biodiesel B20 for the slurry and compared the viscosity results with ULSD in different spindle's speeds. Viscosity values for the slurry were 10 cP more than ULSD in each spindle's speed.

Lee et al. (2014), proposed bimodal PSD for CWS in order to increase the viscosity and solid concentration as in Figure 4-2. They argued that when bimodal PSD is used, fine particles go through the pores of the larger particles and increase the solid concentration. In addition, fine particles remain between bigger particles and act as lubricants results in decreasing the viscosity.

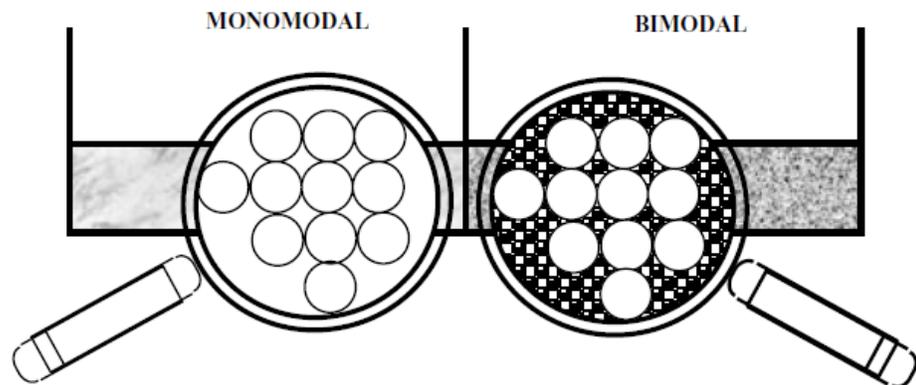


Figure 4-2. PSD for monomodal and bimodal distribution (Lee et al., 2014)

4.2.3.2 Stability

Besides high calorific value and good atomization and pumping characteristics of fuels, a suitable fuel should be homogenous and stable enough in order to be more efficient and valuable. In addition, the stability of a fuel is more important in terms of storage and handling.

Chen et al. (2011b), defined a stable slurry in the engineering aspect as "a slurry which does not settle out rapidly making easy its processing in mixing, pumping, transportation, and atomization". According to Esnouf (1991), a fuel slurry must be stable for a period of at least three months which requires periodical stirring, sometimes.

Obviously, to make a ternary mixture, the presence of a chemical additive is required, which improves the stability and lowers the viscosity (N'kpomin et al., 1995). Moreover, in some cases adding a small amount of cationic surfactant (less than 1 wt. %) to the emulsion reduces corrosion activity of water and fuel oil (Al-Amrousi et al., 1996).

There are three main different surfactant types used as stabilizer based on their dissociation in water, including cationic, anionic and non-anionic surfactants. Anionic surfactants which are the most used surfactants, dissociate in water in an amphiphilic anion, and a cation that is an alkaline metal (Na^+ , K^+) or a quaternary ammonium. Statistics show 50% of the world consumption is the anionic form of surfactant. Anionic surfactants having detergents, fatty acid, foaming agent, wetting agent, and dispersants in their chemical structure. Non-ionic surfactants do not ionize in aqueous solution as their hydrophilic group is of a non-dissociable type such as alcohol, phenol or ether. Non-ionic surfactants have 45% share of the world production of surfactants. Cationic surfactants dissociate in water into an amphiphilic cation and an anion, most often of the halogen type. A very large percentage of cationic surfactants corresponds to nitrogen compounds like fatty amine salts and quaternary ammoniums. Cationic surfactants are the most expensive surfactants. (Kalpesh and Sham, 2012)

In the studies of comparing different surfactants, Al-Amrousi et al. (1996) and N'kpomin et al. (1995), obtained good stability by using non-ionic surfactants in bio-coal slurries. Al-Amrousi et al. (1996), also made a bio-coal slurry with the successful results of stability

by using both anionic and non-anionic surfactants. They noted cationic surfactant is not suitable for the bio-coal-oil-water slurry.

Awang and May (2009), believe that a coal suspension in an oil is usually unstable and coal particles tend to deposit in the slurry. They argued the rate of deposition is dependent on the particle size distribution, viscosity of the mixture, solid concentration in the slurry, and specific gravity of the slurry. They also noticed additives improve the settling index more than 85% in coal-oil slurry. Chen et al. (2011b), had also introduced zeta potential or surface charge and coal morphology as the factors affecting stability of slurry fuel. For making the slurry more stable, Awang and May (2009), proposed following methods:

- Finer particle size
- Establishing a gel structure in the oil with a chemical additive or stabilizer
- Using a peptizing agent
- Selecting oil that gives a stable suspension without adding a stabilizer

Cui et al. (2008), studied the effect of particle size on the stability of an ultra-clean superfine coal-oil slurry which contains 30% of particles less than 1 μm and observed good stability. They believed this stability is the reason of superfine particles and hydrophobicity of both coal and oil, which make very strong binding forces between coal particles and oil.

In the study of oil Mallee char-water slurry, Chen et al. (2011b), observed satisfactory results of stability of the slurry without adding any additive, but as they conclude, this stability is a result of high ash content (more than 15%) which makes the solid more hydrophilic and consequently more stable slurry. Ugwu and Eze (2014), reported a bio-coal-water slurry stability of 60 days for a 30 % solid concentration slurry, 4 days for a 40 % solid concentration slurry, and 1 day for a slurry of 50 % solid concentration while there were no additives in the slurry at the temperature of 30 °C.

4.2.3.3 Stability measurements

In an standard method for measuring the coal-water slurry, the slurry is left for a period of time (such as 10 days) at the ambient temperature, then the container of slurry is poured

slant way to a bottle for 30 s and after that the container is turned upward to let the slurry to flow. Finally the mass of non-flowing part is determined and then the stability of the mixture can be measured by Eq. (1) (Abdullah et al., 2010):

$$SB_{sta} = \left(1 - \frac{M_B}{M_S}\right) \times 100 \quad (1)$$

Where

SB_{sta} is the stability of slurry

M_B is the mass of non-flowing slurry

M_S is the initial mass of bio-slurry sample

In the other method, the slurry is poured in a cylinder type container having some valves at different heights. The solid concentrations are measured over a known time from all the valves. The differences between solid concentrations demonstrates stability (Dinçer et al., 2003).

4.2.3.4 Heating value

Before expressing the literatures about heating values of different bio-coal slurries, it is important to know the heating value of different diesel fuels that are commercially used. According to Biomass Energy Data Book (2011), HHV of the U.S. conventional diesel is 45.77 MJ/kg, for Low-sulfur diesel is 45.57 MJ/kg, and for biodiesel is 40.17 MJ/kg (Boundy et al.).

The heating value of a slurry depends on the type of solid and liquid. Long (2014), had reported heating value of 40.93 MJ/kg for a mixture of 25% bio-coal in biodiesel. N'kpomin et al. (1995), in their study of deashed bio-coal-oil-water found a calorific value of 24.67 MJ/kg for a slurry containing 45 wt. % solid, 30 wt. % oil, and 25 wt.% water. They also had determined the heating values of different slurries with different proportion of ingredients shown in Table 4-2.

Table 4-2. Calorific value of different bio-coal slurries (N'kpomin et al., 1995)

Solid Content (%)	Domestic oil content (%)	Water content (%)	Calorific value (MJ/kg)
4	12	48	17.39
8	14.1	38.9	20.43
11	13.5	41.5	19.56
21	11.4	50.6	16.52
24	9	61	11.51
28	7.2	68.8	10.48

Awang and May (2009), prepared different slurries of bio-coal-oil and measured heating values of them and reported the heating value of 37.89 MJ/kg for a 20% bio-coal slurry and 39.26 MJ/kg for a 5 wt. % bio-coal content slurry. He also investigated the effect of surfactant on heating value and concluded that by increasing surfactant from 0% to 3%, heating value decreases 0.4 MJ/kg from 39.36 MJ/kg to 38.96 MJ/kg.

5 EXPERIMENTS

5.1 Material and methods

Two kinds of torrefied wood and one charcoal sample from different origin and different chemical composition were used to prepare the slurries. The charcoal which is called "sample 1" in the rest of this work, is a commercial charcoal bought from a local supermarket in Finland which is mostly used in household consumption. One of the torrefied woods, which is called "sample 2" in this work was made from a mixture of softwood and hardwood in the torrefaction temperature near to 250°C in a Finnish company and finally the last sample which is called "sample 3" is a torrefied product of spruce chips (without bark) with torrefaction temperature of 280°C and residence time of 30 minutes. Figure 5-1 illustrates the appearance of these three samples. Here, the slurries were made by two different liquids, water and rapeseed oil. Distilled water is used in the water slurries as recommended previously by Boylu et al. (2004) and the rapeseed oil used in this project is ordinary oil used in household and was bought from a local Finnish supermarket.



Figure 5-1. Appearance of three different solid samples (a) sample 1, (b) sample 2, and (c) sample 3

5.1.1 Particle size reduction

According to Figure 5-1, dimensions of "sample 1" and "sample 2" were more than one centimeter therefore they needed to be fined before making the slurries. Particle size reduction was done in two steps. First a laboratory scale hammer mill (AEG AMEB 80 FX2) (Figure 5-2) was used to reduce the particle size below than 0.5 mm and then a laboratory scale ball mill (Figure 5-3) was employed in order to reduce the particle sizes to a few microns. "Sample 3" was received as particles less than 200 μm thus no process for particle size reduction was needed. Then the particles were sieved by the help of a

laboratory scale shaker and four different sieves in order to divide the particles of different particle size. Four different sieves with the orifice size of 38 μm , 50 μm , 63 μm , and 100 μm were used to divide particles with particle size distribution (PSD) of $0 < \text{PSD} < 38 \mu\text{m}$, $38 \mu\text{m} < \text{PSD} < 50 \mu\text{m}$, $50 \mu\text{m} < \text{PSD} < 63 \mu\text{m}$, and $63 \mu\text{m} < \text{PSD} < 100 \mu\text{m}$.



Figure 5-2. Laboratory scale hammer mill



Figure 5-3. Laboratory scale ball mill

5.1.2 Slurry preparation and viscosity measurement

Mixing of solids and liquid phase were done by the help of a high speed homogenizer (Ultra Turrax © model T25) at the speed of 11000 RPM. A known weight of solid was added to a known weight of the liquid phase gradually while the homogenizer was rotating at the constant speed. Manual stirring of slurry was done in case some solid were stuck to the container or mixer. All slurries were mixed until homogenous slurry was observed by the naked eye. Almost in all the slurries the homogeneity was observed in less than one minute therefore mixing time did not exceed a minute for any slurry. The homogenizer shaft is displayed in Figure 5-4.



Figure 5-4. High speed homogenizer shaft

A Brookfield Viscometer of the model "DV-II+" was employed to measure the viscosities of slurries at different shear rates as all the slurries show non-Newtonian fluid behavior.

Spindle number of 6 of the spindle sets of the RV was used to measure viscosities of slurries at three different spindle's speeds of 6, 60, and 100 RPM.

Considering the maximum solid concentration in rapeseed-oil-based slurries, some more experiments were set in order to investigate the effect of increasing temperature on maximum solid concentration and viscosity of the slurries.

In case of increasing the temperature of slurries from ambient temperature to 50, 60, and 70 °C a water bath including a thermometer was used to increase the temperature of the oil (oil was in a container and the container was immersed in a water bath) then the solid was added to the oil while one other thermometer was in direct contact with the slurry. The viscosities also were measured when the slurry container was immersed in a water bath and the temperature of the slurry was at the constant temperature of desire. Temperature error was around $\pm 1^\circ\text{C}$ for all the slurries.

5.1.3 Proximate and Ultimate analysis

All the proximate analysis were done according to the European Standard under a number of EN 14775 for the ash content, SFS-EN 15148 for the volatile matter and SFS-EN 14774-2 for the moisture content. All experiments were done at least for two times and the average values were recorded. The amount of fixed carbon is obtained by the Eq. (2) (Somerville and Jahanshahi, 2015).

$$\% \text{ Fixed Carbon} =$$

$$100\% - (\% \text{ Ash Content} + \% \text{ Volatile matter}) \quad (2)$$

Ultimate analysis, including Carbon, Hydrogen, and Nitrogen contents were done according to standard methods of "EN ISO 16948, EN 15104, EN 15407, ISO 29541".

The amount of Oxygen content was calculated according to the Eq. (3) (Speight, 2012).

$$\text{Oxygen content (\% dry basis)} =$$

$$100\% - (\text{Carbon}(\%) + \text{Hydrogen}(\%) + \text{Nitrogen}(\%) + \text{Ash}(\%)) \quad (3)$$

5.1.4 Measuring of heating values

Heating value of all three samples and also the rapeseed oil were measured by the means of a "6400 Automatic Isoperibol Calorimeter". For the solid samples small amount of them were used to make a small capsule and then the capsule was put into the combustion chamber. Rapeseed-oil were put into the combustion chamber directly as it was not possible to make capsule with liquids. Then the sample was burned in the equipment and device measured the difference of temperature of water around the chamber and calculated the amount of heating values.

The heating value of slurries were calculated according to mass and energy balance according to Eq. (4).

$$\begin{aligned} \text{Heat value of slurry} = & (\text{Heat value of solid} \times \text{solid concentration}(\%)) \\ & + (\text{Heat value of liquid} \times \text{liquid concentratin}(\%)) \end{aligned} \quad (4)$$

Measuring the heating value of water was not possible by the same method as rapeseed oil and it was considered as 0.0042 MJ/kg as it was reported in loads of thermodynamic tables (Sonntag et al., 1998).

