



The University of
Nottingham

**BUBBLING FLUIDIZED BED BIOMASS GASIFICATION
AND PRODUCT GAS CLEANING**

**A thesis submitted to The University of Nottingham
for the degree of Doctor of Philosophy**

By

Irfan Ul Hai

BSc, MSc, MPhil

Supervisors

Prof. Hao Liu and Prof. Saffa B. Riffat

Institute of Sustainable Energy Technology
Department of Architecture and Built Environment
University of Nottingham, UK

December 2017

ACKNOWLEDGEMENTS

First of all, gratitude to Almighty Allah for choosing me to avail this opportunity, also I would like to express my insightful gratefulness to my supervisors Prof. Hao Liu and Prof. Saffa B. Riffat for giving me opportunity to join their research group and for their support and help to understand the fascinating field of Biomass Gasification Technology.

I would like to thank my fellow doctoral students: Dr Wenbin Zhang, Dr Joel Channy, Dr Andrew Rollinson & Dr Farooq Sher for their feedback, cooperation and of course friendship. In addition I would like to express my gratitude to the lab staff Mr. Dave Oliver, Mr. Dave Taylor and Mr. Johnny for their support in smooth running the lab work. I am also grateful to all members of my committee for their patience and support in overcoming numerous obstacles I have been facing through my research.

I would like to thank my friends for accepting nothing less than excellence from me. Last but not the least, I would like to thank my family: my parents and to my brothers and sister for supporting me spiritually throughout writing this thesis and my life in general. I would also like to say a big thank you to my family for their love, moral support, encouragement, patience and bearing my absence, specially to my father who is always there for me at each and every moment. Thanks to my wife to join me in the UK and gifting a cute daughter and son.

ABSTRACT

Biomass is used for fuel by humanity from prehistoric times. With the passage of time and to meet the energy needs, non-conventional ways of utilizing the conventional sources became an interest with use of technologies. Biomass gasification is a proven technology that can economically use alternative energy resource of “Carbon Neutral”. Biomass product gas from biomass gasification is composed of CO, CO₂, CH₄, H₂, other hydrocarbons, traces of other components and tar from biomass gasification. Fluidized bed gasification is one of the promising technologies to achieve high thermal conversion efficiency as it takes great advantages of fluidization in terms of uniform temperature profiles and excellent gas-solid interactions. The present research is aimed to evaluate the performance of a bubbling fluidized bed biomass gasifier for product gas production composition using air as gasification agent and SRC willow chips as biomass. Particle capture efficiency of the mop fan and an effect of different operating conditions such as bed temperature, equivalent ratio on the product gas composition and heating value are also investigated at Institute of Sustainable Energy Technology, University of Nottingham. The concentrations of particulate matter in the product gas before and after the mop fan cleaning unit are measured to assess the performance of the cleaning unit. Different fan rotating speeds and different flow rates of spray water are used to optimise the particle removal efficiency of this unit. It has been found that the mop fan cleaning unit has achieved an efficiency of 90% in removing particle matters and an efficiency of more than 80% in removing N-species presented in the product gas. Tars appear as a major issue in the product gas and should be removed from the product gas before they get condensed in the equipments which utilise product

gas. Tar arrest techniques were successfully tested in this investigation such as woodchips bed, water spray and mop fan. The synergic effect of tar removal of water spray and mop fan found to be more effective in removing tars as if used individually. Different spray water amounts were used with a constant fan speed for keen observation of tars' solubility in the water and found reasonable removal of tars from product gas.

Table of contents

<i>Table of contents</i>	iv
LIST OF FIGURES	IX
LIST OF TABLES	XIV
LIST OF PUBLICATIONS	XVII
CHAPTER 1 INTRODUCTION	1
1.1 <i>Humans, energy and fossil fuel</i>	1
1.2 <i>Current world energy scenario</i>	3
1.3 <i>Fossil fuels' consumption as energy source</i>	4
1.3.1 <i>Fossil fuel and environment</i>	6
1.4 <i>Energy for planet earth</i>	7
1.5 <i>Need of renewable energy</i>	8
1.6 <i>Biomass as an alternative energy source</i>	9
1.7 <i>Biomass to energy conversion technologies</i>	10
1.8 <i>Biomass gasification, gasifier and product gas</i>	12
1.9 <i>Objectives</i>	14
CHAPTER 2 REVIEW OF LITERATURE	15
2.1 <i>Energy synthesis from the biomass</i>	15
2.2 <i>Biomass gasification</i>	19
2.2.1 <i>Biomass gasification chemistry</i>	21
2.2.1.1 <i>Oxidation or exothermic reactions</i>	23
2.2.1.2 <i>Reduction or endothermic reactions</i>	23
2.3 <i>Biomass gasifier types</i>	24
2.3.1 <i>Fixed bed gasifiers</i>	25
2.3.1.1 <i>Updraft or counter-current fixed bed gasifiers</i>	26

2.3.1.2 Downdraft or co-current fixed bed gasifiers.....	27
2.3.2 <i>Fluidized bed gasifiers</i>	29
2.3.2.1 Bubbling fluidized bed gasifier.....	30
2.3.2.2 Circulating fluidized bed gasifier.....	32
2.4 BIOMASS PROPERTIES AS A FUEL SOURCE FOR GASIFICATION.....	35
2.4.1 <i>Moisture contents</i>	35
2.4.2 <i>Calorific value</i>	38
2.4.3 <i>Volatile matter contents</i>	39
2.4.4 <i>Ash contents</i>	39
2.4.5 <i>Alkali metal content</i>	40
2.4.6 <i>Cellulose / lignin ratio</i>	41
2.4.7 <i>Biomass proximate and biomass ultimate analyses</i>	42
2.5 <i>Product Gas</i>	44
2.5.1 <i>Factors affecting product gas composition</i>	45
2.5.1.1 Equivalence ratio (ER).....	46
2.5.1.2 Temperature	50
2.5.1.3 Biomass elemental composition.....	52
2.5.1.4 Biomass particle size.....	53
2.5.1.5 Gasifier pressure.....	55
2.5.1.6 Gasification medium and secondary air.....	56
2.6 <i>Tar and biomass gasification</i>	58
2.6.1 <i>Tar classification</i>	58
2.6.2 <i>Tar formation in biomass gasification</i>	60
2.6.3 <i>Tar treatment (tar removal) from the product gas</i>	63
2.6.3.1 Primary (in-situ) tar removal methods	64
2.6.3.2 Secondary (post gasifier) tar removal methods.....	69

CHAPTER 3 EXPERIMENTAL SETUP	75
3.1 GASIFICATION.....	75
3.1.1 Gasifier description.....	75
3.1.2 Biomass feeding unit	77
3.1.3. Auger	80
3.1.4 Gasifier reactor.....	81
3.1.5 Cyclone	82
3.1.6 Gas cooler and combustor.....	82
3.1.7 Mop fan (the gas cleaning unit)	83
3.2 Gasification operating conditions.....	85
3.2.1 Bed material and fluidization	85
3.2.2 Gasifier operating conditions	88
3.3 PRODUCT GAS COMPOSITION ANALYZERS	89
3.4 DETERMINATION OF CARBON CONVERSION	91
 CHAPTER 4 BIOMASS GASIFICATION AND PRODUCT GAS COMPOSITION ANALYSES.....	 92
4.2 Biomass feeding calibration	93
4.2 Gasification temperature profile and equivalence ratio (ER)	97
4.3 Product Gas Composition Analysis	102
4.3.1 Online analysis	103
4.3.2 Gas Chromatography (GC) analysis	110
4.4 Gasifier performance evaluation.....	110
4.4.1 Determination of carbon conversion.....	111
4.4.2 Estimation of higher heating value (HHV), lower heating value and cold gas efficiency at different ERs	114

CHAPTER 5 PRODUCT GAS CLEANING STRATEGIES FOR PARTICLES	122
5.1 <i>Product gas cleaning strategies</i>	123
5.1.1 <i>Particulate matter capture</i>	123
5.1.1.1 <i>Particulate matter capture with mop fan cleaning unit</i>	124
5.1.1.1.2 <i>Particulate capture with water spray</i>	128
5.1.1.1.3 <i>Particulate capture by mop fan unit with water spray</i>	130
5.1.2 <i>Removal of NO_x, HCN and NH₃ and other nitrogen species from the product gas</i>	133
5.2 <i>Summary</i>	136
 CHAPTER 6 TAR ARREST FROM THE PRODUCT GAS	 139
6.1 <i>Tar and Biomass Gasification</i>	139
6.2 <i>Major contaminants of biomass gasification</i>	140
6.3 <i>Importance of tar removal from the product gas</i>	142
6.4 <i>Experimental set up for tar removal from the product gas</i>	142
6.4.1 <i>Product gas sampling for tar collection</i>	144
6.4.2 <i>Tar sampling and collection</i>	145
6.5 <i>Tar removal techniques from the product gas</i>	148
6.5.1 <i>Dry scrubbing</i>	148
6.5.1.1 <i>Secondary woodchips bed</i>	149
a. <i>Small wood chips bed</i>	150
b. <i>Large wood chips bed</i>	154
BIO-CHAR BED	160
MOP FAN CLEANING UNIT	162
6.5.2 <i>Mop fan with water spray</i>	163
6.5.2.1 <i>Tar capture by mop fan with water spray</i>	163

CHAPTER 7 CONCLUSIONS AND FUTURE WORK RECOMMENDATIONS.....	171
<i>7.1 Conclusions</i>	171
<i>7.2 Future work and recommendations</i>	174
<i>References</i>	175

List of Figures

Figure 1-1: Renewable and non-renewable energy resources.....	2
Figure 1- 2: World energy consumption: Current scenario and future trends (IEA 2016).	4
Figure 1- 3: World energy use by fuel types 1965–2014 (IEA 2014).	6
Figure 1- 4: Greenhouse gases and global warming phenomenon (Trenberth <i>et al.</i> , 2009).	7
Figure 1- 5: Photosynthesis in plants (Singhal <i>et al.</i> , 2012).	8
Figure 1- 6: Different biomasses as source for energy production (Boléo, 2011).....	10
Figure 2-1: Main biomass to energy conversion routes (Turkenburg <i>et al.</i> , 2000).	15
Figure 2-2: Stages of biomass combustion (Le, 2012).	16
Figure 2-3: Schematic of biomass gasification stages(Alberto Gómez-Barea & Leckner, 2010).	20
Figure 2-4: Overview of different gasification technologies (Alberto Gómez-Barea & Leckner, 2010).	22
Figure 2-5: Overview of different gasification technologies.	25
Figure 2-6: Updraft or counter-current fixed bed gasifier.	27
Figure 2-7: Downdraft or co-current fixed bed gasifier.....	28
Figure 2-8: Bubbling fluidized bed biomass gasifier.....	31

Figure 2-9: Circulating fluidized bed gasifier (Lim 2007)..... 33

Figure 2-10: Schematic of particulate matter formation during biomass gasification (Gustafsson, 2011) 40

Figure 2-11: Effect of ER on gas components' concentration (Kook *et al.*, 2016). 48

Figure 2-12: Gas yield as a function of gasification temperature (Rapagna et al., 2000). 50

Figure 2-13: Effect of fuel particle size in relation to the product gas quality in an entrained flow gasifier (Hernández *et al.* (2010) 54

Figure 2-14: Concentrations of product gas components as a function of pressure (Valin *et al.*, 2010). 55

Figure 2-15: Influence of reactor temperature on tar composition in (g/m³) for S/B ratio 1.2 at 0.25 MPa (Mayerhofer *et al.*, 2012). 67

Figure 2-16: Comparison of relative tar composition of pyrolysis and steam gasification at different temperatures (Aigner *et al.*, 2009)..... 68

Figure 3-1: Schematic of bubbling fluidized bed biomass gasifier..... 76

Figure 3-2: Stirrer and pressure gauge installed at woodchips hopper 77

Figure 3-3: Rectangle shaped woodchip feeder hopper..... 78

Figure 3-4: Cylindrical shaped woodchips feeder hopper. 79

Figure 3-5: Auger feeding wood chips to the gasification reactor from the feeder hopper..... 80

Figure 3-6: Bubbling fluidized bed gasifier reactor and cyclone..... 81

Figure 3-7: Schematic diagram of mop fan and its operation process..... 83

Figure 3-8: The mop fan used for product gas cleaning. 84

Figure 3-9: Bed material in the reactor. 86

Figure 3-10: Bubble initiation in the reactor..... 86

Figure 3-11: Air bubble rising in the reactor. 87

Figure 3-12: Air bubble burst in the reactor. 87

Figure 3-13: TSI DustTrak used to measure the concentration of dust particles (<http://www.jiahuazhongxin.com/>). 89

Figure 3-14: ABB online gas analysers equipped with sampling unit..... 90

Figure 3-15: HORIBA NO_x analyser. 91

Figure 4-1: Biomass feeding calibration at different screw feeder speeds. 96

Figure 4-2: Biomass feeding rate (g/h) comparison at different auger speeds. 97

Figure 4-3: Temperature profiles at different heights from main distribution plate in the gasifier reactor at ER 0.319..... 99

Figure 4-4: Temperature profiles at different heights from main distribution plate in the gasifier reactor at ER 0.464..... 99

Figure 4-5: Temperature profile comparison at different ERs.....	101
Figure 4-6: Product gas profile during biomass feeding at 1920.9 g/h.....	101
Figure 4-7: Product gas profile during feeding biomass at 2469.6 g/h.....	102
Figure 4-8: CO concentrations at different biomass feeding rates.....	104
Figure 4-9: CO ₂ concentrations at different ER values.....	105
Figure 4-10: CH ₄ concentrations at different ER values.....	106
Figure 4-11: H ₂ concentrations at different ER values.	107
Figure 4-12: Product gas compositions with GC and online analyser at 1920.9 g/h biomass feeding rate.....	108
Figure 4-13: Product gas composition with GC and online analyser at 2126.8 g/h biomass feeding rate.....	109
Figure 5-1: Mop fan unit installed on the gasifier.....	124
Figure 5-2: Mop fan installed in mop fan unit.	126
Figure 5-3: Particle capture efficiency comparison of mop at different rotational speeds.	127
Figure 5-4: Particulate captures efficiency of spray water and mop fan.....	132
Figure 5-5: Average NO _x concentration in different gas cleaning scenarios.	135
Figure 6-1: Tar in spray water drainage pipe.	141

Figure 6-2: Tar sampling schematic.....	143
Figure 6-3: Tar sampling train.	144
Figure 6-4: Gas flow control meter.....	146
Figure 6-5: Schematic of tar sampling train of connected dreschel bottles.	147
Figure 6-6: Small wood chips (3-10 mm) bed for tar arrest experiment.	150
Figure 6-7: Image of tar trapped by small woodchips (3-10 mm).	151
Figure 6-8: Concentration comparison of tar components at inlet and outlet using small woodchips bed at 1926.9 g/h biomass feeding.....	153
Figure 6-9: Tar components comparison at inlet and outlet using large woodchips (10–25 mm) bed.	157
Figure 6-10: Tar component capture efficiency comparison of small wood chips (3-10 mm) bed and large wood chips (10-25 mm) bed.	159
Figure 6-11: Biochar bed as an unsuccessful attempt in tar capture.....	161
Figure 6-12: Concentration of tar components at inlet and mop fan and spray water outlet sampling points.	166
Figure 6-13: Comparison of tar component capture efficiency using mop fan and mop fan with water spray.....	168

List of Tables

Table 1- 1: Biomass resource types (Demirbaş, 2001).	9
Table 2-1: Comparison of different parameters of combustion, pyrolysis and gasification (Siedlecki <i>et al.</i> , 2011).	19
Table 2-2: Relative advantages and disadvantages of gasifier types (Rajvanshi, 1986). .	34
Table 2-3: Effect of moisture contents on product gas composition	37
Table 2-4: Calorific and cold gas efficiency values of different wood types.	39
Table 2-5: Chemical composition of some wood species (Sjostrom, 2013).....	41
Table 2-6: Proximate and ultimate analysis of different biomass types (Yin, 2011).....	42
Table 2-7: Optimum ER values for different gasifier and biomass type (Gautam, 2010).	47
Table 2-8: Comparison of product gas yield (mol /kg biomass) and gas LHV (kJ/Nm ³) (Wan Ab Karim Ghani, Moghadam et al. 2009).....	49
Table 2-9: effect of gasifying agents including air, pure steam, and steam-O ₂ mixture on the composition of product gas (Gil <i>et al.</i> 1999)	57
Table 3-1: Gasification operating conditions used in gasification and product gas cleaning.	88

Table 4-1: Ultimate analyses of SRC willow woodchips.	92
Table 4- 2: Proximate analyses of SRC willow woodchips.....	93
Table 4-3: Biomass feeding rate calibration.	94
Table 4 -4: Distances of thermocouples from the distribution plate in the reaction tower.	98
Table 4-5: Carbon conversion calculated at different biomass feeding rates.	112
Table 4- 6: Effect of ER on the product gas higher heating values (HHV), lower heating values (LHV) and cold gas efficiency (CGE) and total gas yield.....	120
Table 5-1: Potentials of water spray in capturing particulate matter from the product gas.	129
Table 5-2: Particulate capture efficiency comparison of spray water and spray water and mop fan.....	131
Table 6-1: Tar component capture efficiency of small wood chips bed (3–10 mm).....	152
Table 6-2: Tar component capture efficiency of large wood chips (10–25 mm) bed....	155
Table 6-3: Tar component capture efficiency comparison of small wood chips bed (3–10 mm) and large woodchips bed (10–25mm).	158
Table 6-4: Tar capture by mop fan without water spray.....	162
Table 6-5: Efficiency of mop fan with water spray in capturing tar.....	164

Table 6-6: Efficiency comparisons of mop fan and mop fan with water spray. 167

Table 6-7: Total tar capture in different tar arrest techniques at 1920.6 g/h biomass feeding rates. 169

List of Publications

Neubauer, Y., A. Kölling, A., Schröder, P., Behrendt, F., Hellwig, U., Sachno, N., Liu, H., W. Zhang, *Ul Hai, I.*, Riffat, S., & H. Oldenburg, H. (2012). Gas Treatment of Fuel Gases from Biomass Gasification with Structured Tube Gas Cooling, Quench, Electrostatic Precipitator and Mop-Fan filter (EMF)- Effectiveness and Viability of Components developed in ERA- Net Bioenergy Project. Proc. 20th EUBC&E, 18 th - 22 nd June 2012, Milano, Italy, pp. 844-49.

Zhang, W., Liu, H., *Ul Hai, I.*, Neubauer, Y., Schröder, P., Oldenburg, H., Seilkopf, A. & Kölling, A. (2012). Gas cleaning strategies for biomass gasification product gas. *International Journal of Low-Carbon Technologies*, 7(2), 69-74.

Zhang, W., H. Liu, *I. Ul Hai*, Y. Neubauer, P. Schröder, H. Oldenburg, A. Seilkopf, and A. Kölling, Recent Developments on Product Gas Cleaning Technologies for Biomass Gasification, SET2011, Istanbul, September 2011.

Zhang, W., Liu, H., *Ul Hai, I.* and Riffat, S. Biomass Gasification in a Bubbling Fluidized Bed and Efficiency of a Mop Fan Cleaning Unit. SET2010 - 9th International Conference on Sustainable Energy Technologies; Shanghai, China. 24-27 August, 2010

Chapter 1 Introduction

1.1 Humans, energy and fossil fuel

Human beings made use of different forms of energy knowingly or unknowingly especially in the form of heat and light from prehistoric times and they are still dependent on most of the natural resources such as sun and biomass for their energy needs. As biomasses remained and are still the main source of food, shelter and medicine for humans from antiquated times, they still provide humanity with their services in one way or the other.

Wood has been utilized as fuel for thousands of years before the advent of coal and it is making its comeback in the energy sector as the planet is predicted to face a fossil fuel shortage in the future due to fossil fuels' depleting nature, time constraint for its reproducibility and environmental issues regarding fossil fuels' emissions: the greenhouse effect and global warming (IEA., 2013).

As the humanity urbane from hunter-gatherer to agricultural life and then achieved mechanically accomplished stage, new horizons and dimensions opened to utilize the available resources both in conventional and non-conventional ways for their lifeline needs. Energy consumption also increased with the rising human life standards for domestic, transportation and commercial purpose.

Mainly energy comes from two sources i.e.; Renewable and Non-Renewable as grouped in Figure 1-1. Non-renewable energy is from fossil fuels such as coal etc. which needs millions of years to be reproduced while renewable energy resources such as biomass, solar, hydropower and nuclear are easy to be reproduced as compared to non-renewable energy sources.

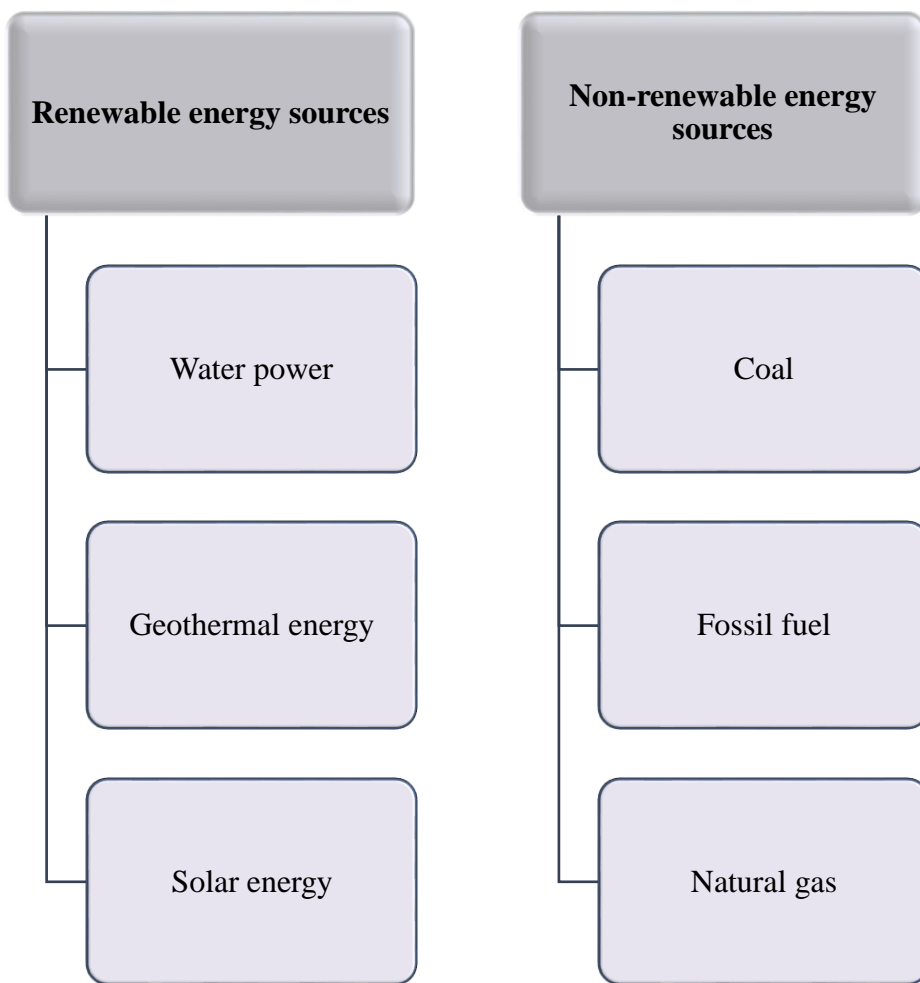
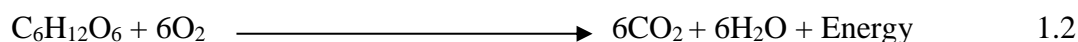
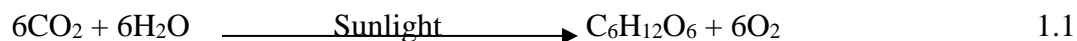


Figure 1-1: Renewable and non-renewable energy resources.

Plant biomass is an example of renewable energy resources. Plants transform solar energy into a chemical form of energy through photosynthesis for their life cycle completion while extra energy molecules produced by plants are consumed by other living organisms on the planet (Lincoln & Zeiger, 2006). Plants convert CO₂ (carbon dioxide) and H₂O (water) in the existence of sunlight into carbohydrates and other vital molecules for their growth and development as depicted by the following reactions (Lincoln & Zeiger, 2006).