5.1.5 Density

There are two types of density of the porous material naming solid or true density and bulk or apparent density. The apparent density includes the pores of a matter, thus the value is lower than solid density. Here, the apparent density of the samples was measured by the simplest method. Each sample was poured into a known volume container and weighted. The apparent density is the division of weight (in kg) to volume (in m³).

5.1.6 Stability measuring method

Measuring the exact stability of the slurries were out of the scope of this work, however, it was tried to determine a rough amount of stabilities in order to have an order of magnitude about the slurries. All the stabilities were reported, according to observations in the laboratory.

5.2 Results and discussion

5.2.1 Proximate and ultimate analysis

Proximate and ultimate analysis of the samples are mentioned in

Table 5-1. It is clear that "sample 1" is the most hydrophobic material amongst three samples because this sample comprise the least amount of oxygen to carbon ratio. "Sample 1" also contains low amount of volatiles in comparison with "sample 2" and "sample 3" which contain 79.26% and 73.83% volatiles respectively.

Table 5-1. Ultimate and Proximate analysis of the samples

	Sample 1	Sample 2	Sample 3
Ash Content (%)	2.49	2.01	0.5
Moisture Content (%)	3.7	7.1	3.4
Volatile Matter (%)	12.98	79.07	74.37
farbone (%)	84.53	18.92	25.13
C (%)	86.9	52	56.5
H (%)	3	5.9	5.8
N (%)	0.36	< 0.1	< 0.2
O (%)	7.2	40.01	37
O/C	0.08	0.77	0.65

5.2.2 Water-based slurries

Before going through the viscosity values of the samples, it should be noted that "sample 1" displayed the maximum solid concentration in water-based slurries while it can be mixed up to 45 wt. %. Slurryability of "sample 2" and "sample 3" in water-based slurries were 28 wt. % and 23 wt. %, respectively. The maximum solid concentrations were recorded when the slurry lost fluid properties, i.e. the slurry behaves like a solid. The precise amount of viscosity of all the slurries of experiments are presented in appendix.

5.2.2.1 Sample 1-water slurry

The viscosity of all the slurries was measured by the means of a Brookfield Viscometer. As it was previously reported by the other researchers (Soloiu et al., 2011), the charcoal slurries behave like Non-Newtonian fluids, therefore, here the viscosities are measured at different spindle's speeds. Five different solid concentrations of 25, 35, 37, 40, and 43 wt. % were prepared from different PSD for "sample 1"-water slurry as shown in Figure 5-5, Figure 5-6, Figure 5-7, and Figure 5-8.

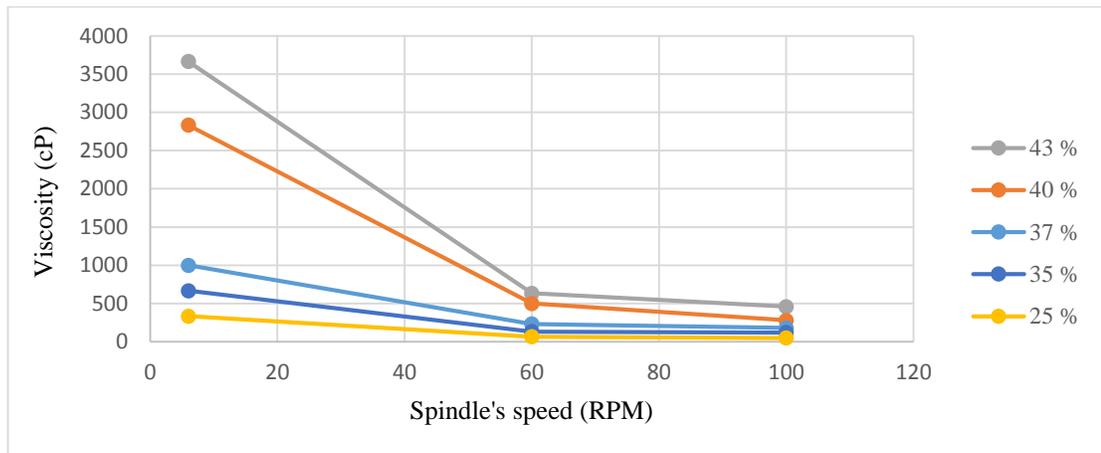


Figure 5-5. Viscosity of "sample 1"-water slurry at different solid concentrations ($0 < PSD < 38 \mu\text{m}$)

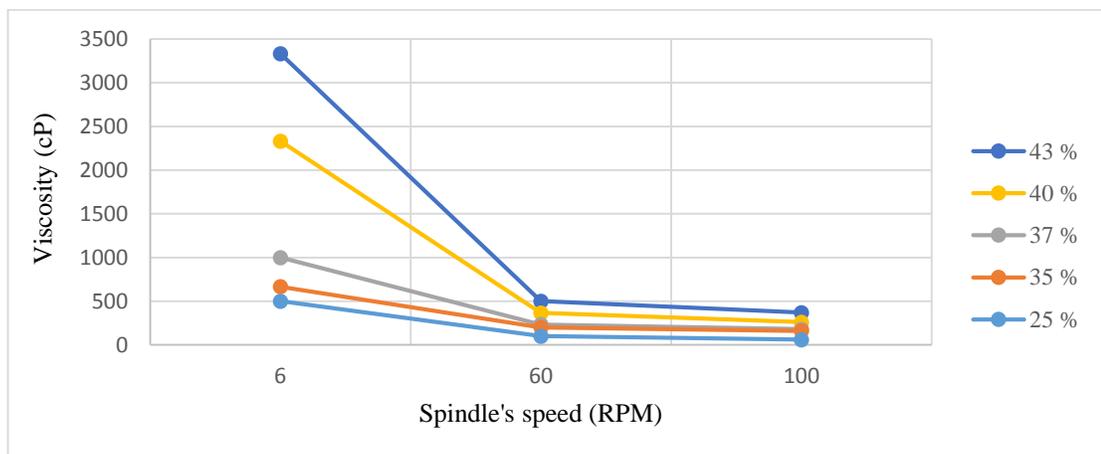


Figure 5-6. Viscosity of "sample 1"-water slurry at different solid concentrations ($38 \mu\text{m} < PSD < 50 \mu\text{m}$)

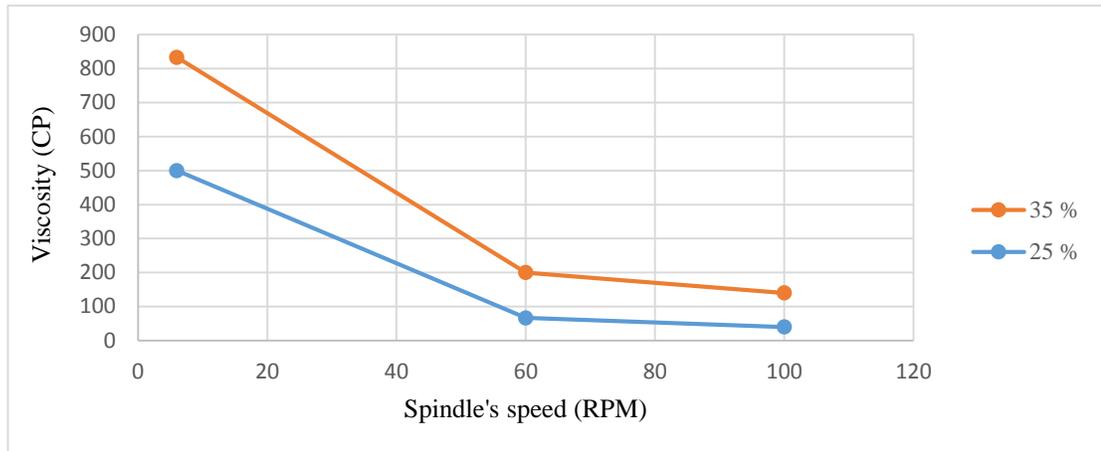


Figure 5-7. Viscosity of "sample 1"-water slurry at different solid concentrations ($50 \mu\text{m} < \text{PSD} < 63 \mu\text{m}$)

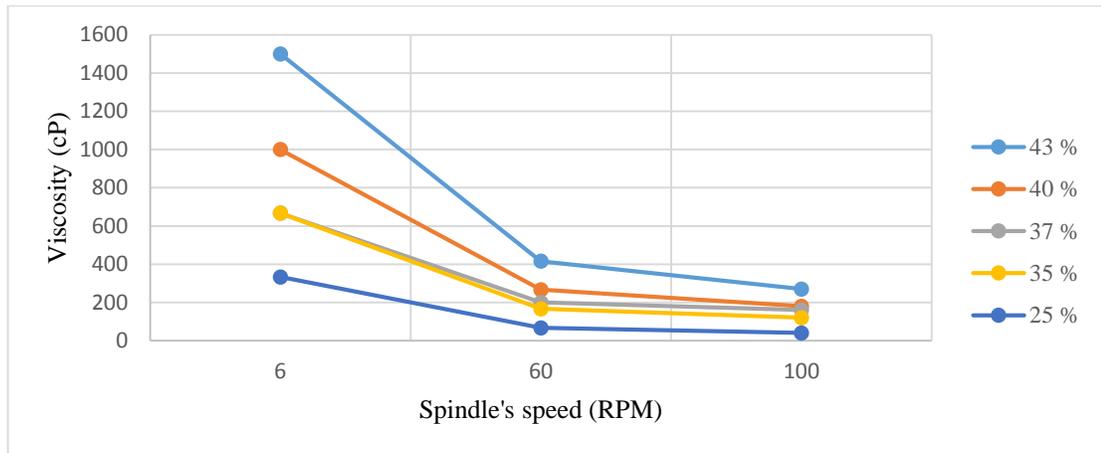


Figure 5-8. Viscosity of "sample 1"-water slurry at different solid concentrations ($63 \mu\text{m} < \text{PSD} < 100 \mu\text{m}$)

In order to better understand and compare the effect of different PSD, it was tried to show all the viscosities of different PSD at one figure. Figure 5-9 illustrates this comparison for viscosities at the spindle's speed of 100 RPM. The trend of viscosities of spindle's speeds of 6 and 60 RPM is roughly the same as 100RPM, thus, they are not shown here.

Resulting from Figure 5-9, PSD of between $63 \mu\text{m}$ to $100 \mu\text{m}$ exhibit the least viscosity value amongst the four PSD.

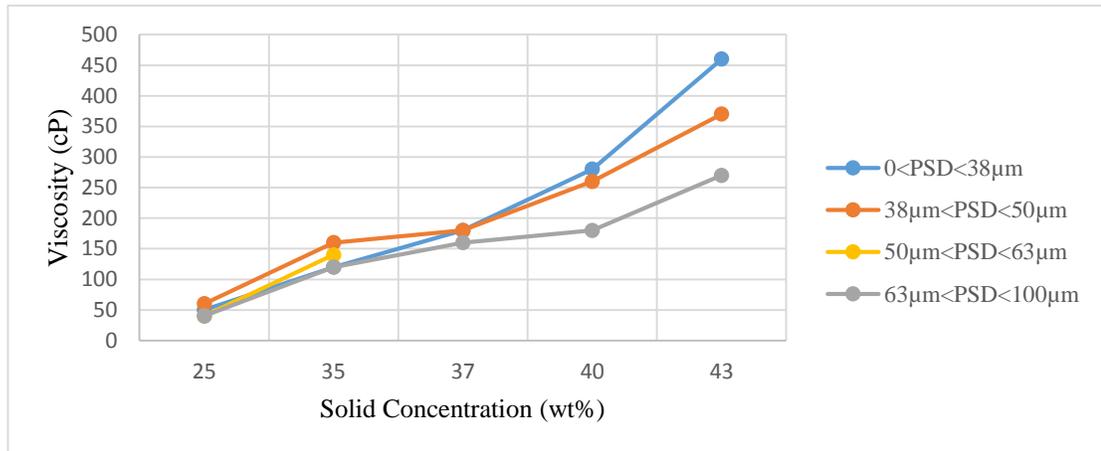


Figure 5-9. Viscosity of "sample 1"-water slurries at different PSD and solid concentration at 100RPM

5.2.2.2 Sample 2-water slurry

"Sample 2"-water slurries were made only of 25 wt. % solid concentration. The reason lies in the fact that slurries at concentrations more than this value behave like solid and concentrations less than 25 wt. % were worthless in terms of heating value and economically. Results of viscosities are presented in Figure 5-10.

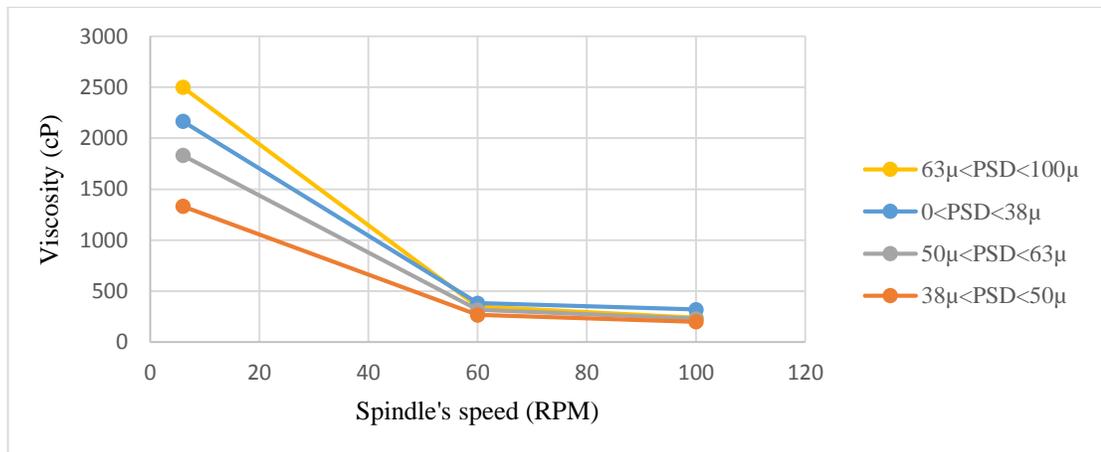


Figure 5-10. Viscosity of 25 wt. % "sample 2"-water slurry at different particle sizes

At the maximum solid concentration of 25 wt. %, the least viscosity values belongs to particle size between 38 μm to 50 μm for "sample 2"-water slurry.

5.2.2.3 Sample 3-water slurry

"Sample 3" displays the least amount of slurryability among the other samples. The more PSD, the less slurryability was obtained. The most solid concentration in the water-based slurry was obtained at $0 < \text{PSD} < 38 \mu\text{m}$ at 20 wt. %. The rest of the results could be found in Figure 5-11.

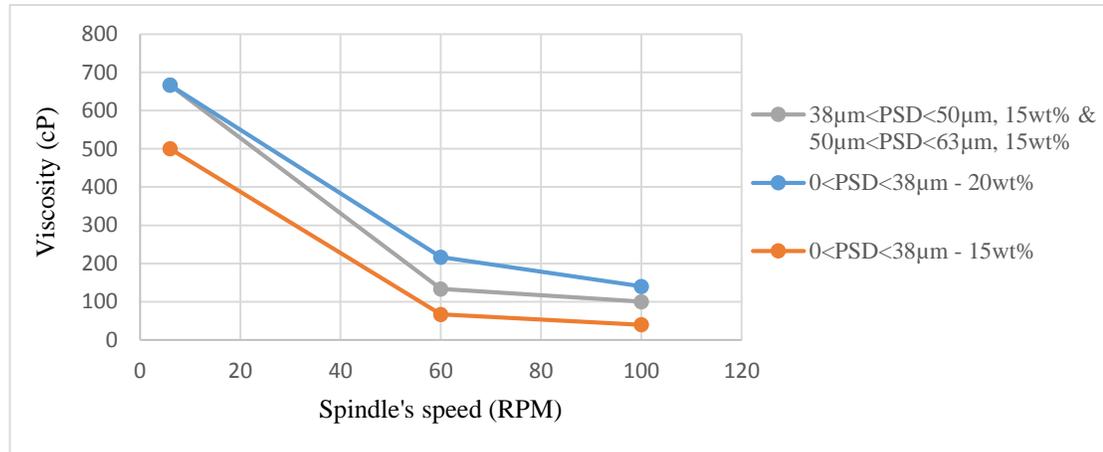


Figure 5-11. Viscosity of "sample 3"-water slurry at different particle size and solid concentration

It could be clearly seen that $0 < \text{PSD} < 38 \mu\text{m}$ is the optimum particle size distribution of "sample 3"-water slurry.

5.2.3 Rapeseed oil –based slurries

All the slurries made from rapeseed-oil were prepared by the same method as water slurries. The maximum solid content of the samples in rapeseed oil is 45, 38, and 23 wt. % for "sample1", "sample 2", and "sample 3", respectively.

5.2.3.1 Sample 1- rapeseed oil slurry

Viscosity values of "sample 1"-rapeseed oil slurry are given in Figure 5-12, Figure 5-13, and Figure 5-14.

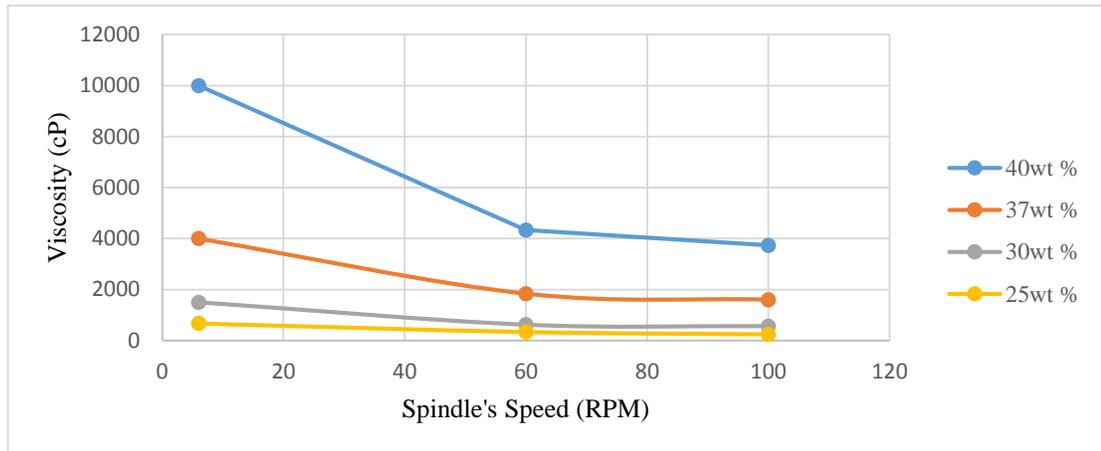


Figure 5-12. Viscosity of "sample 1"-rapeseed oil slurry at different solid concentrations ($0 < PSD < 38 \mu\text{m}$)

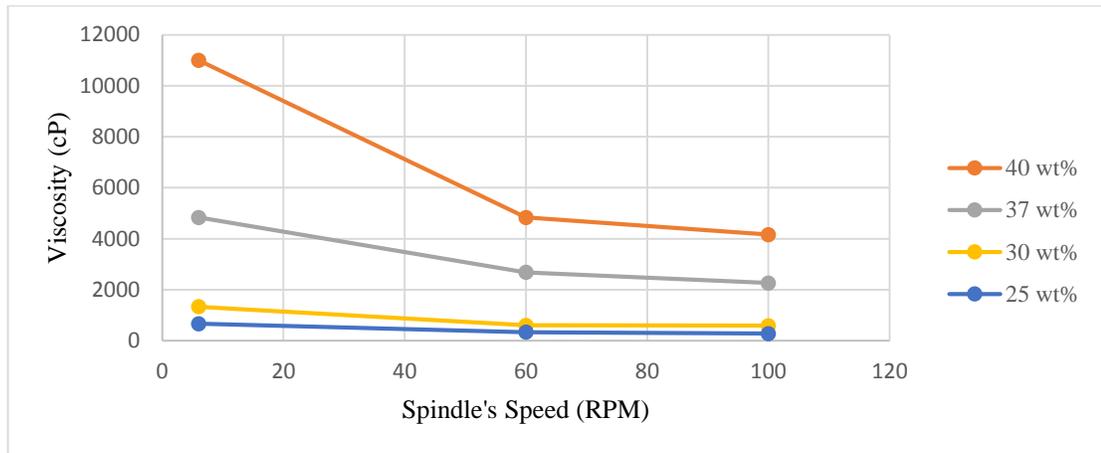


Figure 5-13. Viscosity of "sample 1"-rapeseed oil slurry at different solid concentrations ($38 \mu\text{m} < PSD < 50 \mu\text{m}$)

In order to have a glance at all the viscosities of different PSD at one figure, Figure 5-15 is created. This figure indicates viscosity values at 100RPM and shows the optimum particle size for "sample 1"-rapeseed oil slurry which are particles less than $38 \mu\text{m}$. The same figure for the spindle's speeds of 6 and 60 were the same as Figure 5-15 with some small fluctuations.

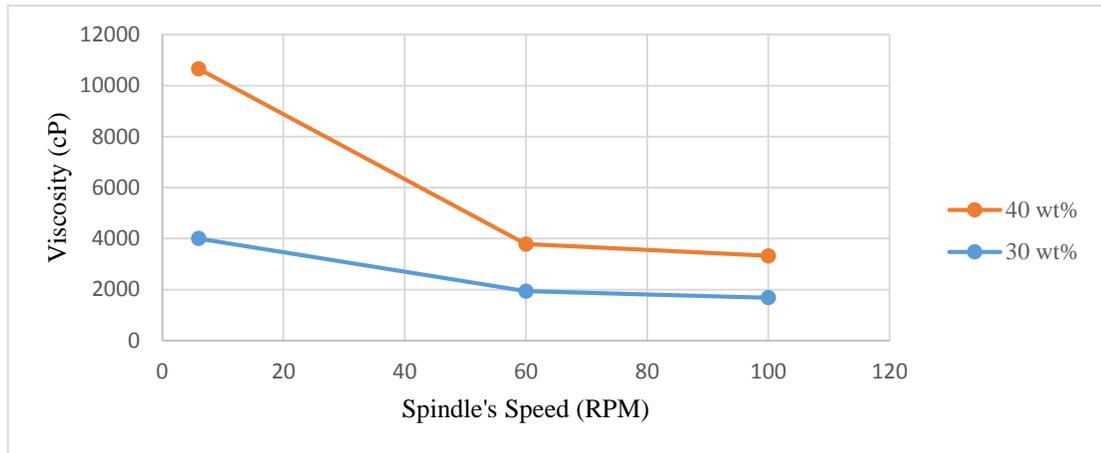


Figure 5-14. Viscosity of "sample 1"-rapeseed oil slurry at different solid concentrations ($63 \mu\text{m} < \text{PSD} < 100 \mu\text{m}$)

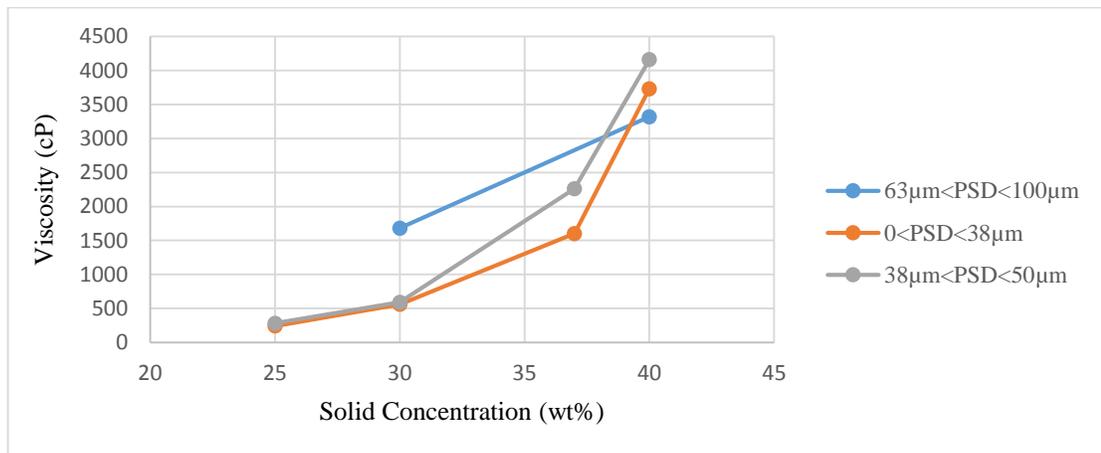


Figure 5-15. Viscosity of "sample 1"-rapeseed oil slurry at different PSD and solid concentration at 100RPM

5.2.3.2 Sample 2- rapeseed-oil slurry

The maximum solid concentration for "sample 2"-rapeseed oil slurry was around 38 wt. %. As it is clear in Figure 5-16, the minimum viscosity values are belong to $0 < \text{PSD} < 38 \mu\text{m}$ and $63 \mu\text{m} < \text{PSD} < 100 \mu\text{m}$ while the values are a little less in $0 < \text{PSD} < 38 \mu\text{m}$.

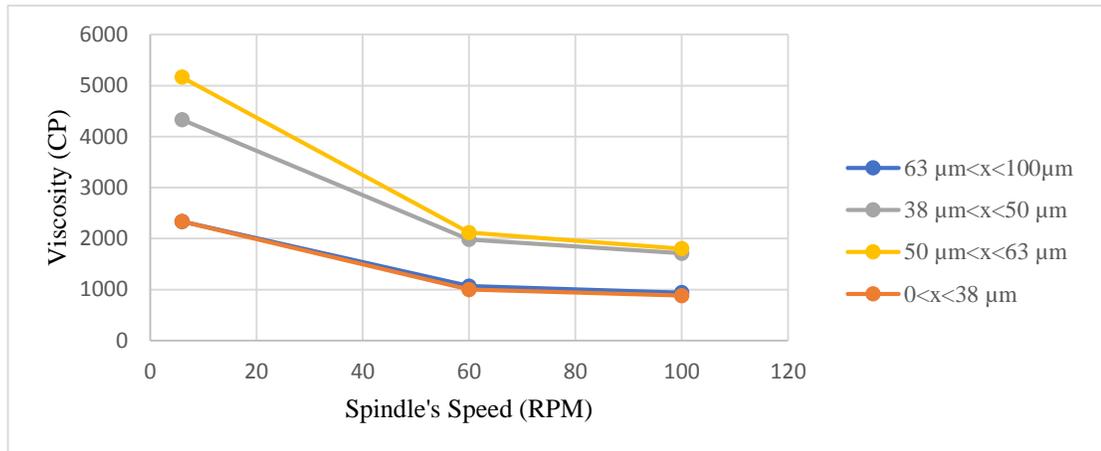


Figure 5-16. Viscosity 30wt. % "sample 2"-rapeseed oil slurry at different PSD

5.2.3.3 Sample 3- rapeseed-oil slurry

The same as water slurry, "sample 3" does not show higher slurryability more than 23 wt. % when mixing with rapeseed oil. Anyway, the less particle size distribution, the more slurryability and less viscosity is observed.