The dead or harvested plants can be used as biomass fuel. When this fuel is combusted, useful energy and the same amount of CO₂ is released which was absorbed during the plant life cycle. Therefore, biomass fuels can be said to “Carbon neutral” as there is no net release of CO₂ to the atmosphere.

1.2 Current world energy scenario

In the last few decades the global energy consumption has increased at a very high pace. The world energy consumption increases from 524 quadrillion Btu in 2010 to 630 quadrillion Btu in 2020 and 820 quadrillion Btu in 2040, a 30-year increase of 56 percent in IEO 2013 reference case. At present, with the high growing industrial and

domestic needs of energy utilization, the shortage of fossil energy is predictable in the near future as predicted in Figure 1-2.

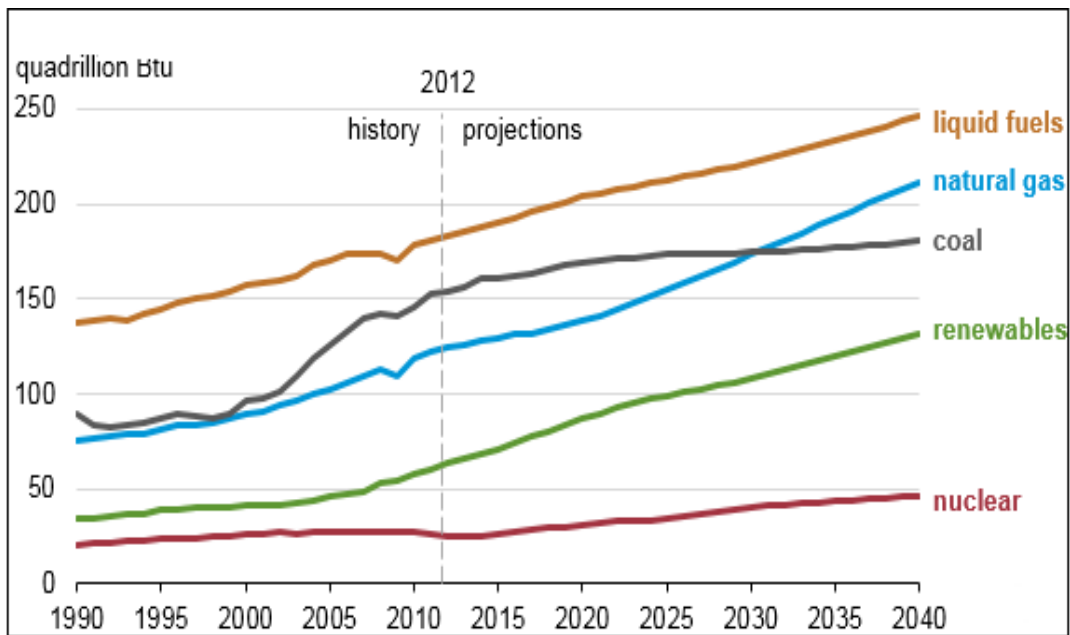


Figure 1- 2: World energy consumption: Current scenario and future trends (IEA 2016).

1.3 Fossil fuels' consumption as energy source

Fossil fuels are the remains of animals and plants which were buried under soil 300-400 million years ago and that carbon containing deposits changed into combustible fuel forms under high pressure and temperature Casper (2010). Primarily the fossil fuels comprise petroleum, natural gas and coal. Petroleum, for the most part, comprises of hydrocarbons. Main components from petroleum are gasoline, diesel and fuel oil, used chiefly for fuel energy in transportation, machinery and in the industry. Natural

gas is mainly composed of methane and is used for domestic and the industrial fuel as well as the power generation (IEA 2013). Coal is another very important fossil fuel mainly composed of elemental carbon, hydrocarbons, oxygen, nitrogen and sulphur. Coal played an important role in domestic heating and cooking, electricity generation at commercial and industrial scales (IEA 2013). (Herzog *et al.*, 2001) viewed fossil fuels as a major source of energy in the 20th century. This importance of fossil energy as a backbone in the economy of the world revealed it as the most important commodity.

Exploitation of fossil fuels is now at its peak predicting the upcoming shortage of fossil fuels energy resources for the coming generations as these resources are depleting very fast while it takes millions of years for their natural production (Allen *et al.*, 2009). Especially in the developed world, the equilibrium in the energy equation, i.e.; energy production and energy consumption are in the threat as fossil fuels are depleting fast and replenish of these fuels in nature takes millions of years. Since the beginning of the Industrial Revolution in the 18th century, the demand for energy started to increase because of industries and later also to households (IEA., 2013).

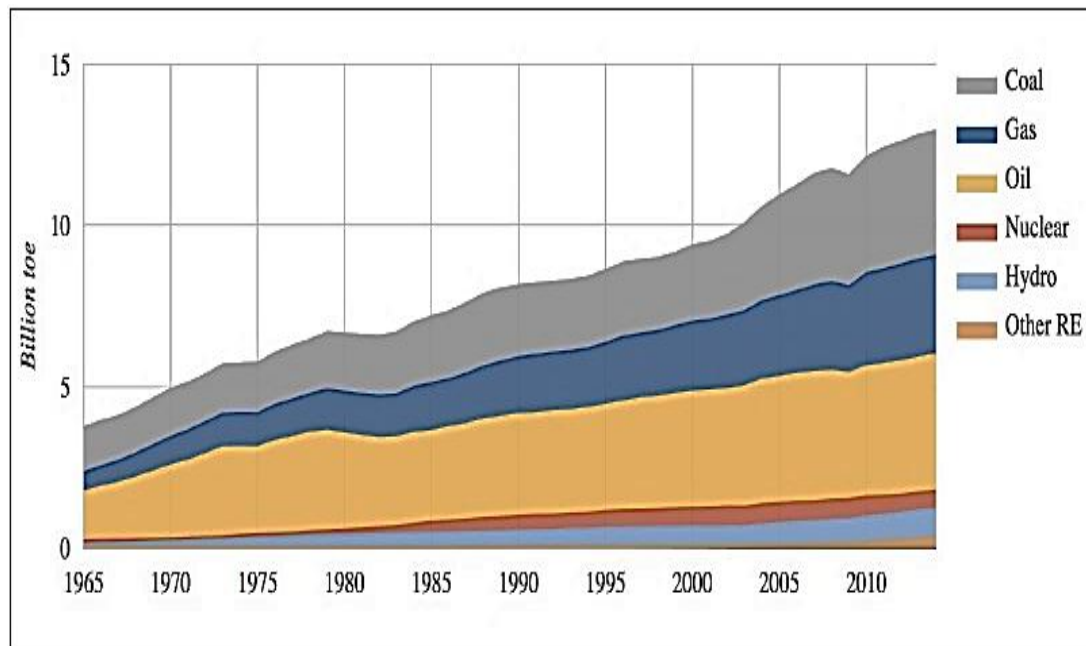


Figure 1- 3: World energy use by fuel types 1965–2014 (IEA 2014).

1.3.1 Fossil fuel and environment

Fossil fuel consumption rate and an environmental pollution issues such as greenhouse gases and carbon emissions have attracted the attention of researchers to find a sustainable and eco-friendly substitute alternative energy resource for the future on the planet earth. As shown in Figure 1-3, the world energy consumption inclining trend attracted research and development to find advanced methods for alternative and renewable energy production. This human need to search and research has uncovered new horizons in the field of sustainable energy technologies for the more efficient use of conventional and renewable fuels such as biomass with less harm to the environment. “Recent and current interest in biomass and its related research and development, for the most part, dates back to 1970’s oil crisis (Feldman, 1995).

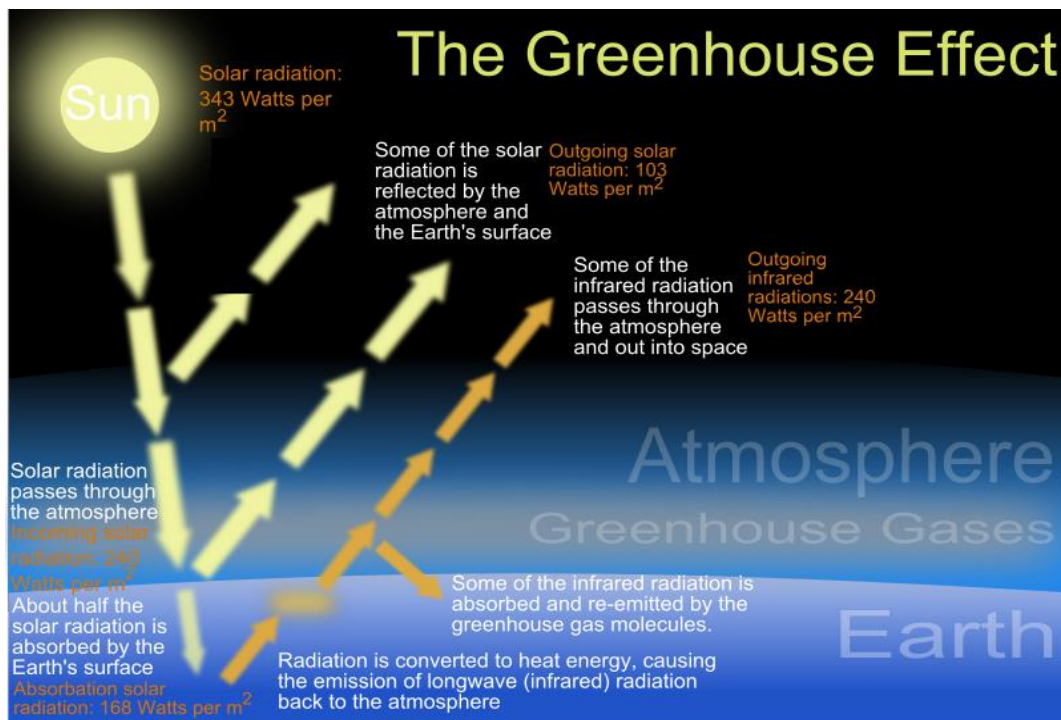


Figure 1- 4: Greenhouse gases and global warming phenomenon (Trenberth *et al.*, 2009).

1.4 Energy for planet earth

In addition to fossil fuels, energy is dispersed around us in many other non-conventional forms such as solar energy, wind energy, hydropower energy, geothermal energy and biomass (Herzog *et al.*, 2001). With the advent of technology and advancement in research and development, new techniques are found to convert these non-conventional energy resources into useful energy to fulfil our energy needs. These non-conventional energy resources are known as an alternative energy sources. Solar energy is the ultimate source of energy for the planet earth. Plants capture solar energy and convert it into the chemical form of energy through a series of biochemical reactions called the photosynthesis. This results in the production of chemical energy

which is utilized by living beings on the planet and by the plants themselves for completion of their life cycle.

1.5 Need of renewable energy

An energy resource that is renewed by nature and whose supply is not affected by the rate of consumption is often termed as renewable energy (Ramachandra & Shruthi, 2005). Shortage of fossil fuels, economic crises and environmental issues resulted from accelerated use of fossil fuels such as greenhouse gases emissions and global warming as shown in Figure 1-4, have driven the world to find better alternative renewable energy sources to fossil fuels.