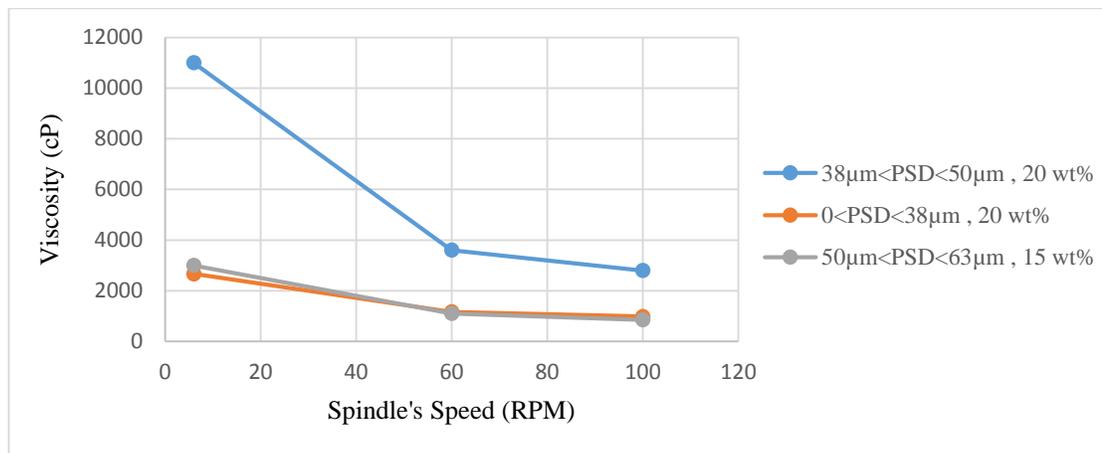


Figure 5-17. Viscosity of "sample 3"- rapeseed oil slurry at different PSD and different solid concentrations

As shown in Figure 5-17, the least viscosity value is attributed to 0 < PSD < 38 μm .

5.2.4 Effect of high temperature

Considering three different samples with four different PSD and also various solid concentrations and different temperatures (50, 60, and 70 °C), preparing the slurry and measuring the viscosity of all samples in different PSD and temperature was not needed,

therefore, just the optimum PSD of each sample and reasonable temperatures were chosen for this part of the study.

The effect of increasing temperature (from 21 to 60 °C) on the maximum solid concentration of samples in the rapeseed oil slurries was increasing the solid content up to 4 wt. %, 1 wt. %, and 5 wt. % for "sample 1", "sample 2", and "sample 3" respectively.

5.2.4.1 "Sample 1"-oil slurry at high temperature

Figure 5-18 shows the effect of temperature on the viscosity of "sample 1"-rapeseed oil slurry. As can be seen in this figure, by increasing the temperature, viscosity decreases while viscosity values less than 1000 cP are accessible at a solid concentration of 35 wt. % at the temperatures higher than 50°C.

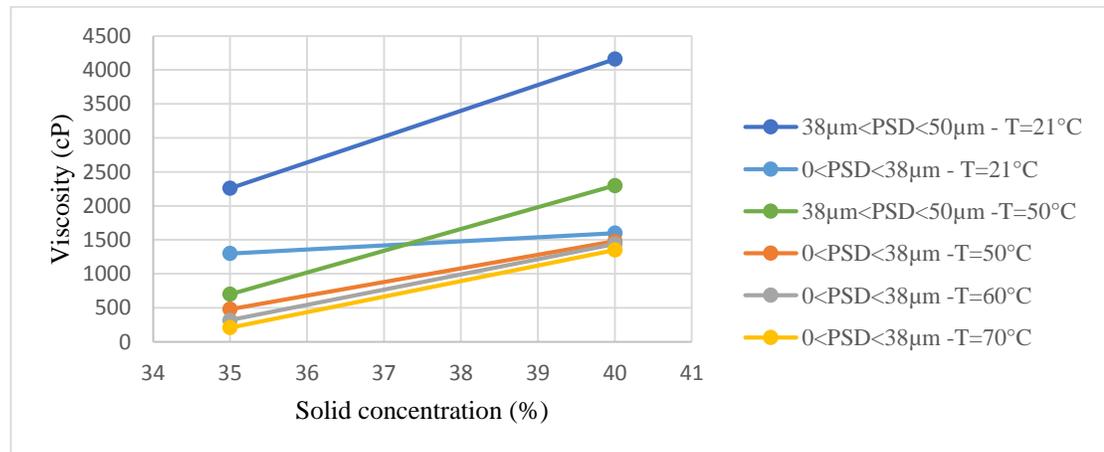


Figure 5-18. Viscosity of "sample 1"-rapeseed oil slurry at 100RPM vs solid concentration at different temperatures and PSD

5.2.4.2 "Sample 2"-oil slurry at high temperature

According to section 5.2.3.2 the optimum PSD for the oil slurry was 0<PSD<38 µm, therefore, here just the particles of this PSD were chosen to make the slurry. As illustrated in Figure 5-19, in order to achieve viscosity values less than 1000 cP the solid concentration should not exceed 30 wt. %.

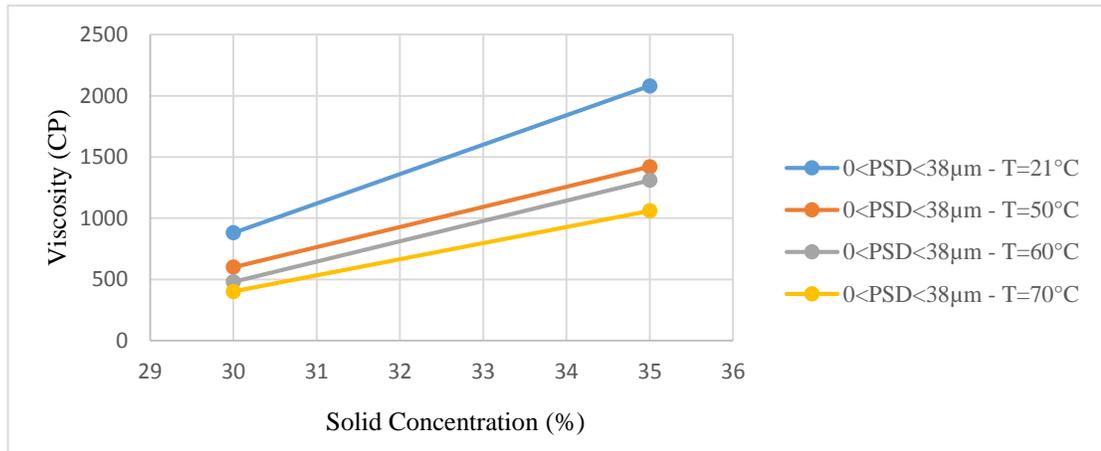


Figure 5-19. Viscosity of "sample 2"-rapeseed oil slurry at 100RPM vs solid concentration at different temperatures and $0 < \text{PSD} < 38 \mu\text{m}$

5.2.4.3 "Sample 3"-oil slurry at high temperature

As the $0 < \text{PSD} < 38 \mu\text{m}$ exhibit the least viscosity value in Figure 5-17, high temperature experiments were set at this PSD and results are clear in Figure 5-20. The viscosity value reduction is twice when increasing the temperature from 21 to 60°C at 100 RPM.

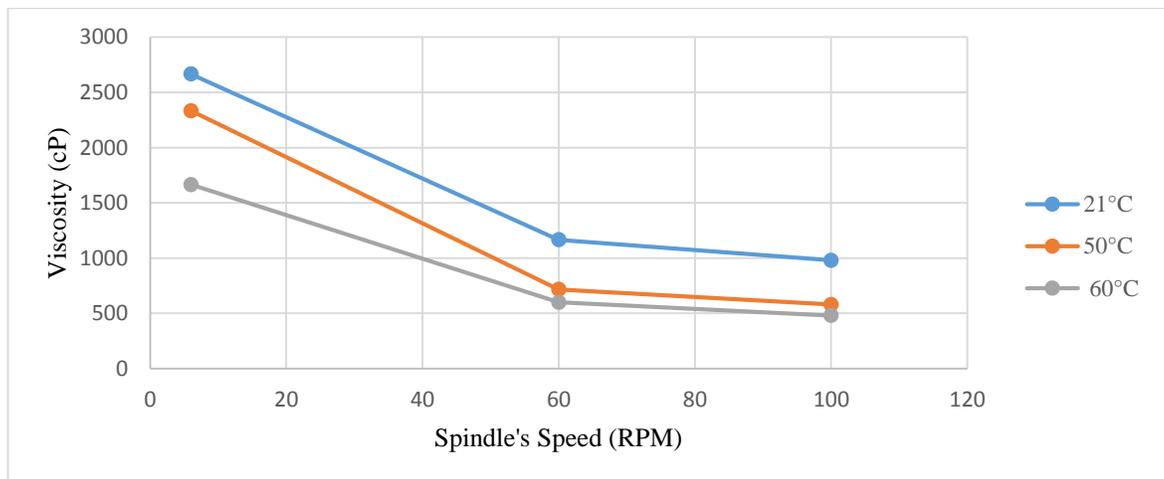


Figure 5-20. Viscosity of "sample 3"-rapeseed oil at different temperatures at 20 wt. % and $0 < \text{PSD} < 38 \mu\text{m}$

5.2.5 Heating value

Table 5-2 indicates the amount of heating values of the samples.

Table 5-2. Heating values of samples

Sample type	Heating value (MJ/kg)
Sample 1	31.83
Sample 2	19.22
Sample 3	21.94
Rapeseed oil	39.64

Calculated heating values of some of the slurries regardless of their viscosity values are shown in Table 5-3. The maximum solid concentration water-based slurry includes 13.7 MJ/kg heating value which is very low amount in comparison to diesel fuel and HFO which contain 42.7 and 41 MJ/kg heating values, respectively (MOTIVA, 2010).

Table 5-3. Calculated heating values of different slurries

Type of Slurry	Solid Concentration (wt. %)	Calculated Heating value (MJ/kg)
Sample 1 - water	43	13.7
Sample 1 - oil	40	36.5
Sample 2 - water	25	4.8
Sample 2 - oil	35	32.5
Sample 3 - water	20	4.4
Sample 3 - oil	20	36.1

5.2.6 Density

The result of sample densities are shown in Table 5-4.

Table 5-4. Apparent density of three samples used in this work

Sample	Apparent density (kg/m³)
Sample 1	342
Sample 2	300
Sample 3	214

It is clear that "sample 1" comprise the most value of apparent density among the other samples.

5.2.7 Stability of the slurry

In total, rapeseed oil slurries show more stability than water-based slurries. This could be due to more viscosity of the rapeseed oil. It was also observed that slurries with high content of solids displayed more stability regardless of the liquid carrier type. It is believed that in this case, two different issues are responsible. Firstly the viscosity, i.e. the more solid concentration in the slurry, the more viscosity, thus more stability is observed and secondly, by increasing the solid particles, more agglomeration occurs among particles which bonds particles to each other and prevents sedimentation.

The most stable slurry according to observations was belong to "sample 1"-rapeseed oil slurry with around 20 hour's stability. "Sample 2" shows medium stability while "sample 3"-water slurry exhibit very low stability of less than half an hour which has made some disturbance when measuring the viscosities.

5.3 Summary

It is now well understood that different slurry made from different samples show diverse properties and behaviors. This could be due to differences in the raw material, wood conversion process, and physical properties of samples. Anyway, the maximum solid concentration of these three samples while using these particle size distribution is not high enough for a high quality slurry because of low heating value and high viscosity of the slurry and also high price which is explained in the next chapter of this work in more details.

Generally, "sample 1" comprise the most solid concentration in both liquid carriers. This could be due to the higher apparent density of this sample or/and more carbon and less

oxygen content of that. The charcoal raw material could be also the other reason which help increasing maximum solid concentration.

This is unclear why do "sample 2"-rapeseed oil viscosity increases in particle size distribution of $38 \mu\text{m} < \text{PSD} < 63 \mu\text{m}$ while in both $0 < \text{PSD} < 38 \mu\text{m}$ and $63 \mu\text{m} < \text{PSD} < 100 \mu\text{m}$ viscosity values in all spindle's speeds are almost the same and are at the least amount. Here, only the viscosity values in 30 wt. % are reported and more investigations in the other solid concentrations are necessary to be done in future.

Furthermore, in order to use slurry fuels in the large diesel engines, atomization of the slurry which was not studied empirically during the present work, should be studied in more details. Surely, there will be some more challenges with the slurry atomization and there might be some necessary modifications of slurry or engine components.

6 COST ANALYSIS

Price is almost the main factor to evaluate the feasibility of a new product. Due to huge amounts of fuel usage by companies daily, a small fluctuation in the fuel price may lead to save or lose a huge amounts of money. Therefore, the fuel cost estimates should be as accurate as possible.

Below, it is trying to indicate the price of torrefied wood and rapeseed oil followed by the price of the 35 wt. % slurry because in this work, the viscosity value was under 1000 cP at 35 wt. % solid concentration. Then the price of other fuels will be represented according to worldwide price reports in October 2015 and finally there will be a comparison amongst the different fuel prices. The price analysis is presented without Value added tax (VAT).

6.1 Bio-coal slurry price

As torrefied wood currently are not commercially produced and used, there are no precise statistics about the prices. In fact, torrefied wood is in the chicken or the egg scenario which had made the market more complicated. On one hand, demand is increasing every day and on the other hand, there is not enough justification and confidence to convince producers to invest in this new market. The production is still in small scales and no torrefaction unit was established so far.

Anyway, there has been a lot of researches on the feasibility and economy of torrefaction unit and the final product. For instance, VTT Finland, had published a report about the market of torrefied wood and the possibility of integration of forest and energy in 2014. In this report the production cost of torrefied wood of a CHP plant in Baltic area was reported as 32 €/MWh (Wilén et al., 2014). Estimated production costs for the torrefied pellets in Baltic area are presented in Figure 6-1. In this thesis the price of torrefied biomass is estimated to be 35 €/MWh.

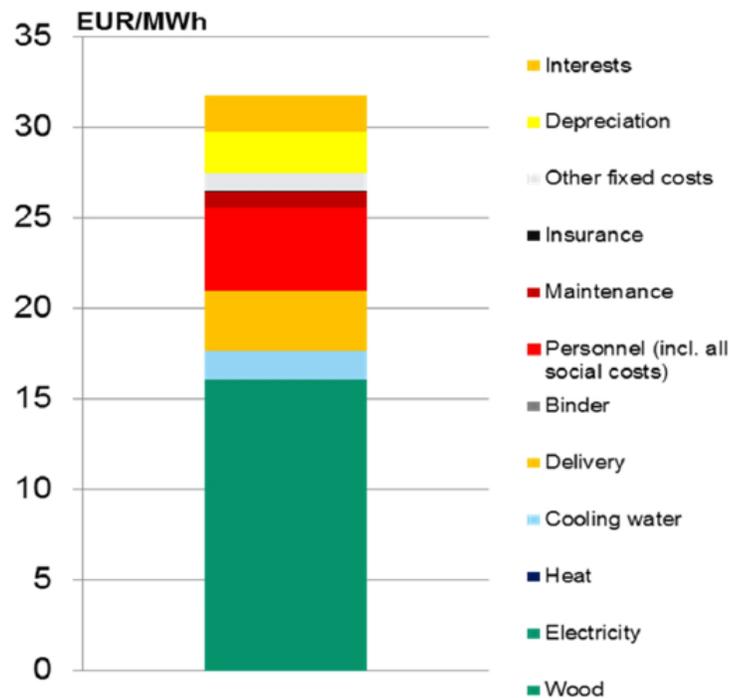


Figure 6-1. Production costs of torrefied wood pellets integrated into a CHP plant in the Baltic area (Wilén et al., 2014)

For the rapeseed oil price, according to the International Monetary service report (Fund, 2015), the international price of rapeseed oil has always met fluctuations. Regardless of the reasons for the increase or decrease in the price, the reported price published on October 2015 indicates that the highest price so far was reported on July 2008 with 1736 \$/ton and the minimum price during the last 10 years was reported on March 2009 when the price was 731 \$/ton. Regarding this report, the price for 1 ton of rapeseed oil in October 2015 was 805 \$ which seems a middle to low price during recent years. Considering 1\$ equal to 0.94 € and also the average heating value of rapeseed oil as 37 MJ/kg, the above mentioned prices are equal to 159 €/MWh in July 2008, 67 €/MWh in March 2009, and 73 €/MWh in October 2015. Figure 6-2 shows the price fluctuations during 10 recent years.

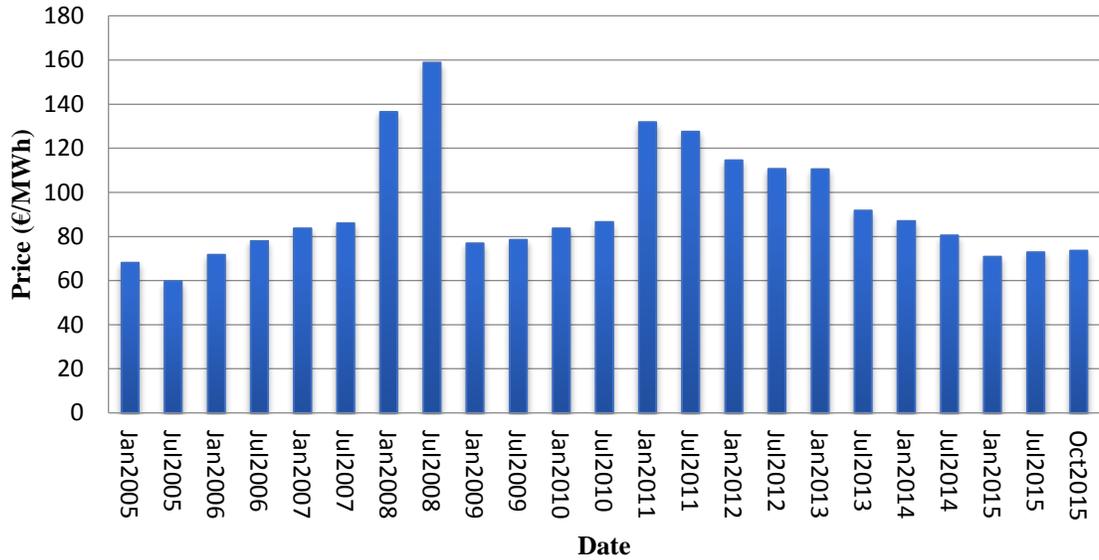


Figure 6-2. Rapeseed oil price from Jan 2005 to present (Fund, 2015)

In the present study the price of rapeseed oil will be considered as the latest price (October 2015) as this study was done in the last months of 2015 and the current prices are counted for the economy section of this work. Therefore the price is considered 0.76 €/kg or 73 €/MWh.

In order to calculate the average price for the bio-coal slurry, the average price of bio-coal and rapeseed oil should be considered as the reference, thus, the final price would be the sum of each matter's price share.

As mentioned before, the heating value of the torrefied wood depends on many factors, including the raw material, torrefaction process temperature, torrefaction process residence time, heating rate, and etc. However, (Hopkins, Bagramov, 2010), had reported the heating value of two different torrefied woods around 25.5 and 21 MJ/kg. Considering the average amount, the heating value of torrefied wood is around 23MJ/kg. Regarding Figure 6-1, the price for one kg of torrefied wood is counted as below:

$$35 \frac{\text{€}}{\text{MWh}} \times \frac{1 \text{ MWh}}{3600 \text{ MJ}} \times 23 \frac{\text{MJ}}{\text{kg}} = 0.22 \frac{\text{€}}{\text{kg}}$$

As mentioned in this section before, the current price of rapeseed oil is 0.76 €/kg. The optimum solid concentration for a flowing slurry in this work was reported to be around 35 wt. %. Considering 35 wt. % torrefied wood-rapeseed oil slurry (regardless of the value of viscosity which is high in comparison to diesel fuel), the price for 1kg of the slurry is calculated as:

$$\left(0.35 \times 0.22 \frac{\text{€}}{\text{kg}}\right) + \left(0.65 \times 0.76 \frac{\text{€}}{\text{kg}}\right) = 0.571 \frac{\text{€}}{\text{kg}}$$

Which includes the heating value of:

$$\left(0.35 \times 23 \frac{\text{MJ}}{\text{kg}}\right) + \left(0.65 \times 37 \frac{\text{MJ}}{\text{kg}}\right) = 32.1 \frac{\text{MJ}}{\text{kg}}$$

Knowing all the above equations, results in the final price of:

$$0.571 \frac{\text{€}}{\text{kg}} \times \frac{1 \text{ kg}}{32.1 \text{ MJ}} \times \frac{3600 \text{ MJ}}{1 \text{ MWh}} = 64.04 \frac{\text{€}}{\text{MWh}}$$

It should be noted that this calculated price is only the price of the combination of the current torrefied wood and rapeseed oil price and does not include the cost of the preparation process of the slurry. In addition, the expressed price does not include taxes.

6.2 Fuel oil price

Diesel fuel

According to the updated diesel fuel price in Finland on December 2015, price of diesel fuel, including tax, is 1.224 €/lit (fuel-prices-europe.info, 2015). As 24% of the price is attributed to tax, then the price of diesel fuel excluding tax is counted as:

$$1.224 \frac{\text{€}}{\text{l}} \div 1.24 = 0.99 \frac{\text{€}}{\text{l}}$$

Considering the average heating value of diesel fuel as 42.7 MJ/kg and average density of 850 kg/m³, the price for 1MWh of diesel fuel will be 98.2 € (Boundy et al.).

$$0.99 \frac{\text{€}}{\text{l}} \times \frac{1000 \text{ l}}{\text{m}^3} \times \frac{1 \text{ m}^3}{850 \text{ kg}} \times \frac{1 \text{ kg}}{42.7 \text{ MJ}} \times \frac{3600 \text{ MJ}}{1 \text{ MWh}} = 98.2 \frac{\text{€}}{\text{MWh}}$$

Light fuel oil

Light fuel oil is also a kind of fuel same as diesel fuel, which is used mostly in the energy sector. According to (Tilastokeskus, 2016) the price of light fuel oil on Oct 2015 in Finland was 77.4 €/MWh. The net price before tax would be:

$$77.4 \frac{\text{€}}{\text{MWh}} \div 1.24 = 62.42 \frac{\text{€}}{\text{MWh}}$$

Heavy fuel oil (Bunker fuel)

Any fuel poured into a ship's bunker aiming to power that is called bunker fuel. The fuel is consistent of residual heavy oil left after extraction of diesel or other light hydrocarbons from crude oil. There are three different grades of bunker fuel named grade A, B, and C. The grade C often called heavy fuel oil, is the most viscous fuel which often requires heating or blending with some light oils to flow. The fuel is one of the cheapest fuel for the marine purposes (shippipedia, 2016).

According to Studies (2015), which reported the heavy fuel oil price monthly from 1990, the price of heavy fuel oil had the same trend as the rapeseed oil which comprise the most price in July 2008. Figure 6-3 indicates some of the data of (Studies, 2015). According to these data the price of heavy fuel oil on October 2015 was 254 \$/ton. Considering 1 \$=0.94 € and 41 MJ/kg heating value of HFO (MOTIVA, 2010), the price of 1 MWh of HFO is equal to 21 €. These prices are reported without any tax delivered in Rotterdam.

$$254 \frac{\$}{\text{ton}} \times \frac{0.94 \text{ €}}{1 \$} \times \frac{1 \text{ ton}}{1000 \text{ kg}} \times \frac{1 \text{ kg}}{41 \text{ MJ}} \times \frac{3600 \text{ MJ}}{1 \text{ MWh}} = 21 \frac{\text{€}}{\text{MWh}}$$

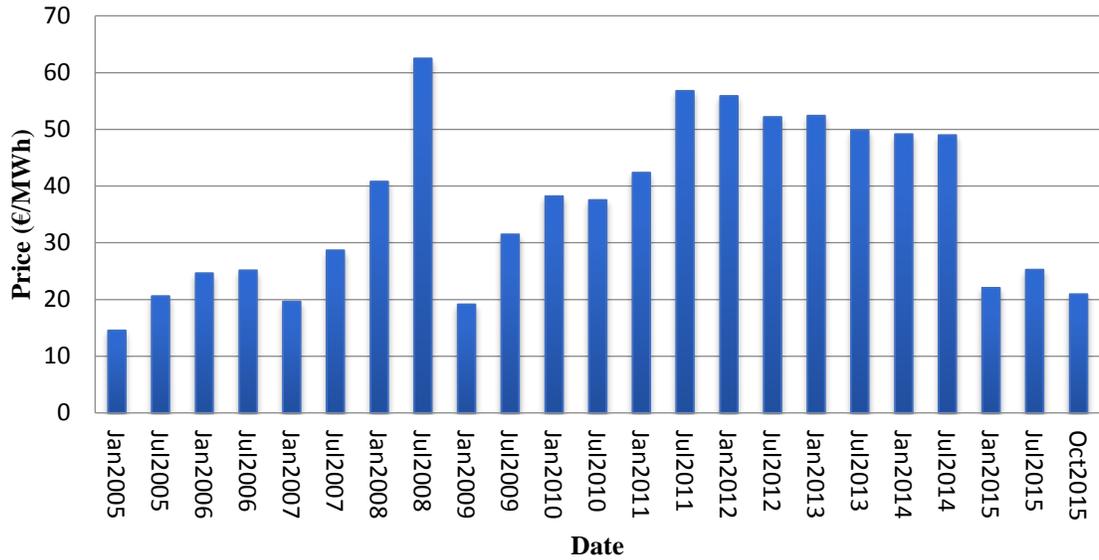


Figure 6-3. Heavy fuel oil price from Jan 2005 to present (Studies, 2015)

6.3 Price of slurry using HFO as the liquid carrier

Regardless of the maximum possible solid concentration and rheology measurements of the slurry containing HFO as the liquid phase, here it was trying to obtain the price and heating value of the same slurry that was made from rapeseed oil. As mentioned in section 6.2, HFO price on October 2015 was 21 €/MWh and the average heating value of that was reported as 41 MJ/kg. In addition, the price of torrefied wood in section 6.1 was calculated as 0.22 €/kg. Thus the price of 1 kg of 35 wt. % slurry will be:

$$\left(0.35 \times 0.22 \frac{\text{€}}{\text{kg}}\right) + \left(0.65 \times 0.24 \frac{\text{€}}{\text{kg}}\right) = 0.23 \frac{\text{€}}{\text{kg}}$$

And the heating value is calculated as:

$$\left(0.35 \times 23 \frac{\text{MJ}}{\text{kg}}\right) + \left(0.65 \times 41 \frac{\text{MJ}}{\text{kg}}\right) = 34.7 \frac{\text{MJ}}{\text{kg}}$$

Therefore, the price for 1 MWh is calculated as:

$$0.23 \frac{\text{€}}{\text{kg}} \times \frac{1 \text{ kg}}{41 \text{ MJ}} \times \frac{3600 \text{ MJ}}{1 \text{ MWh}} = 20.5 \frac{\text{€}}{\text{MWh}}$$

6.4 Summary

Summary of all the prices are shown in Table 6-1. It should be highlighted that the price of all the mentioned fuels excludes value added tax (VAT). It is estimated that the final price (including taxes) of the fuels will be doubled, thus in addition to high heating value and low viscosity, diesel fuel price is still competitive with the other fuel's cost. However, it needs to be reminded that one of the main disadvantages of the diesel fuel is the environmental impact which makes slurry fuels more interesting.