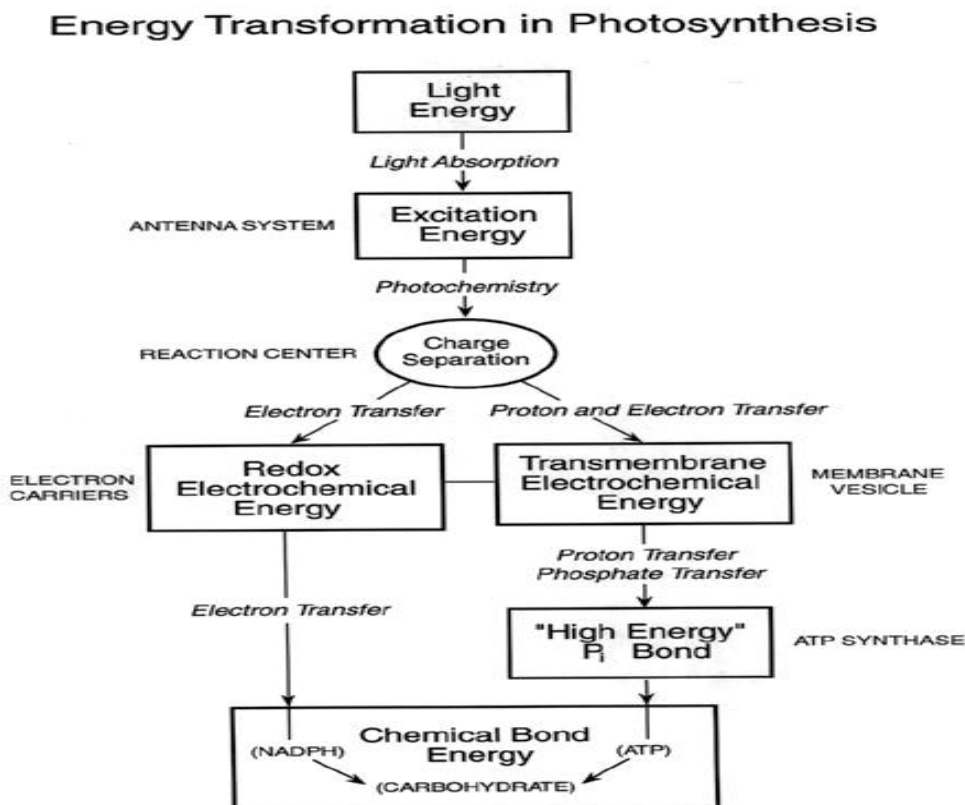


Figure 1- 5: Photosynthesis in plants (Singhal *et al.*, 2012).

1.6 Biomass as an alternative energy source

Biomass is the most abundant carbon containing source on the planet. Biomass is often referred to plants' originating materials and hence biomass fuels are commonly regarded as fuels originating from plants but scientifically biomass fuels include fuel sources originated from plants, animals and micro-organisms as well as industrial organic wastes (Demirbas, 2008). Biomass encompasses all the living and biological origin matter existing on the planet earth. Biomass can be obtained from different vegetative masses as shown in Figure 1-6, including microscopic and non-microscopic, trees and crops or from organic wastes such as animal manure.

Table 1- 1: Biomass resource types (Demirbaş, 2001).

Aquatic plants	Water weed, Water hyacinth, Reed and rushes
Wastes	Agricultural production wastes, Agricultural processing wastes, Crop residues, Mill wood wastes, Urban wood wastes, Urban organic wastes
Forest products	Wood, Logging residues, Trees, Shrubs and wood residues, Sawdust, Bark etc. from forest clearings
Energy crops	Short rotation woody crops, Herbaceous woody crops, Grasses, Starch crops (corn, wheat, barley), Sugar crops (cane, beet), Forage crops (grasses, alfalfa, clover), Oilseed crops (soybeen, sunflower, safflower)



Figure 1- 6: Different biomasses as source for energy production (Boléo, 2011).

1.7 Biomass to energy conversion technologies

Wood is the most common biomass resource which is used by the human being as a source of energy in the form of fire from prehistoric. According to Dong *et al.* (2009) “biomass is the fourth largest energy resource which is contributing about 14% of world's total primary energy consumption”. As Klass (2004) described, biomass is the only available source in abundance for the production of alternative energy. Biomass can be converted into biomass fuels through biochemical conversions or thermochemical conversions. Biochemical conversions of biomass to fuel involve

biological processes such as fermentation and anaerobic digestion etc. Fermentation results in the production of ethanol primarily while anaerobic digestion results in methane as the major product (Kumar *et al.*, 2009). With the advent of technology and research interest in the alternative energy sources all over the world, wood and wood residues became a focus for energy production through different conversion methods with biomass gasification being one of the most important such technology.

Over the past two decades, biomass technologies have attracted the attention of many researchers and scientists as it is the most abundant carbonaceous material which can be converted into solid, liquid or gaseous form of fuel and integrated to the current energy sector to cope up with constantly rising energy needs (Vasudevan *et al.*, 2005). Biomass can be reliable in long term availability of resource for the purpose of energy production in the power generation technology. On the other hand, it is environment friendly as exhausts and discharges from the fossil fuels such as greenhouse gases which include carbon dioxides, nitrogen oxides and sulfur dioxides, resulted in environmental pollution and environmental health issues. As biomass energy is considered “CO₂ neutral” and emissions of sulfur dioxides and nitrogen oxides are very low, biomass is a good option as a clean fuel for the environment (Lim, 2007).

Thermochemical conversion of biomass is the conversion of the biomass feedstock into energy through combustion, pyrolysis or gasification which is carried out with or without the presence of the oxygen. Biomass gasification is a kind of thermochemical

conversion. A biomass gasifier is used to convert solid biomasses into gaseous fuels under certain controlled circumstances. Biomass gasification is not a new science but fossil fuels' convenient availability dominated biomass gasification till late nineteenth century (IEA., 2013).

1.8 Biomass gasification, gasifier and product gas

Biomass contains carbon, hydrogen, oxygen and moisture. When biomass is burnt under controlled conditions of temperature and gasifying medium, it can be converted into a combustible gas that serves as an energy carrier. Biomass gasification is a thermochemical conversion process that involves chemical reactions of biomass with the sub-stoichiometric quantities of oxygen, air, steam or with a mixture of these oxidants. The thermochemical process of energy conversion through gasification is mainly comprised of drying, pyrolysis and gasification.

Biomass gasification converts solid biomass fuels into product gas or syngas which mainly consists of carbon monoxide (CO), hydrogen (H₂), carbon dioxide (CO₂), water (H₂O), nitrogen (N₂) and some traces of hydrocarbons and tars. Char is a by-product of gasification which is unreacted carbon with high the carbon contents. Product gas or syngas can be burnt in an internal combustion engines, gas turbines or other combustion devices (Lim, 2007; Safitri, 2005). The product gas can also be utilized in the production of chemical species such as methanol and other synthetic fuels (Safitri, 2005).

Klass (1998) pointed out that biomass gasification chemistry is similar to that of coal gasification as the thermal decomposition of both fuels results in the yield of the same sort of combustible gases. However operating conditions for the gasification of biomass are much more flexible than those of the coal gasification. Biomass contains celluloses and hemicelluloses which are highly rich in oxygen and more reactive in the gasification process as compared to carbonaceous constituents of the coal. Mahishi and Goswami (2007) described that “thermal decomposition of biomass takes place in the gasifier and results in releasing the volatiles produce different gases and liquids when get reacted with the gasifying medium”.

Different biomass gasification technologies developments had been made to extract energy from a different type of biomass materials. “As per classification of biomass gasifiers by Lim (2007), there are basically four major types of gasifiers existing in the industry: downdraft and updraft gasifiers, which are in the fixed bed category; and fluidized bed gasifiers, which consist of bubbling fluidized bed biomass gasifiers (BFBG) and circulating fluidized biomass bed gasifiers (CFBG) (Lim, 2007).

Up-draft fixed bed gasifier transforms woody residues into gaseous fuel and that is suitable as boiler fuel (Leung *et al.*, 2004). Down-draft fixed bed gasification technology is used to convert crop straw and wood waste for production of domestic cooking gas and in wood drying process in factories. Circulating fluidized bed gasifier is run for gasification of wood and crop wastes to fuel boiler or to generate electricity

(Leung *et al.*, 2004). Bubbling fluidized bed gasifiers are competitive in medium scale applications (A Bridgwater, 2008).

1.9 Objectives

This research aims to investigate the cleaning strategies of biomass gasification product gas resulted from a bubbling fluidized bed biomass gasifier. Specifically, this research endeavors to:

- Investigate biomass gasification in a bubbling fluidized bed biomass gasifier under different operating conditions focusing on product gas composition, effect of operating parameters on gasification and temperature profile in a bubbling fluidized bed biomass gasifier.
- Conduct tar sampling and tar GC-MS analysis for the characterization of tar contents and components of product gas.
- Investigate the effectiveness of mop fan in different tar removal strategies, including mop fan and biomass bed.

Chapter 2 Review of Literature

2.1 Energy synthesis from the biomass

As described in many literatures, biomass can be transformed into energy by means of different routes (Kurchania, 2012), but mainly depending on the factors such as biomass feedstock type and quantity, end-use requirements, environmental standards and economic conditions etc. Thermochemical and biochemical conversion technologies are the two main means for biomass conversion into energy (McKendry, 2002).

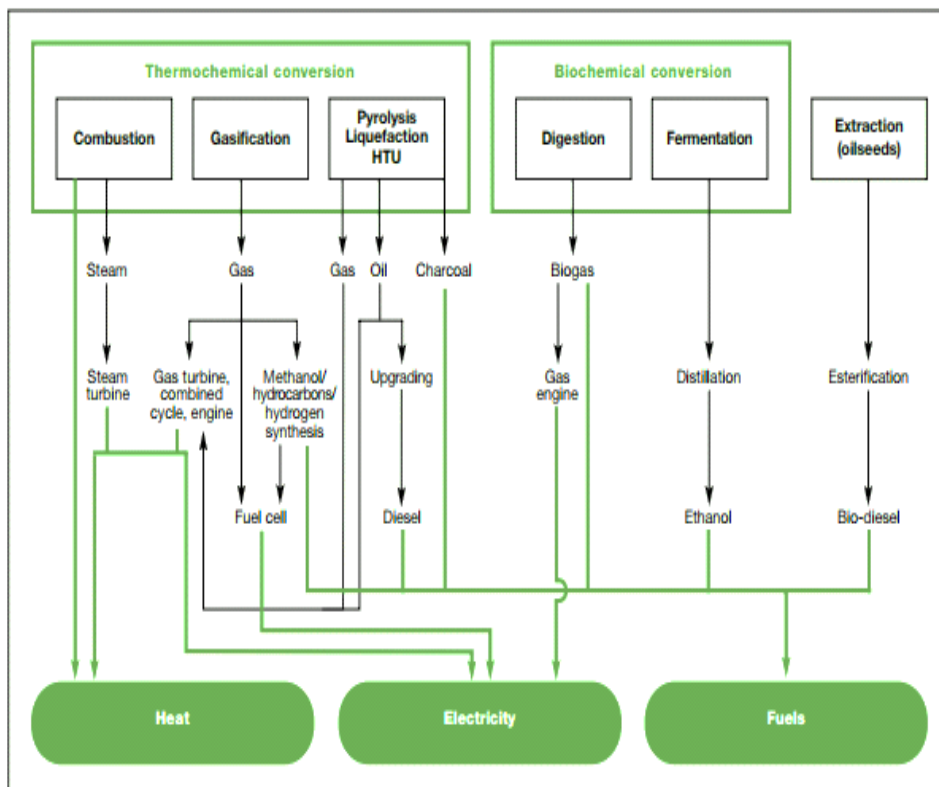


Figure 2-1: Main biomass to energy conversion routes (Turkenburg *et al.*, 2000).

Biochemical conversion of biomass to energy involves fermentation, anaerobic digestion and transesterification. Fermentation results in the production of ethanol primarily while anaerobic digestion results in methane as the major product (Kumar *et al.*, 2009) and transesterification results in biodiesel as the major product of plants based fats conversion into biofuel as presented in Figure 2-1.

The three main thermochemical conversion techniques for the production of energy from biomass are combustion, pyrolysis and gasification (Wang *et al.*, 2008). The combustion of biomass provides about 90% of energy generation from biomass (Van Loo & Koppejan, 2008). Any solid biomass can be used for combustion theoretically, but practically only biomass with less than 50% moisture content is feasible (Goyal *et al.*, 2008). The process of biomass combustion can be further divided into three stages i.e. drying, volatile burning and char combustion as shown in Figure 2-2.