Table 6-1. Summary of the prices and different properties of different diesel fuels excluding tax

Fuel type	Price (€/MWh)	Heating value (MJ/kg)	Viscosity (cP)	Comments
Diesel Fuel	98.2	42.7	2.6 @ 40°C	Price in Finland (Dec 2015)
Rapeseed-oil	73	37	45 @ 40°C	-
HFO	21	41	ND*	-
LFO	62.42	44	ND	-
Torrefied wood-rapeseed oil slurry (35 wt. %)	64.04	32	480 @ 50°C	Exclude production cost
Torrefied wood-HFO slurry (35 wt. %)	20.5	35	ND	Exclude production cost

*ND: Not Determined

7 DIFFERENCES BETWEEN COAL AND BIO-COAL

Solid volume fraction, particle size, particle size distribution, particle shape, and bunches of other physical properties have direct influence on the maximum solid concentration of a slurry. However, there might be some other factors which make differences between coal and bio-coal maximum solid concentration. As mentioned in section 4.2.1, there are an overwhelming number of literatures about coal slurries which they had reported solid concentrations of more than 60 to 70 wt. % of their studies (Chen et al., 2011b), but in the present work the maximum solid concentration was 45 wt. %. In order to make a valuable and cost effective slurry fuel it should be tried to mix more solid to the liquid carrier otherwise the slurry making is not logical in terms of heating value and economy. Here, some literatures and their comments about this difference is reviewed and then the possible reasons of differences between coal concentration and bio-coal concentration are discussed.

Chen et al. (2011a), have studied the slurryability of lignite char, bituminous coal, and oil Mallee biochar in water and observed 65 wt. %, 56-64 wt. %, and only 42 wt. % solid concentration, respectively. They had suggested low amounts of zeta potential (low repulsion forces) is the reason of differences between different coal concentrations.

Yuchi et al. (2005), investigated the effect of coal characteristics on properties of coal slurries. In this research 16 different coal samples from different regions were used to make coal-water slurries and concluded that lignite has the least and Anthracite coal has the most slurryability among the other coal samples. Some of the coal sample analysis and their slurryability are shown in Table 7-1.

Mishra and Kanungo (2000), studied factors affecting the preparation of highly concentrated CWS and claim that the pore structure of coal is of vital significance in the slurryability of that. They also believed that according to the previous literatures, increasing the pH value could also improve the preparation of highly concentrated CWS. The reason lies in the negative surface energy supported by high zeta potential of coal in aqueous medium.

Table 7-1. Analysis and slurryability of different coals (Yuchi et al., 2005)

R	Coal rank	M_{ad}	A_d	V_{daf}	C (%)	O (%)	O/C	Slurry ability (%)
1	lignite	15.76	17.96	42.62	71.09	20.30	0.28	59.14
2	long flame	8.67	10.87	39.25	76.22	17.16	0.24	65.25
3	non-caking	7.77	5.08	36.31	80.18	13.93	0.17	64.44
4	weakly caking	1.90	34.75	41.47	78.39	13.49	0.17	70.33
5	gas	1.54	3.95	43.73	81.80	7.95	0.09	68.60
6	1/3 coking	1.26	6.67	36.17	85.35	7.62	0.09	72.32
7	fat	0.59	13.55	31.33	86.26	5.85	0.07	73.66
8	primary coking	1.09	17.08	22.56	89.14	3.88	0.04	76.09
9	lean	0.71	25.84	19.51	90.98	2.40	0.03	75.47
10	meager lean	0.83	13.70	17.21	89.80	3.84	0.04	74.82
11	anthracite	1.01	9.38	9.10	92.61	1.83	0.02	75.33

M_{ad}: moisture, air dry basis

A_d: ash, dry basis

V_{daf}: volatile, dry and ash free basis.

In addition, they had also reviewed the effect of oxygen content, especially in the hydroxyl and carboxyl functional groups which are the main factors in wettability of coal and claimed that highly concentrated CWS could be made more easily with hydrophobic coals than hydrophilic ones because in hydrophobic material less water is going inside the particles thus more concentration of particle is observed.

7.1 Possible affecting factors

The major factors making differences between coal and bio-coal seem to be:

1. More hydrophobicity (less oxygen to carbon ratio) of coal
2. More ash and minerals in coal
3. More zeta potential of coal
4. More apparent density of coal

Below, these answers are discussed more.

7.1.1 More hydrophobicity (less oxygen content) of coal

According to

Table 5-1 and Table 7-1, the value of oxygen to carbon ratio of "sample 1" which was used in this study was 0.08 while this value for different coals is varied from 0.02 to 0.28. On the other hand, the maximum solid concentration of "sample 1" was 45 wt. %, while coals indicate slurryability of more than 59 wt. %. By knowing all this information and also referring to Figure 7-1, oxygen to carbon ratio, i.e. hydrophobicity has some influences on the slurryability of the particles but is not the key factor in slurryability.

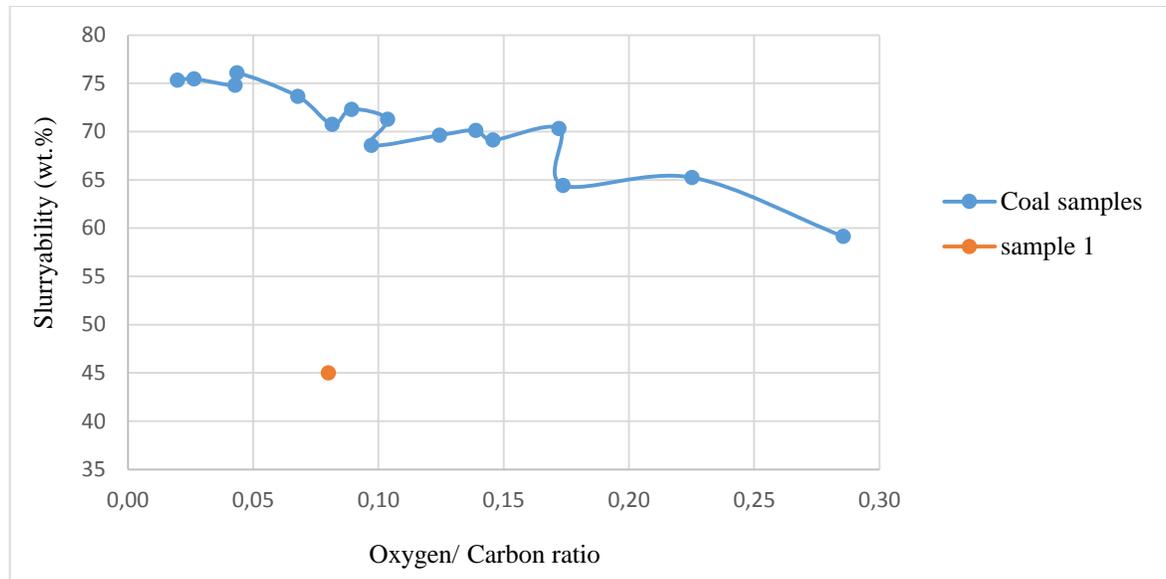


Figure 7-1. Slurryability vs O/C ratio of different coals (Yuchi et al., 2005) and "sample 1" of the present study

7.1.2 More ash and minerals in coal

Figure 7-2 represents the fact that minerals in the coal sample will not always lead to more slurryability as there can be seen a lot of fluctuations in this figure by increasing the ash content. This fact, makes the effect of ash more worthless.

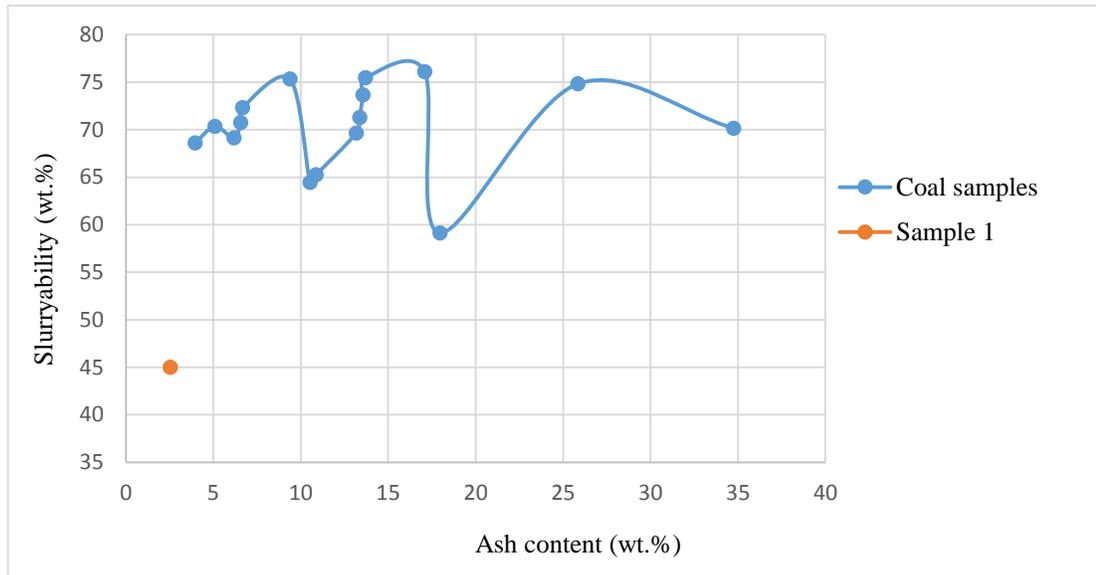


Figure 7-2. Slurryability vs ash content of different coals (Yuchi et al., 2005) and "sample 1" of the present study

7.1.3 More zeta potential of coal

Zeta potential is defined as the electrostatic potential near the surface of a particle in a suspension (Kulshreshtha et al., 2010). As reported previously, the zeta potential value is one of the most important factors in the stability of a suspension (Chen et al., 2011b, Wamankar and Murugan, 2015, Kalpesh and Sham, 2012). However, some researchers proposed the zeta potential might be responsible for low slurryability of a matter. The idea is that more zeta potential creates more repulsion forces between particles which not only increase stability, but also prevents particles to agglomerate thus more particles could be mixed into the slurry (Chen et al., 2011b).

Zeta potential value could be increased by mixing a wide range of additives into the slurry (Chen et al., 2011b, Dinçer et al., 2003).

7.1.4 More apparent density of coal

Bulk or apparent density is a property of particles differ from the true or solid density. According to Lehmann and Joseph (2012), apparent density is defined as " the density of the material consisting of multiple particles and includes the macro porosity within each particle and the inter-particle voids". Thus, particles may have almost the same solid density

and different apparent density. By the definition of apparent density, it is clear that the less porosity leads to more apparent density.

As claimed before, setting the conditions so that less water enters the particle porosity, is one of the major paths for increasing solid concentration in a slurry (Yuchi et al., 2005). It is believed that by increasing the apparent density, pores will be more compressed, thus less water could go through the pores. On the other hand, as previously reported by (Roh et al., 1995, Son and Kihm, 1998), the less surface area leads to less total hydrogen bonding between particles and water and also less capillary holding forces between solid particles. This reduction in adsorption forces may result in increasing the particle concentration as the liquid is less involved with the same amount of solid.

So far, no literature was found who investigates the effect of bulk density on the slurryability of nor coal neither bio-coal. Chen et al. (2011b), investigated the effect of solid density on slurryability and reported 55 wt. % solid concentration of nut coal having 1470 kg/m^3 solid density while sub-bituminous coal represents 54 wt. % solid concentration with solid density of 1330 kg/m^3 .

In case of accepting the effect of bulk density on slurryability, the next question would be the possibility of making bio-coal with more apparent density? Somerville and Jahanshahi (2015), had answered the question by setting some experiments on the bio-coal pyrolysis process. They had surveyed the effect of different temperatures and pressures on the porosity and apparent density of bio-coal. Regarding Figure 7-3 and Figure 7-4, porosity of bio-coal could improve from 0.5 to around 2.4 at low temperature of 300°C . Then the apparent density will increase from 680 to 1050 kg/m^3 at 300°C and 0.5 MPa compression.

Yet, it is not clear how much the apparent density influence the slurryability, but increasing about two times of the bulk density could have a remarkable effect on slurryability. More investigations are needed to study this issue.

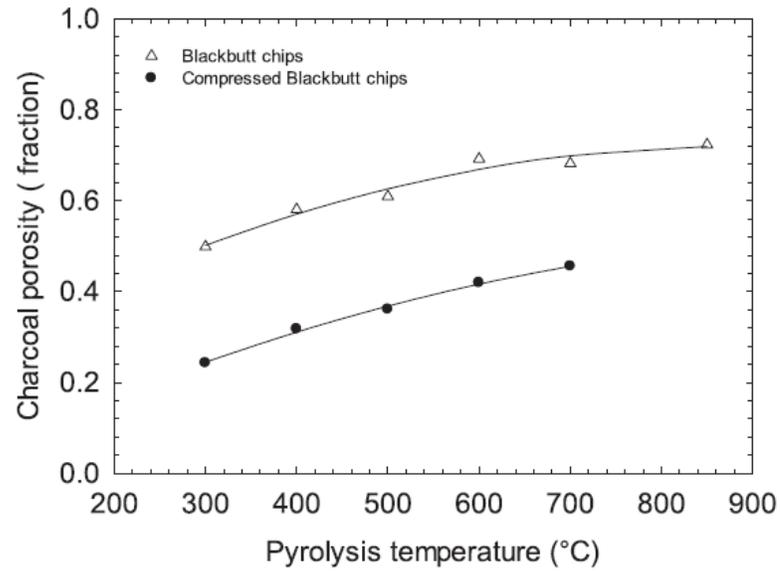


Figure 7-3. Effect of pyrolysis temperature and compression on blackbutt chips porosity. Compression is done at 0.5 MPa (Somerville and Jahanshahi, 2015)

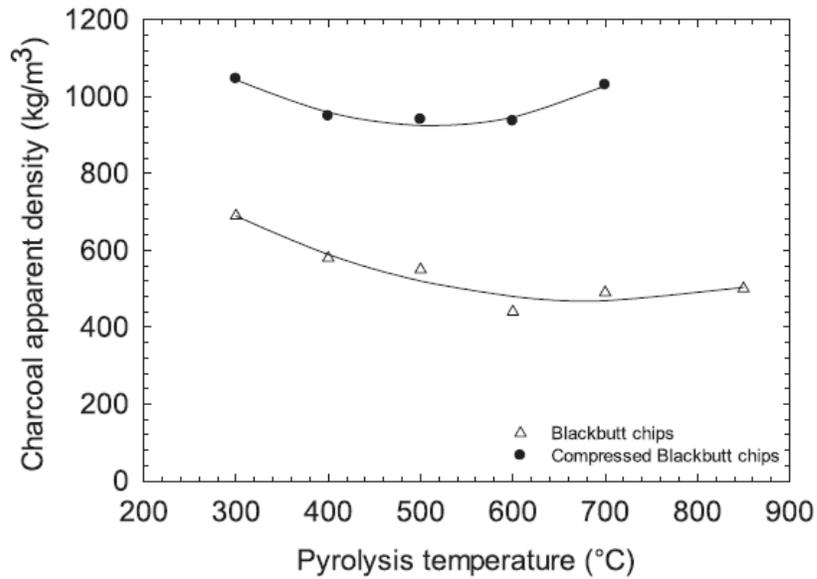


Figure 7-4. Effect of pyrolysis temperature and compression on blackbutt chips apparent density. Compression is done at 0.5 MPa (Somerville and Jahanshahi, 2015)

8 SUMMARY AND CONCLUSION

The ultimate goal of this study was to determine the feasibility of preparation and using the bio-coal slurry in large diesel engines. Rudolf Diesel proposed different fuel types to use in his invented IC engine, but so far, cheap price and high quality properties of fossil fuels had stopped loads of research on the alternative fuels. Today, by increasing concerns about the climate change and environmental impact of fossil fuels, clean energies have attracted the interests to use more environmentally friendly fuels.

Diesel engines require liquid fuels while the abundant potential of clean energy, i.e. biomass, is in the form of solid. Considering coal slurry which is used as a liquid fuel for some boilers and furnaces, and also acceptable heating value of the products of biomass thermal conversion, these products could be a good substitute to prepare the slurry fuels.

In the current study, bio-coal slurries were prepared empirically in order to investigate the effect of solid type, particle size distribution, solid concentration, liquid carrier type, and high temperature on the viscosity behavior of the slurry. The maximum solid concentrations and also the viscosity of all the slurries at three different shear rates were recorded. In addition, for slurries containing rapeseed oil as the liquid carrier, the effect of increasing temperature on the maximum solid concentration and viscosity value was investigated.

Slurries made by "sample 1" showed the highest solid concentration in both liquid carriers amongst the other samples by around 45wt. % maximum solid content of the flowable slurry. Also for "sample 3" the maximum solid concentration was the same in both liquids with only 23 wt. %, while it differs for "sample 2" slurry since its maximum solid concentration was 28 wt. % in water and 38wt. % in rapeseed oil slurries.

The results show that for all three samples the less particle size leads to the less viscosity value in case of rapeseed oil slurries. In contrast, in water slurries the situation is complicated. In order to obtain the least viscosity values, the optimum particle size is $63\mu\text{m} < \text{PSD} < 100\mu\text{m}$ for the "sample 1", $38\mu\text{m} < \text{PSD} < 50\mu\text{m}$ for the "sample 2" and $0 < \text{PSD} < 38\mu\text{m}$ for the "sample 3".

The high temperature of 50°C to 70°C does not have a drastic effect on the maximum solid amount, but has vital influence on the viscosity values of rapeseed oil slurries. In the case of "sample 1", by raising the temperature from 21°C to 70°C, the viscosity values decrease to about 36% of the initial value in the slurries containing 35 and 40 wt. % at the spindle's speed of 100 RPM. For instance, at 40 wt. % the viscosity value at 21°C is 3730 cP while at 70°C is 1350 cP. For "sample 2" the viscosity reduction in the same temperature range is around 45-50% of the initial value. The viscosity value of "sample 3" reduces around 50% when raising the temperature from 21 to 60°C.

Besides high energy density and relatively low price, bio-coal is an environmentally friendly energy source which is growing its share of energy production rapidly. Even though there are some reports about the bio-coal slurry preparation and properties, this is in the initial phase of research which requires the vast majority of investigations.

Considering the ultimate and proximate analysis and physical properties of the samples in one hand, and differences in maximum solid concentration and viscosity behavior of the slurries in the other hand, results in a very complex and confusing relationship between various factors. For instance, hydrophobicity of the solid was reported as one of the main factors for improving the maximum solid concentration while according to the experiments done during this work, despite "sample 3" contains more carbon and oxygen to carbon ration than "sample 2", the slurryability of "sample 2" is more than "sample 3" in both liquid carriers. However, there might be some other factors affecting these results which confirm complexity of the relations.

There are many studies investigated the effect of additives on viscosity reduction and they obtained very good results. Basically, using additives were out of scope of this project, otherwise the stability and the viscosity of solid may improve which result in decreasing the problems in pumping and atomization of the slurry fuels.

Ash contents in the slurry are also the other challenge which may cause a lot of unexpected problems when using bio-coal slurry as a fuel in a diesel engine. Some literatures were mentioned about ash removal in this work, but still it is needed to investigate more about

the effects of ash on engine parts and the optimal ways to reduce the ash content in slurry fuels.

The estimated prices of the slurry were measured and compared with the other diesel engine fuels. This is obvious that the price of bio-coal slurry is still higher than diesel fuel and HFO when using rapeseed oil as the liquid carrier. It is believed that by increasing the solid concentration and also using water as the liquid phase, it is possible to reduce the slurry price so that it can compete with the other fuels.

Generally, the coal concentration in the slurry fuel is higher than bio-coal concentration. The results of theoretical studies done during this project on the origin of the differences, indicates that the higher apparent density of coal is the main responsible factor. More apparent density decreases the total surface area of the matter and also reduces pores of the particles which prevent liquids go inside the pores. More study is needed to determine the real effect of apparent density on the maximum solid concentration.

In conclusion, bio-coal slurry is a new, clean, and beneficial way to use biomass while drastically reduce greenhouse emissions. Bio-coal slurry is in its initial steps of investigation and more studies dealing with methods to increase solid loading and decreasing viscosity value in order to have a good pumping and atomization quality is needed. More research on diverse bio-coals with different raw material sources is recommended in order to find out the exact relationship between the amounts of elements such as carbon to the properties of the slurry. In addition, future research on the effect of bulk density on the solid loading is highly recommended. In order to increase the heating value and reduce the viscosity values, blend of existing diesel fuels with the slurry fuel seems to be beneficial while this might meet some new problems as it creates a ternary mixture and requires a surfactant.

REFERENCES

- Abdullah, H., Mourant, D., Li, C.-Z. & Wu, H. 2010. Bioslurry as a fuel. 3. Fuel and rheological properties of bioslurry prepared from the bio-oil and biochar of mallee biomass fast pyrolysis. *Energy & Fuels*, 24, 5669-5676.
- Al-Amrousi, F. A., Al-Sabagh, A. M. & Osman, M. M. 1996. Physicochemical characterization of emulsion fuel from fuel oil-water-charcoal and surfactants. *Fuel*, 75, 1193-1198.
- Altin, R., Cetinkaya, S. & Yücesu, H. S. 2001. The potential of using vegetable oil fuels as fuel for diesel engines. *Energy conversion and management*, 42, 529-538.
- ASTM 1999. ASTM D975: Standard Specification for Diesel Fuel Oils.
- Atesok, G., Dincer, H., Ozer, M. & Mutevellioglu, A. 2005. The effects of dispersants (PSS-NSF) used in coal-water slurries on the grindability of coals of different structures. *Fuel*, 84, 801-808.
- Awang, R. & May, C. Y. 2009. Charcoal-oil mixture as an alternative fuel: A preliminary study. *American Journal of Applied Sciences*, 6, 393.
- Bagramov, G. 2010. *Economy of converting wood to biocoal*. Lappeenranta University Of Technology.
- Boundy, B., Diegel, S. W., Wright, L. & Davis, S. C. Biomass Energy Data Book, US Dep. Of Energy, 2011. *ORNL/TM-2011/446*, <http://cta.ornl.gov/bedb/download.shtml>.
- Boylu, F., Dinçer, H. & Ateşok, G. 2004. Effect of coal particle size distribution, volume fraction and rank on the rheology of coal-water slurries. *Fuel Processing Technology*, 85, 241-250.
- Cai, Z., Narine, L. L., D'amato, A. & Aguilar, F. X. 2016. Attitudinal and revenue effects on non-industrial private forest owners' willingness-to-harvest timber and woody biomass. *Forest Policy and Economics*, 63, 52-61.
- Chen, Q., Zhou, J., Liu, B., Mei, Q. & Luo, Z. 2011a. Influence of torrefaction pretreatment on biomass gasification technology. *Chinese Science Bulletin*, 56, 1449-1456.
- Chen, R., Wilson, M., Leong, Y. K., Bryant, P., Yang, H. & Zhang, D. K. 2011b. Preparation and rheology of biochar, lignite char and coal slurry fuels. *Fuel*, 90, 1689-1695.

- Corrosionpedia. 2015. Available:
<https://www.corrosionpedia.com/definition/1153/volatile-matter> [Accessed 13 Dec 2015].
- Council, W. E. 2015. *Energy Resources* [Online]. Available:
<https://www.worldenergy.org/data/resources/resource/biomass/> [Accessed 13 Dec 2015].
- Cui, L., An, L. & Jiang, H. 2008. A novel process for preparation of an ultra-clean superfine coal–oil slurry. *Fuel*, 87, 2296-2303.
- Dinçer, H., Boylu, F., Sirkeci, A. A. & Ateşok, G. 2003. The effect of chemicals on the viscosity and stability of coal water slurries. *International Journal of Mineral Processing*, 70, 41-51.
- Donnelly, M. 2012. Biomass – Role in achieving the 20% target.
- Ellem, G. K. & Mulligan, C. J. 2012. Biomass char as a fuel for internal combustion engines. *Asia-Pacific Journal of Chemical Engineering*, 7, 769-776.
- Esnouf, C. 1991. Charcoal–Water Slurries: State of the Art and Future Prospects. *Biomass Pyrolysis Liquids Upgrading and Utilization*. Springer.
- FAO 1985. Industrial Charcoal Making. FAO.
- FAO 2012. *Forest products*, FAO.
- Flynn, P., Leonard, G. & Mehan, R. 1989. Component wear in coal-fueled diesel engines. *Journal of Engineering for Gas Turbines and Power*, 111, 521-529.
- Frank Rosillo-Calle, L. P., Arnaldo Walter, 2009. A global overview of vegetable oils, with reference to biodiesel. Iea bioenergy.
- Fuel-Prices-Europe.Info. 2015. *fuel prices* [Online]. Available:
<http://www.fuel-prices-europe.info/index.php?sort=6> [Accessed 10 Dec 2015].
- Fund, I. M. 2015. *Rapeseed oil price* [Online]. Available:
<http://www.imf.org/external/index.htm> [Accessed 13 Dec 2015].
- Gravelsins, R. J. 1998. Studies of grinding of wood and bark-wood mixtures with the Szego mill.
- Hopkins, C. Using Torrefied Wood for Electricity and Pellet Production in South Carolina. North Carolina State University.