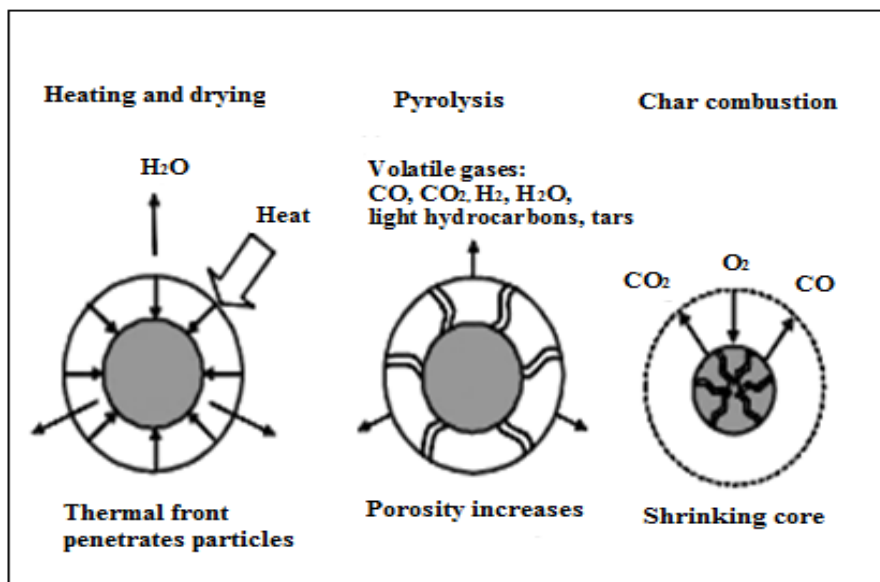


Figure 2-2: Stages of biomass combustion (Le, 2012).

The evaporation of the moisture contained in biomass at above 100 °C is known as drying of biomass and at this stage the water in biomass is converted into steam. Most of this steam ends up as moisture in the product gas while some vapors from this steam may reduce to hydrogen (Ciferno & Marano, 2002). Devolatilization of solid biomass results in the release of a mixture of vapors, which, with further increase in temperature of the fuel, produces a flame around the burning solid fuel. This stage leads to char combustion which results in CO₂ release and ash formation.

Biomass pyrolysis is also known as the initial stage in the process of gasification as well. Pyrolysis can be stated as a thermal decomposition process of the biomass into liquid, charcoal and non-condensable gases. Pyrolysis is an endothermic process and hence requires heat to drive chemical reactions to convert large hydrocarbon molecules into small hydrocarbon molecules and also to produce syngas or product gas mainly comprising of carbon monoxide (CO), carbon dioxide (CO₂), methane (CH₄) and hydrogen (H₂). As described by Pinto *et al.* (2003), pyrolysis or devolatilization converts solid fuel feedstock to tar, char and gases at high temperatures (Figure 2-6).

Tars are heavier gaseous organic compounds released during pyrolysis and may condense as a liquid while char is un-reacted carbon residuals and composed of mostly carbon contents and some mineral matter. Pyrolysis of biomass starts at a temperature higher than 200 °C as the thermal decomposition of biomass into volatile gases and char starts. Properties of gas components and char are dependent on the operating

conditions of the gasifier and chemical composition of biomass fed into the gasifier reactor (Wei *et al.*, 2007).

Gasification is economical in all capacities from 5kWe onward (Gungor & Yildirim, 2013) and this has led to the great interest of research and development in the production of energy from biomass through gasification (Kirubakaran *et al.*, 2009). The main advantage of the biomass gasification is the feedstock versatility. Almost all biomass types can be converted into energy by this technology. Forest residues, municipality wastes, wood residues, agricultural wastes and any by-product from biorefineries can be utilized in this thermochemical technology to produce energy in the form of gaseous fuels.

The main disadvantage of this thermochemical technology is the cleaning cost of product gas for tars and other non-desirable particles (Vasudevan *et al.*, 2005). Caballero *et al.* (2000) identified the formation of tar in the gasification process as a most severe problem particularly at small scale gasification. Biomass gasification will be further discussed in detail in the following section. Table 2-1 compares the three thermochemical conversions of the biomass in terms of their main characteristic parameters.

Table 2-1: Comparison of different parameters of combustion, pyrolysis and gasification
(Siedlecki *et al.*, 2011).

Parameters	Combustion	Pyrolysis	Gasification
Main Products	Heat, Flue Gas	Oil, Combustible Gas, Char	Heat, Combustible Gas
Carbon Conversion	>99%	~75% (Oil yield)	80-95%
Raw Gas Composition	CO ₂ , H ₂ O, N ₂	Oil, Tar Vapour, CO, H ₂ , CH ₄ , CH ₂ , H ₂ O, Char	CO, CO ₂ , CH ₄ , H ₂ , H ₂ O, N ₂ , Tar
Oxygen Stoichiometry (λ)	>1, typically 1.3 for solid fuels	0	$0 < \lambda < 1$ typically $0.2 < \lambda < 0.4$
Chemical reactivity of main product	Inert	combustible, reactive	combustible, but stable
Physical appearance	Gas	solid, liquid & gas	Gas
Heating value [MJ kg ⁻¹] HHV	0	16–19	typically 5–20

2.2 Biomass gasification

The gasification transforms the biomass into a mixture of combustible gases which can successively be utilized for the production of heat and electricity. Biomass gasification is an established technology for the production of combustible gases and has been around for more than a century (Liu and Neubauer, 2010). Turare (1997) describes

biomass gasification as an old technology, well known before and during the Second World War, but with the wide availability of fossil fuels for energy purpose, biomass gasification technology lost its interest to researchers. Now, thanks to the environmental, economic issues and scarcity of fossil fuels, biomass gasification has re-emerged as one of the main popular and practicable technologies.

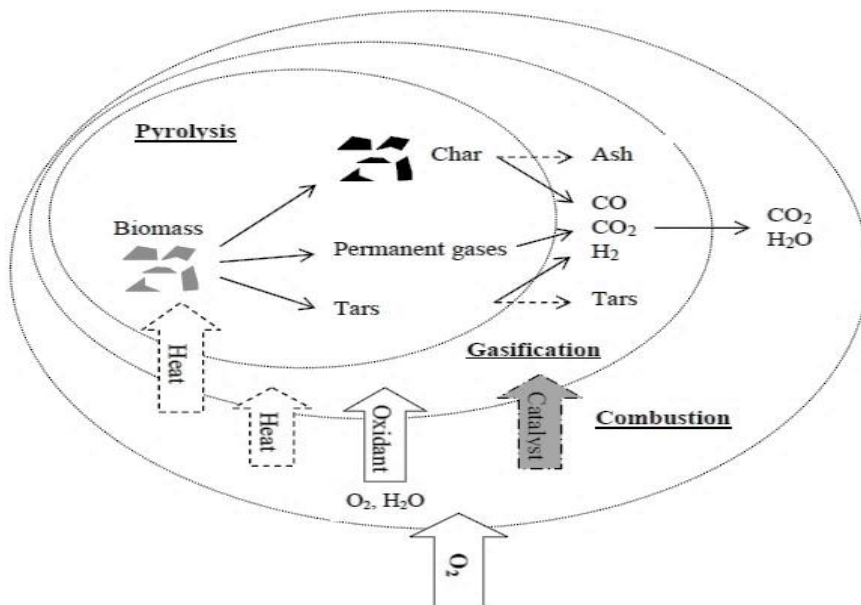


Figure 2-3: Schematic of biomass gasification stages (Alberto Gómez-Barea & Leckner, 2010).

Biomass gasification is a thermochemical conversion process through partial oxidation of a carbonaceous material (biomass) which results in a gas identified as the product gas or syngas that can be utilized in high efficiency power generation, heat and/or combined heat process (CHP) applications as substitute of fossil fuels (Maniatis, 2008; Safitri, 2005). This product gas is a combination of CO (carbon monoxide), CO₂

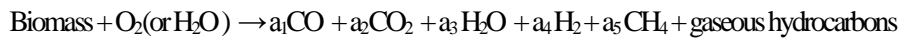
(carbon dioxide), H₂ (hydrogen), H₂O (water), N₂ (nitrogen) and some traces of hydrocarbons and tars (Ściążko & Stępień, 2015). Char is a by-product of gasification which is unreacted carbon with high carbon contents (Moulijn *et al.*, 2013).

2.2.1 Biomass gasification chemistry

Klass (1998) pointed out the similarity of biomass gasification chemistry to that of coal gasification as the thermal decomposition of both fuels results in a yield of same sort of combustible gases. However, the gasification of biomass takes place at less severe operating conditions as compared to gasification of coal mainly due to main constituents of biomass, the high-oxygen cellulosic and hemicelluloses have higher reactivity than the oxygen-deficient, carbonaceous materials in coal (Klass, 1998). The thermo-chemical processes involved in gasification are drying, pyrolysis, oxidation, and reduction (Quaak *et al.*, 1999).

Gasification involves an incomplete combustion by partial oxidation. The product gas produced during the gasification contains about 15-21% Hydrogen, 10-20% Carbon Monoxide (CO), 11-13% Carbon Dioxide (CO₂) and 1-5% Methane (CH₄) and some non-combustible Nitrogen (N₂) (van Heesch *et al.*, 1999). Complete gasification of biomass involves a number of sequential and parallel reactions. Most of these reactions are endothermic and must be balanced by the partial combustion of gas or an external heat source. A limited supply of oxygen, air, steam or a combination of these serves as

the oxidizing agent (Balat, 2008). Safitri (2005) generalized the biomass gasification process involving air (oxygen) or steam as follows:



2.2

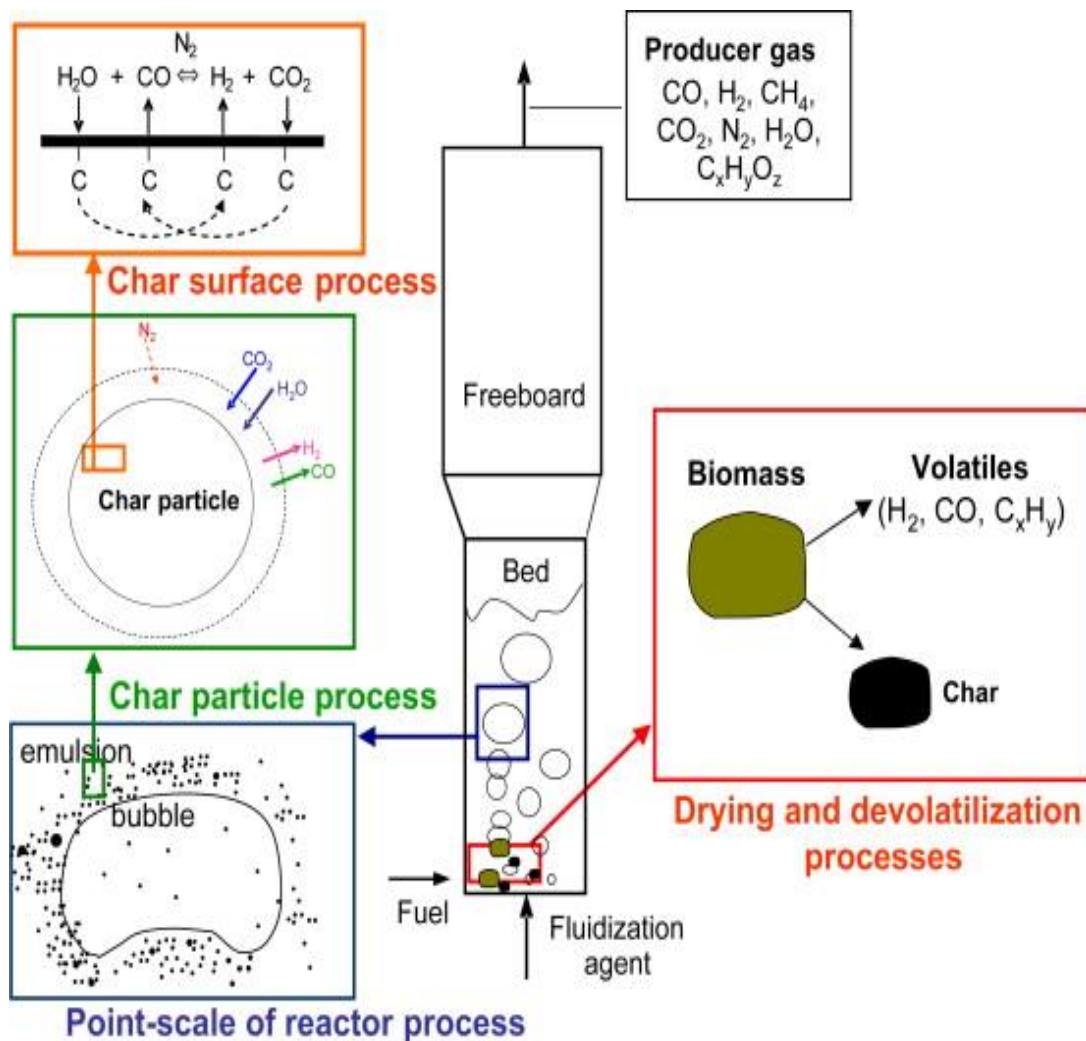


Figure 2-4: Overview of different gasification technologies (Alberto Gómez-Barea & Leckner, 2010).