- Kalpesh, V. & Sham, D. 2012. Review of charcoal-Diesel slurry: An Alternative fuel for compression Ignition Engine. *International Journal of Advanced Engineering Research and Studies*, 1, 143-147.
- Kan, T., Strezov, V. & Evans, T. J. 2016. Lignocellulosic biomass pyrolysis: A review of product properties and effects of pyrolysis parameters. *Renewable and Sustainable Energy Reviews*, 57, 1126-1140.
- Koppejan, J., Sokhansanj, S., Melin, S. & Madrali, S. 2012. Status overview of torrefaction technologies. IEA bioenergy task. 1-54.
- Kulshreshtha, A. K., Singh, O. N. & Wall, G. M. 2010. Pharmaceutical suspensions. *From Formulation Development to Manufacturing*. Springer, New York.
- Lee, S., Speight, J. G. & Loyalka, S. K. 2014. *Handbook of alternative fuel technologies*, crc Press.
- Lefebvre, A. H. 2010. *Gas turbine combustion*, CRC Press.
- Lehmann, J. & Joseph, S. 2012. *Biochar for environmental management: science and technology*, Routledge.
- Long, J. M. 2014. *Development of a Charcoal Slurry for Compression Ignition Internal Combustion Engines*. Doctor of Philosophy, North Carolina State University.
- Meijer, R. 2011. Overview of European torrefaction landscape. Proceedings of the EPRI Biomass Torrefaction Workshop. 13-14.
- Mishra, S. & Kanungo, S. 2000. Factor Affecting the Preparation of Highly Concentrated Coal-Water Slurry (HCCWS). *Journal of Scientific and Industrial Research*, 59, 765-790.
- Motiva 2010. Polttoaineiden lämpöarvot, hyötysuhteet ja hiilidioksidin ominaispäästökertoimet sekä energian hinnat. [Online]. Available: [http:// www.motiva.fi](http://www.motiva.fi) [Accessed 10 Dec 2015].
- Mulhem, B., Schulte, G. & Fritsching, U. 2006. Solid-liquid separation in suspension atomization. *Chemical Engineering Science*, 61, 2582-2589.
- Murugesan, A., Umarani, C., Subramanian, R. & Nedunchezian, N. 2009. Bio-diesel as an alternative fuel for diesel engines—A review. *Renewable and Sustainable Energy Reviews*, 13, 653-662.

- N'kpomin, A., Boni, A., Antonini, G. & François, O. 1995. The deashed charcoal—oil—water mixture: a liquid fuel for biomass energetical valorization. *The Chemical Engineering Journal and the Biochemical Engineering Journal*, 60, 49-54.
- National Energy Technology Laboratory 2007. Clean Coal Diesel Demonstration Project.
- Nordwaeger, M., H. K., Li. C. 2010. Parametris Study of Pilot-Scale Biomass Torrefaction. *18th European Biomass Conference and Exhibition*.
- Noureddini, H., Teoh, B. & Clements, L. D. 1992. Viscosities of vegetable oils and fatty acids. *Journal of the American Oil Chemists Society*, 69, 1189-1191.
- Papachristodoulou, G. & Trass, O. 1987. Coal slurry fuel technology. *The Canadian Journal of Chemical Engineering*, 65, 177-201.
- Patton, R., Steele, P. & Yu, F. 2009. Coal vs. Charcoal-fueled Diesel Engines: A Review. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 32, 315-322.
- Prins, M. J. 2005. *Thermodynamic analysis of biomass gasification and torrefaction*, Netherlands, Ridderprint bv.
- Roh, N.-S., Shin, D.-H., Kim, D.-C. & Kim, J.-D. 1995. Rheological behaviour of coal-water mixtures. 1. Effects of coal type, loading and particle size. *Fuel*, 74, 1220-1225.
- Rousset, P., Macedo, L., Commandré, J. M. & Moreira, A. 2012. Biomass torrefaction under different oxygen concentrations and its effect on the composition of the solid by-product. *Journal of Analytical and Applied Pyrolysis*, 96, 86-91.
- Schorr, C., Muinonen, M. & Nurminen, F. 2012. Torrefaction of biomass. *Publication no. Graanintie*, 5, 50190.
- Shippedia 2016. Marine Fuel (ISO 8217).[Online]. Available: <http://www.shippiedia.com/marine-fuels/> [Accessed 10 Dec 2015].
- Shivaram, P., Leong, Y. K., Yang, H. & Zhang, D. K. 2013. Flow and yield stress behaviour of ultrafine Mallee biochar slurry fuels: The effect of particle size distribution and additives. *Fuel*, 104, 326-332.
- Soloiu, V., Lewis, J., Yoshihara, Y. & Nishiwaki, K. 2011. Combustion characteristics of a charcoal slurry in a direct injection diesel engine and the impact on the injection system performance. *Energy*, 36, 4353-4371.

- Soloiu, V. A., Yoshihara, Y., Nishiwaki, K., Hiraoka, M., Hayashi, K. & Shinchi, K. 2005. The development of a Bio-COM fuel for diesel generation systems. Proc. 7th International Symposium on Marine Engineering, CD-ROM. Tokyo, Japan: Japan Institution of Marine Engineering.
- Somerville, M. & Jahanshahi, S. 2015. The effect of temperature and compression during pyrolysis on the density of charcoal made from Australian eucalypt wood. *Renewable Energy*, 80, 471-478.
- Son, S. & Kihm, K. D. 1998. Effect of coal particle size on coal-water slurry (CWS) atomization. *Atomization and Sprays*, 8.
- Sonntag, R. E., Borgnakke, C., Van Wylen, G. J. & Van Wyk, S. 1998. *Fundamentals of thermodynamics*, Wiley New York.
- Speight, J. G. 2012. *The chemistry and technology of coal*, CRC Press.
- Studies. 2015. *International prices of imported raw materials - Heavy fuel oil (Rotterdam)* [Online]. Available: <http://www.insee.fr/en/bases-de-donnees/bsweb/serie.asp?idbank=001642883> [Accessed 13 Dec 2015].
- Tilastokeskus 2016. Consumer Prices of Liquid Fuels
- Tsai, S. C. & Vu, T. 1987. Atomization of coal-water slurry using twin-fluid jet atomizer. *Fuel*, 66, 1596-1602.
- Tse, H., Leung, C. W. & Cheung, C. S. 2015. Investigation on the combustion characteristics and particulate emissions from a diesel engine fueled with diesel-biodiesel-ethanol blends. *Energy*, 83, 343-350.
- UFA. 2015. *Diesel fuel characteristics and resources* [Online]. Available: http://www.ufa.com/petroleum/resources/fuel/diesel_fuel_resources.aspx [Accessed 14 Dec 2015].
- Ugwu, K. & Eze, S. 2014. Physicochemical and rheological characteristics of charcoal slurry fuel. *Journal homepage: www. IJEE. IEEFoundation. org*, 5, 119-126.
- Van Der Stelt, M. J. C., Gerhauser, H., Kiel, J. H. A. & Ptasinski, K. J. 2011. Biomass upgrading by torrefaction for the production of biofuels: A review. *Biomass and Bioenergy*.
- Wamankar, A. K. & Murugan, S. 2015. Review on production, characterisation and utilisation of solid fuels in diesel engines. *Renewable and Sustainable Energy Reviews*, 51, 249-262.

WÄRTSILÄ 2010. Wärtsilä 46F.

Wilén, C., Sipilä, K., Tuomi, S., Hiltunen, I. & Lindfors, C. 2014. *Wood Torrefaction: Market Prospects and Integration with the Forest and Energy Industry.*

Yuchi, W., Li, B., Li, W. & Chen, H. 2005. Effects of Coal Characteristics on the Properties of Coal Water Slurry. *Coal Preparation*, 25, 239-249.

Zhao, H., Liu, H.-F., Xu, J.-L., Li, W.-F. & Cheng, W. 2012. Breakup and atomization of a round coal water slurry jet by an annular air jet. *Chemical Engineering Science*, 78, 63-74.

APPENDIX

Viscosity values of all the slurries.

R	Solid Sample No.	PSD (μm)	Liquid type	Solid Concentration (wt. %)	Temperature ($^{\circ}\text{C}$)	Viscosity (cP)		
						Spindle's speed (RPM)		
						6	60	100
1	1	0 <PSD< 38	Water	25	21	333	67	50
2	1	0 <PSD< 38	Water	35	21	667	133	120
3	1	0 <PSD< 38	Water	37	21	1000	233	180
4	1	0 <PSD< 38	Water	40	21	2833	500	280
5	1	0 <PSD< 38	Water	43	21	3666	633	460
6	1	38 <PSD< 50	Water	25	21	500	100	60
7	1	38 <PSD< 50	Water	35	21	667	200	160
8	1	38 <PSD< 50	Water	37	21	1000	233	180
9	1	38 <PSD< 50	Water	40	21	2333	367	260
10	1	38 <PSD< 50	Water	43	21	3333	500	370
11	1	50 <PSD< 63	Water	25	21	500	67	40
12	1	50 <PSD< 63	Water	35	21	833	200	140
13	1	50 <PSD< 63	Water	40	21	Highly viscous slurry		
14	1	50 <PSD< 63	Water	43	21	Highly viscous slurry		
15	1	63 <PSD<100	Water	25	21	333	67	40
16	1	63 <PSD<100	Water	35	21	667	167	120
17	1	63 <PSD<100	Water	37	21	667	200	160
18	1	63 <PSD<100	Water	40	21	1000	267	180
19	1	63 <PSD<100	Water	43	21	1500	416	270
20	2	0 <PSD< 38	Water	25	21	2166	383	320
21	2	38 <PSD< 50	Water	25	21	1333	267	200
22	2	50 <PSD< 63	Water	25	21	1833	317	230

R	Solid Sample No.	PSD (μm)	Liquid type	Solid Concentration (wt. %)	Temperature ($^{\circ}\text{C}$)	Viscosity (cP)		
						Spindle's speed (RPM)		
						6	60	100
23	2	63 <PSD< 100	Water	25	21	2500	350	240
24	3	0 <PSD< 38	Water	20	21	667	216,7	140
25	3	0 <PSD< 38	Water	15	21	500	67	40
26	3	38 <PSD< 50	Water	15	21	667	133	100
27	3	50 <PSD< 63	Water	15	21	667	133	100
28	3	63 <PSD< 100	Water	15	21	Highly viscous slurry		
29	1	0 <PSD< 38	Oil	25	21	667	333	240
30	1	0 <PSD< 38	Oil	30	21	1500	617	560
31	1	0 <PSD< 38	Oil	35	21	3666	1450	1300
32	1	0 <PSD< 38	Oil	37	21	4000	1833	1600
33	1	0 <PSD< 38	Oil	40	21	10000	4333	3730
34	1	38 <PSD< 50	Oil	25	21	667	333	280
35	1	38 <PSD< 50	Oil	30	21	1333	600	590
36	1	38 <PSD< 50	Oil	37	21	4833	2683	2260
37	1	38 <PSD< 50	Oil	40	21	11000	4833	4160
38	1	38 <PSD< 50	Oil	43	21	27000	9916	5900
39	1	63 <PSD<100	Oil	30	21	4000	1933	1680
40	1	63 <PSD<100	Oil	40	21	10660	3783	3320
41	2	0 <PSD< 38	Oil	30	21	2333	1000	880
42	2	38 <PSD< 50	Oil	30	21	4333	1983	1710
43	2	50 <PSD< 63	Oil	30	21	5166	2116	1800
44	2	63 <PSD<100	Oil	30	21	2333	1066	940
45	2	0 <PSD< 38	Oil	35	21	6666	2516	2080
46	3	0 <PSD< 38	Oil	20	21	2666	1166	980
47	3	38 <PSD< 50	Oil	20	21	11000	3600	2800

R	Solid Sample No.	PSD (μm)	Liquid type	Solid Concentration (wt. %)	Temperature ($^{\circ}\text{C}$)	Viscosity (cP)		
						Spindle's speed (RPM)		
						6	60	100
48	3	50 <PSD< 63	Oil	15	21	3000	1100	850
49	3	50 <PSD< 63	Oil	20	21	Highly viscous slurry		
50	3	63 <PSD<100	Oil	15	21	Highly viscous slurry		
51	1	0 <PSD< 38	Oil	35	50	1666	600	480
52	1	0 <PSD< 38	Oil	40	50	5166	1766	1480
53	1	0 <PSD< 38	Oil	47	50	Highly viscous slurry		
54	1	0 <PSD< 38	Oil	35	60	1333	400	320
55	1	0 <PSD< 38	Oil	40	60	5500	1733	1440
56	1	0 <PSD< 38	Oil	47	60	Highly viscous slurry		
57	1	0 <PSD< 38	Oil	35	70	1000	266	210
58	1	0 <PSD< 38	Oil	40	70	5000	1583	1350
59	1	38 <PSD< 50	Oil	35	50	2133	813	700
60	1	38 <PSD< 50	Oil	40	50	7500	2833	2300
61	1	38 <PSD< 50	Oil	44	50	Highly viscous slurry		
62	1	63 <PSD<100	Oil	33	50	2000	1333	1240
63	2	0 <PSD< 38	Oil	30	50	3333	766	600
64	2	0 <PSD< 38	Oil	35	50	5666	1766	1420
65	2	0 <PSD< 38	Oil	37	50	Highly viscous slurry		
66	2	0 <PSD< 38	Oil	30	60	2666	666	480
67	2	0 <PSD< 38	Oil	35	60	5333	1650	1310
68	2	0 <PSD< 38	Oil	37	60	Highly viscous slurry		
69	2	0 <PSD< 38	Oil	30	70	1333	500	400
70	2	0 <PSD< 38	Oil	35	70	5000	1400	1060
71	3	0 <PSD< 38	Oil	20	50	2333	717	580
72	3	0 <PSD< 38	Oil	20	60	1666	600	480