Rezaiyan and Cheremisinoff (2005) divided the gasification reactions into two main categories as exothermic reactions which are involved in the oxidation stage and endothermic reactions which are involved in the reduction stage.

2.2.1.1 Oxidation or exothermic reactions

Oxidation is the next step which follows the pyrolysis in which products of the pyrolysis move to a higher temperature zone (700–1000 °C) of a gasifier reactor. Air is introduced into the oxidation zone under the starved oxygen conditions. The oxidation takes place at temperatures ranging from 700–1000 °C (Wei *et al.*, 2007).

$C + O_2 \leftrightarrow CO_2$	(Oxidation)	2.3
$2C + O_2 \leftrightarrow 2CO$	(Partial Oxidation)	2.4
$C + 2H_2 \leftrightarrow CH_4$	(Hydrogasification)	2.5
$CO + 3H_2 \leftrightarrow CH_4 + H_2O$	(CO Methanation)	2.6

2.2.1.2 Reduction or endothermic reactions

The reaction products of the oxidation zone continually move into the reduction zone where there is an insufficient oxygen, leading to reduction reactions between the hot gases and char. In this zone, the sensible heat of the gases and char is transformed into the stored chemical energy in the syngas. Therefore, the temperature of gases is reduced during this process (Akudo, 2008) (Wei *et al.*, 2007).

$\text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2$	(Water Gas Shift)	2.7
$\text{C} + \text{H}_2\text{O} \leftrightarrow \text{CO} + \text{H}_2$	(Water Gas Reaction)	2.8
$\text{C} + \text{CO}_2 \leftrightarrow 2 \text{CO}$	(Boudourd Reaction)	2.9

Exothermic reactions through partial combustion in biomass gasification provide energy to the endothermic reactions and a steady state can be achieved where gasifier maintains the gasification operation at certain required operating temperatures (Boerrigter *et al.*, 2004; A Gómez-Barea *et al.*, 2005).

2.3 Biomass gasifier types

Hos and Groeneveld (1987) pointed out that the product gas composition is mainly dependent on gasification process, gasifying agent and feedstock composition. Different biomass gasification technologies had been made to harvest energy from different biomasses. Lim (2007) classified biomass gasifiers into four major types existing in the industry, each with specific use, advantages and disadvantages over other gasification technologies: downdraft and updraft gasifiers, which are in the fixed bed category; and fluidized bed gasifiers, which consist of bubbling fluidized bed biomass gasifiers (BFBG) and circulating fluidized biomass bed gasifiers (CFBG). Up-draft fixed bed gasifier converts biomass into a gaseous fuel that is suitable for direct combustion in the boiler. Down-draft fixed bed gasification technology is often used to convert crop straw and wood waste for production of domestic cooking gas and in wood drying process in factories. Circulating fluidized bed gasifiers are often used to

gasify wood and crop wastes to fuel boilers or to generate electricity (Leung *et al.*, 2004). Bubbling fluidized bed gasifier are competitive in the medium scale applications (Lim, 2007).

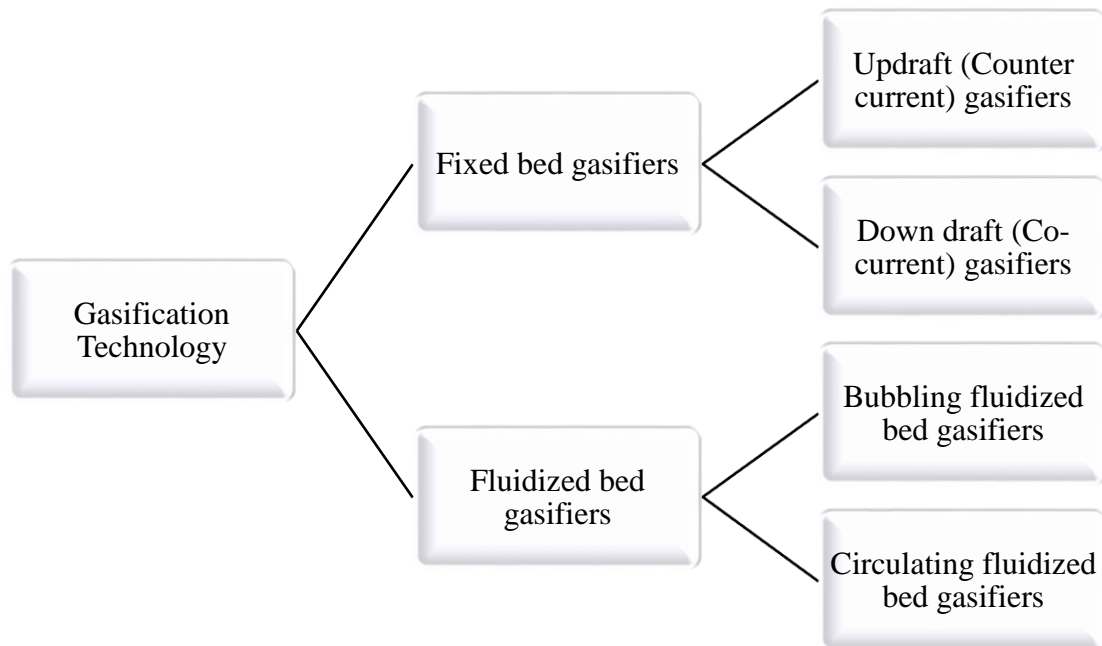


Figure 2-5: Overview of different gasification technologies.

2.3.1 Fixed bed gasifiers

Klein (2002) described fixed bed gasifiers as preferred types for a small scale to medium scale applications as they are comparatively easy to design and simple in operation as compared to the fluidized bed gasifiers. The main drawback of the fixed bed gasifiers is the difficulty in maintaining the constant operational temperature which results inadequate gas mixing in the reaction zone of the reactor (Couto *et al.*, 2013). Fixed bed gasifiers can further be classified into counter-current fixed bed (updraft) or

co-current fixed bed (down draft) gasifier depending on the method of gasifying medium introduction.

2.3.1.1 Updraft or counter-current fixed bed gasifiers

In this type of gasifier, the gasifying medium (air, oxygen or steam) enters in the gasifier reactor from the bottom and biomass is being fed from top of the gasifier, hence the gasifying medium and biomass enters and moves in the reactor in a counter-current manner (Belgiorno *et al.*, 2003). As biomass passes from drying, pyrolysis and then gasification zones, the product gas leaves from the top of the gasifier reactor.

According to Quaak *et al.* (1999), updraft or counter current gasifiers are advantageous in use as these are simple in construction, low gas exit temperatures and high thermal efficiency. These features allow biomasses with high moisture contents (up to 60%) to be gasified without pre-drying. Beenackers and Maniatis (1998) found out that the size of biomass particles was not very critical in this type of gasifiers. Only major issue with updraft fixed bed gasifiers is a high tar concentration in the product gas as compared to other gasifier types and therefore the product gas is often directly burned in the boilers (Lim, 2007).

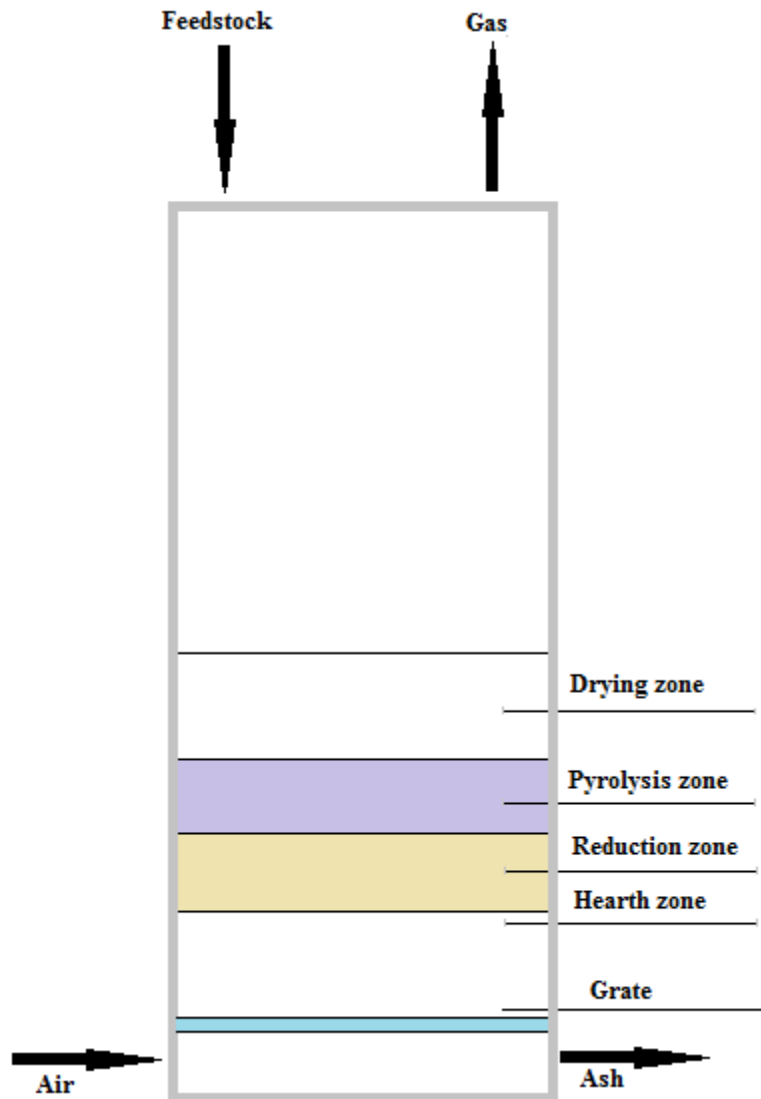


Figure 2-6: Updraft or counter-current fixed bed gasifier.

2.3.1.2 Downdraft or co-current fixed bed gasifiers

In downdraft or co-current gasifiers, the gasifying agent is introduced from the top and flows in co-current configuration with biomass fuel which is also fed from the top of the reactor.

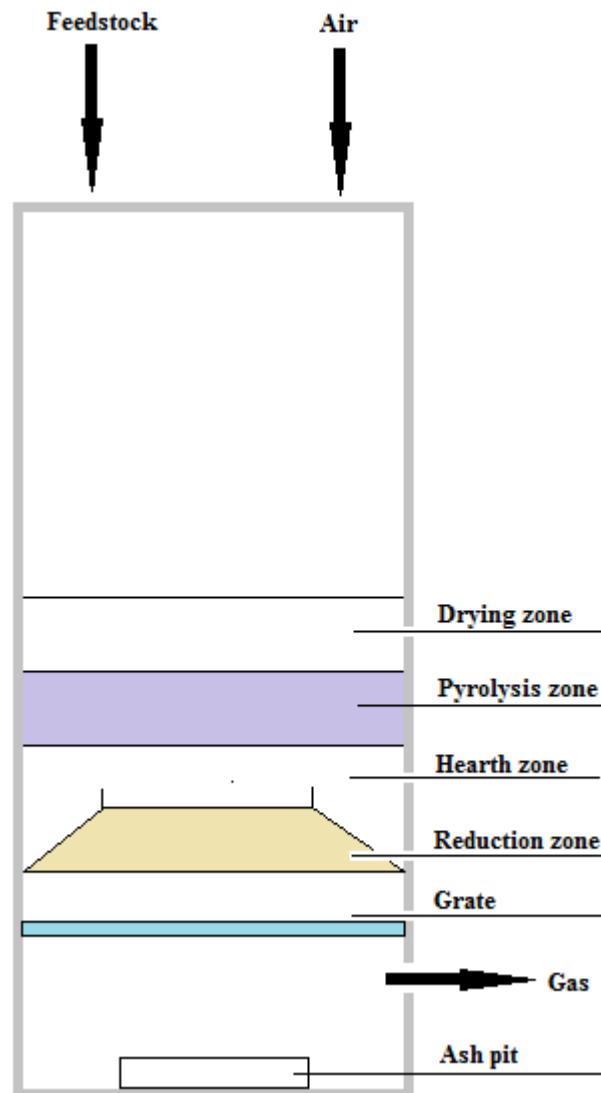


Figure 2-7: Downdraft or co-current fixed bed gasifier.

Gasification reactor zones are similar to that of counter-current fixed bed gasifier but occur in a different order. As product gas is drawn off from the bottom of the gasifier, all the tars present in product gas pass through the hot bed and hence most of them are cracked at this stage (Patra & Sheth, 2015). Therefore, the tar concentrations in the

product gases are much lower in these gasifiers and are preferred in the internal combustion engines.

2.3.2 Fluidized bed gasifiers

A fluidized bed gasifier has an air distribution plate which has two functions. It serves as a support to the bed material and also has nozzles or air caps or a porous distribution plate that allows air to flow into the reactor (Kim *et al.*, 2013). The externally supplied heat (e.g. electrical heaters, combustion of a gaseous fuel) and gasifier heats up the bed material and the reactor walls until a certain temperature is reached. Biomass feeding commences once the required temperature is reached and biomass gasification tests can be started. In fluidized bed gasifiers the fuel particles are fluidized in the gasifying medium into a fluid like state through suspension in a gasifying medium. Air coming from the distributor plate lifts the inert bed material with biomass particles which results in the fast pyrolysis of the biomass fuel (Hoque & Bhattacharya, 2001).

Fluidized bed gasifiers are more flexible in the selection of fuel (Warnecke, 2000). They can gasify various types of biomass without much difficulty and achieve high carbon conversion rates as well as have high heat transfer rates which enable this kind of system to handle a larger quantity and lower quality of fuels.

The major advantages of fluidized bed gasifiers reported by van den Aarsen (1985) include feedstock flexibility, easy control of temperature, which can be kept below the

melting or fusion point of the ash (rice husks), and their ability to deal with fluffy and fine grained materials (sawdust etc.) without the need of pre-processing. Biomass feeding issues, fly-ash sintering in the gas channels and instability of the bed can occur with some biomass fuels. Other drawbacks of the fluidized bed gasifier lie in the rather high tar content of the product gas (up to 500 mg/m³ gas), the incomplete carbon conversion, and poor response to load changes. Fluidized bed biomass gasifiers are capable of handling smaller sized biomass particles as compared to fixed bed biomass gasifiers. Mainly there are two types of fluidized bed gasifiers: bubbling fluidized bed gasifier and circulating fluidized bed gasifier (Richardson *et al.*, 2015).

2.3.2.1 Bubbling fluidized bed gasifier

These gasifiers are made up of a vessel like a reactor which is provided with a grate or a distribution plate at the bottom of which uniformly distributes gasifying agent that moves bed material in the form of bubbles as gasifying medium moves from bottom to upwards in the gasifying reactor. Biomass is introduced into or above the bed material.

In bubbling fluidized bed biomass gasifiers, the gasifying reactor can be virtually divided into the bed (reaction) zone and the freeboard zone (Kaushal & Tyagi, 2017). The main gas-solid reactions take place in the bed (reaction) zone whereas the freeboard zone provides the additional space for gas phase reactions and prevents the movement of excessive bed material particles from being carried to the cyclone.

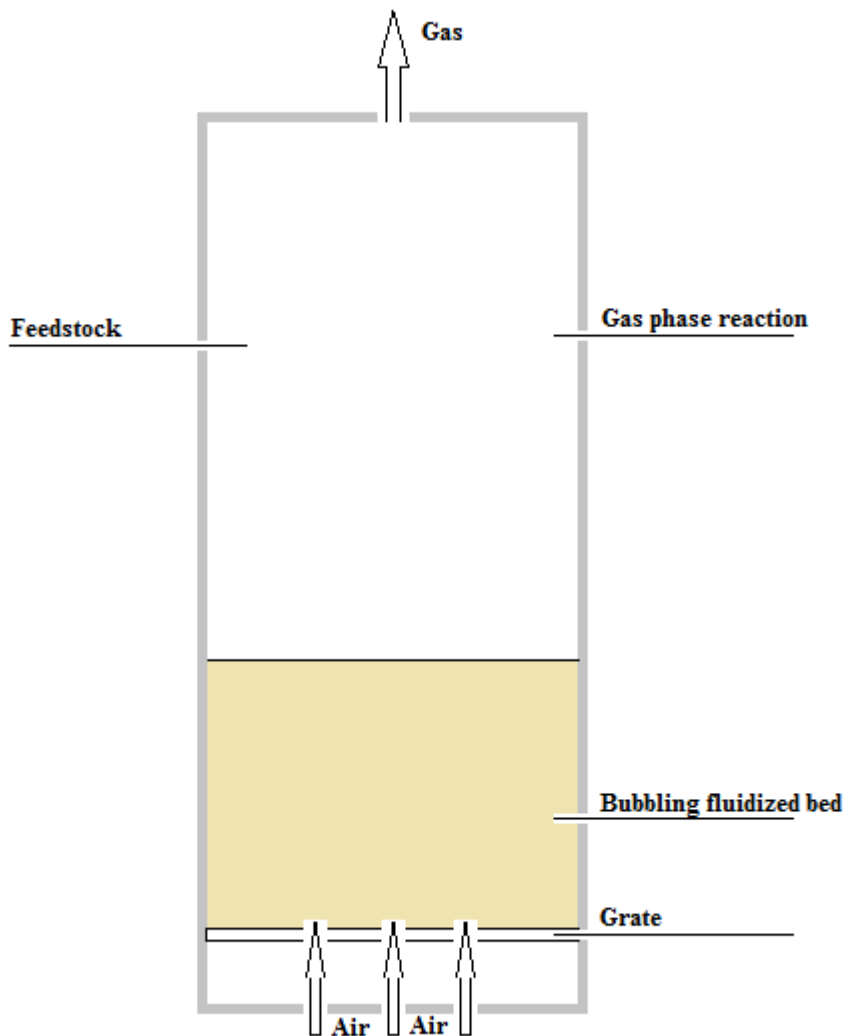


Figure 2-8: Bubbling fluidized bed biomass gasifier.

In a bubbling fluidized bed biomass gasifier, bubbles formation takes place within the bed. These bubbles move upward carrying along some bed material with it, called a wake. As the bubble bursts, the bed material falls down towards the bed under gravitational force. “When it’s free fall gravity is balanced by the force of the minimum fluidization velocity, the bed material flow upwards again along with new bubbles formed. This is a cycle that will happen throughout the process, thus increasing the

mixing efficiency of the bed material, fuel particles and gasifying agent. This will, in turn, increase the heat transfer mechanism. Also, due to the fluidization the gasifier is in a 'boiling' state, the temperature would be uniform in the reactor.

2.3.2.2 Circulating fluidized bed gasifier

In circulating fluidized bed biomass gasifiers, the biomass is fed into the bed material of the gasifier reactor. Gasifying agent is introduced from the bottom of the gasifying reactor at some specific velocity, enough to suspend the particles of bed material in a fluid like a state. With the increasing gas velocity in the turbulent fluidized chamber, the bed continues to expand and the product gas containing ash, char and some bed material particles leaves the gasifier from top and exits to a cyclone which is to remove these particles from the product gas and sends them back to the gasifier reactor through a connecting leg, hence, it is called a circulating fluidized bed biomass gasifier.

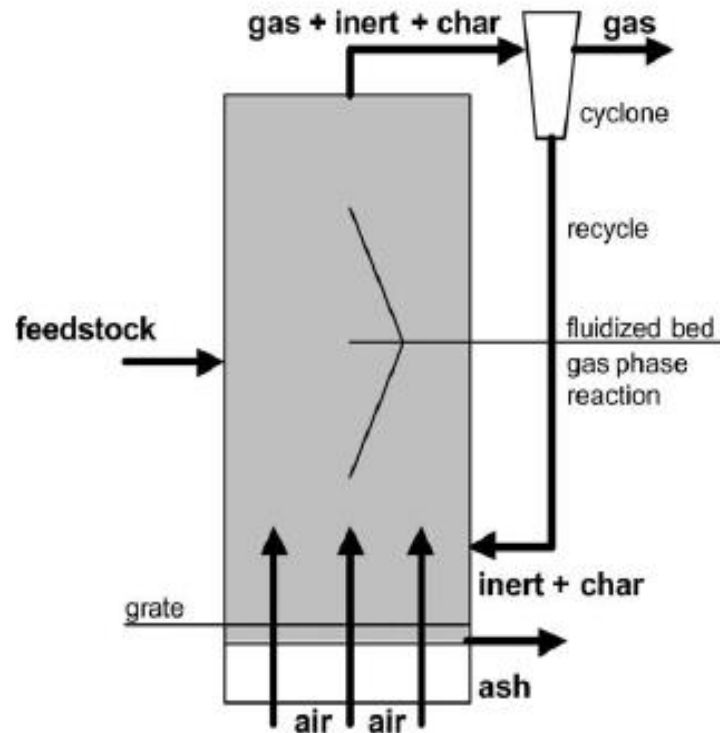


Figure 2-9: Circulating fluidized bed gasifier (Lim 2007).

A circulating fluid bed is differentiated from a bubbling fluid bed in that there is no distinct separation between the dense solids zone and the dilute solids zone. All the gasifiers have some advantages and disadvantages over the others which are summarized in table 2-2.

Table 2-2: Relative advantages and disadvantages of gasifier types (Rajvanshi, 1986).

Gasifier Type	Advantages	Disadvantages
Updraft fixed bed	Mature for small-scale heat applications Can handle high moisture No carbon in ash	Feed size limits High tar yields Scale limitations Low heating value gas Slagging potential
Downdraft fixed bed	Small-scale applications Low particulates Low tar	Feed size limits Scale limitations Low heating value gas Moisture-sensitive
Bubbling fluid bed	Large-scale applications Feed characteristics Direct/indirect heating Can produce higher heating value gas	Medium tar yield Higher particle loading
Circulating fluid bed	Large-scale applications Feed characteristics Can produce higher heating value gas	Medium tar yield Higher particle loading

2.4 Biomass properties as a fuel source for gasification

For selection of a biomass as a fuel source in gasification, its properties (composition, moisture contents etc.) and characteristics should be considered and analyzed. Quaak *et al.* (1999) pointed out that each type of biomass has particular properties that govern its performance as a fuel in the combustion or gasification devices or both.

According to McKendry (2002), “moisture contents, calorific value, fixed carbon and volatiles, ash/ residue contents, alkali metal contents and cellulose/lignin ratio are the properties which should be considered when selecting a biomass and its conversion technology”.

2.4.1 Moisture contents

The moisture content in biomass is defined as the amount of water in the material, expressed as a percentage of the material’s weight (Quaak *et al.*, 1999). This weight can be on a wet basis, on a dry basis, and on a dry-and-ash basis”. Biomass materials exhibit a wide range of moisture content and since this affects its value as a fuel source, it is important that the basis is clearly stated whenever the moisture content is measured.

The moisture in a solid fuel will be evaporated to steam when the fuel is burned and this takes away the useful energy generated from the combustion of a biomass fuel. In excessive moisture contents, the combustion process may not be self-sustaining and supplemental fuel may be needed which could defeat of producing energy by biomass combustion for captive use or market (Klass, 1998). According to McKendry (2002), two types of moisture are under consideration while assessing a biomass for gasification i.e.; an intrinsic moisture and an extrinsic moisture. The intrinsic moisture is unaffected by external factors such as weather conditions, rain water etc. while the extrinsic moisture is due to prevailing weather conditions. Both types of moistures play an important role in the gasification and can affect product gas composition. Also, moisture contents of a material are of importance for selecting the conversion technology. In this scenario, wood and small herbaceous plants with low moisture contents are more suitable for the production of liquid fuels by thermochemical conversion.

Roy *et al.* (2009) observed that in a downdraft gasifier, when the moisture content increased from 0 to 40%, the heating value of the syngas decreased by 8.72% at ER of 0.45 while the decrease was of 4.7% when the ER used was 0.29. A moisture content of biomass about 30% or more makes ignition difficult and also results in a lower calorific value of the product gas as more heat is needed for the evaporation of the moisture prior to combustion/gasification. Higher moisture content results in a reduced temperature in the oxidation zone which ultimately releases incompletely cracked hydrocarbons from pyrolysis zone (McKendry, 2002).

Table 2-3: Effect of moisture contents on product gas composition

	Gasifier type	CO	CO₂	CH₄	H₂	Maximum limit (% wet basis)
Moisture content (MC)	Updraft	-	+	~	+	<50 (Beenackers & Maniatis, 1998)
	Downdraft	-	+	~	+	<40 (Dogru <i>et al.</i> , 2002)
	Fluidized	-	+	~	+	<10 (Basu, 2006)

During gasification, the concentration of CO₂ increases in water-gas shift reaction in which H₂ is produced and CO is consumed (Chum & Overend, 2001) while the equilibrium constant for water-shift reaction varies little over a wide range of temperatures, the direction tends to reverse at a higher temperature. Since more heat is required for moisture evaporation than the small amount of heat gained due to the exothermic behavior of the water-shift reaction, the thermal energy inside the gasifier reduces when gasifying biomass with higher moisture content (Basu, 2006).

Thus, the decrease in temperature further intensifies the scenario and forms more CO₂ since the water-shift reaction is improved at lower temperatures. The overall effect is the reduction in calorific value of syngas because, the small increase in H₂ is not sufficient to compensate for the loss of significant amount of CO with an increase in moisture content. The negative effect of moisture content on the calorific value of syngas is lower at lower equivalence ratio (Gautam, 2010).

An increase in moisture content results in a decrease in biomass consumption as more heat is needed for drying biomass before pyrolysis is started in the gasification reactor (Sheth & Babu, 2010). However, some moisture content is always desirable since it enhances steam reforming and helps to crack tar, and at a higher temperature, also enhances other reactions such as char gasification.

2.4.2 Calorific value

The calorific value (CV) of a material is expressed as an energy content, or heat value released when burnt in the air. The CV is usually measured in terms of the energy content per unit mass, or volume; hence MJ/ kg for solids, MJ /L for liquids, or MJ/Nm³ for gases. The CV of a fuel can be expressed in two forms, the gross CV (GCV), or high heating value (HHV) and the net CV (NCV), or low heating value (LHV) cannot be used effectively, LHV is often the appropriate value to determine the energy available for subsequent use. Heating values of solid fuels are usually measured by Bomb Calorimetry but can also be calculated by correlations using proximate and ultimate analyses.

High heating value is the amount of the total energy content released when fuel is burned in the air. It represents the maximum amount of energy potential of a material or fuel as it includes the latent heat of water vapor. Low heating value is the amount of heat released when hydrogen is burned to gaseous water.

Table 2-4: Calorific and cold gas efficiency values of different wood types.

Research	Wood Type	Calorific value (MJ/Nm ³)	Cold gas efficiency (%)
Dogru <i>et al.</i> (2002)	<i>Hazellnut</i> shell	5.15	80.91
Zainal <i>et al.</i> (2002)	Furniture wood+ charcoal	5.34	80
Sheth and Babu (2009)	Furniture waste	6.34	56.87
Ummadisingu <i>et al.</i> (2010)	<i>Pinus roxburghii</i> wood shavings	6.14	45

2.4.3 Volatile matter contents

Volatile matter content is the portion of a biomass sample driven off as a gas by heating the biomass sample to 900 °C for 7min. The amount of volatile matter in the feedstock is important in determining the gasifier design and in gas cleaning strategies. It was observed that higher the biomass volatile matter contents resulted in an increase in the peak temperature(Haykırı-Açma, 2003).

2.4.4 Ash contents

The ash content is the solid content left as biomass is combusted in air. It affects the biomass conversion processes which can cause operational problems such as forming slag which is a liquid phase formed at elevated temperatures (Livingston & Babcock,

2006). Rajvanshi (1986) stated that the ash contents are the minerals in the biomass which remain in an oxidized form after complete combustion. Ash composition and ash contents affect the design and operation of a gasifier. Ash basically interferes with gasification process in two ways: a) It can fuse together to form slag or clinker which stops or inhibits the downward flow of biomass feed; b) Even if it does not fuse together it shelters the points in fuel where ignition is initiated and thus lowers the fuel's reaction response.

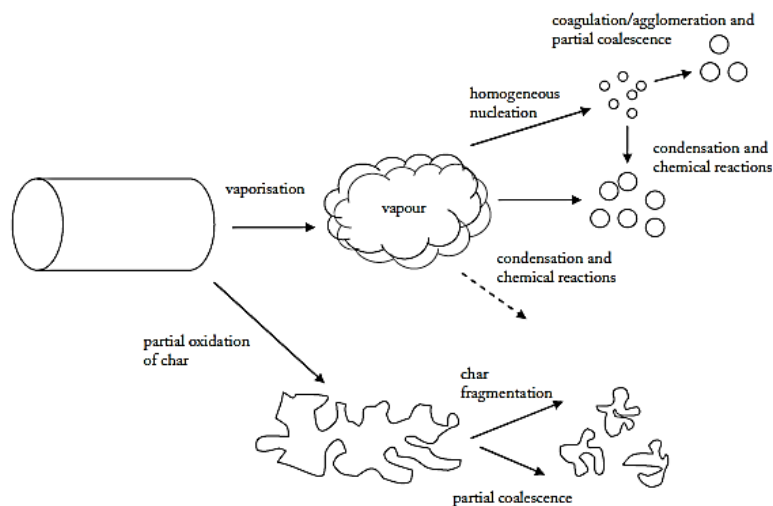


Figure 2-10: Schematic of particulate matter formation during biomass gasification

(Gustafsson, 2011)

2.4.5 Alkali metal content

As described by Dayton and Milne (1996), the alkali metals, in particular potassium have been associated as a vital constituents for increasing the fouling and slagging of

heat transfer surfaces in biomass to electricity conversion facilities. Important alkali metals in biomass are Na, K, Mg, P and Ca (McKendry, 2002) which can react with silica or the bed material in gasifying reactor to produce sticky mobile liquid phase which may lead to blockage of the reactor (Chiang *et al.*, 2013).

2.4.6 Cellulose / lignin ratio

Cellulose is a polysaccharide consisting of chains of glucose monomers and is the main constituent of plant cell walls and of vegetable fibres such as cotton (H. Chen, 2014). Lignin is the second most abundant natural polymer and renewable carbon source in the world found in plant cell wall (Welker *et al.*, 2015). The cellulose and lignin fractions in biomass are more significant in biochemical conversion processes and regarded as important parameters to evaluate the pyrolysis characteristics (Gani & Naruse, 2007). Celluloses are biodegraded more quickly than that of lignin, therefore, the total conversion of the carbonaceous plant material containing as cellulose is more than that of plants with a higher proportion of lignin.

Table 2-5: Chemical composition of some wood species (Sjostrom, 2013).

Constituents	Scot Pine	Spruce	Eucalyptus	Silver Burch
Cellulose (%)	40.0	39.5	45.0	41.0
Lignin (%)	27.7	27.5	31.3	22.0

2.4.7 Biomass proximate and biomass ultimate analyses

In a biomass, the proximate analyses determine the moisture contents, volatile matter, fixed carbon and ash contents (García *et al.*, 2013). Ultimate analysis gives the main elemental composition of biomass in weight percentage of carbon, hydrogen, oxygen, sulphur and nitrogen (J. Chen *et al.*, 2016). Table 2-6 shows the proximate and ultimate analyses of a number of different biomass materials.

Table 2-6: Proximate and ultimate analysis of different biomass types (Yin, 2011).

	Proximate Analysis			Ultimate Analysis				
	VM	FC	Ash	C	H	N	O	S
Pistachio soft shell	67.85	8.69	14.21	45.53	5.56	1.74	47.17	–
Coconut shell	77.19	22.1	0.71	50.22	5.7	43.37	–	–
Wheat straw	82.12	10.98	6.9	42.95	5.35	–	46.99	–
Rice husk	61.81	16.95	21.24	38.5	5.2	0.45	34.61	–
Sugarcane bagasse	83.66	13.15	3.2	45.48	5.96	45.21	0.15	–
Bamboo wood	86.8	11.24	1.95	48.76	6.32	0.2	42.77	–
Olive stones	78.3	19.5	2.2	49	6.1	0.8	42	–
Almond shell	80.5	18.4	1.1	48.8	5.9	0.5	43.7	–

Sunflower seed shell	84.7	11.7	3.6	51.7	6.2	1	41.1	–
Esparto plant	80.5	16.8	2.2	46.94	6.44	0.86	43.56	–
Sugarcane bagasse	81.5	13.3	5.2	43.79	5.96	1.69	43.36	–
Cotton stalk	76.1	18.8	5.1	47.07	4.58	1.15	42.1	–
Peanut shell	84.9	13.4	1.7	47.4	6.1	2.1	44.4	–
Hazelnut shell	68.9	30	1.1	50.9	5.9	0.4	42.8	–
Wet grains	83.18	13.58	2.58	52.53	6.6	5.35	32.28	0.66
Corn stover	66.58	26.65	6.73	45.48	5.52	0.69	41.52	0.04
Coffee husk	78.5	19.1	2.4	47.5	6.4	–	43.7	–
Sugar cane straw	76.2	14.6	9.2	43.5	6.1	–	41.1	–
<i>Lantana camara</i> leaf	70.46	11.83	7.26	45.01	6.68	2.02	43.79	–
Oil palm fruit bunch	78.2	16.46	4.53	45.9	5.8	1.2	40.1	–
Olive kernel	63.9	32.8	1.7	54.6	6.8	0.8	36.1	–
Olive kernel shell	60.5	36.1	3.3	53.2	6.7	0.5	36.3	–
Olive cake	62.1	34.6	2.8	53.7	6.7	0.6	36.2	–
Olive kernel	73.62	24.25	2.13	52.44	6.17	1.32	37.85	0.09
Forest residue	79.8	20	0.2	53.16	6.25	0.3	40	0.09
Cotton residue	72.8	20.59	6.61	47.03	5.96	1.79	38.42	0.19
Alfalfa stems	78.92	15.81	5.27	47.17	5.99	2.68	38.19	0.2
Rice straw	65.47	15.86	18.67	38.24	5.2	0.87	36.26	0.18

Switch grass	76.69	14.34	8.97	46.68	5.82	0.77	37.38	0.19
Willow wood	82.22	16.07	1.71	49.9	5.9	0.61	41.8	0.07
Hybrid poplar	84.81	12.49	2.7	50.18	6.06	0.6	40.43	0.02
Almond hulls	73.8	20.07	6.13	47.53	5.97	1.13	39.16	0.06
Oak wood branch (small)	77.45	18.5	4.05	48.76	6.35	2.81	42.08	–
Oak wood branch (medium)	80.82	16.18	3	48.62	6.52	2.58	42.28	–
Oak wood branches (large)	81.75	16.18	2.07	48.57	6.81	2.39	42.23	–
Pine chips	72.4	21.65	5.95	49.66	5.67	0.51	38.07	0.08
Corn straw	73.15	19.19	7.65	44.73	5.87	0.6	40.44	0.07
Rape straw	76.54	17.81	4.65	46.17	6.12	0.46	42.47	0.1
Palm kernels	77.28	17.59	5.14	48.34	6.2	2.62	37.44	0.26

2.5 Product Gas

Product gas is a mixture of combustible gases produced by gasification, containing H₂, CO, CH₄, CO₂, H₂O, C_xH_y, benzene, toluene, aliphatic hydrocarbons and tars (Đurišić-Mladenović *et al.*, 2016). When air is used as the gasifying medium, this mixture of combustible gases is termed as “product gas” whereas the term “syngas” is often used to denote the mixture of these gases where oxygen or steam is used as the gasifying agent (Sethupathy & Natarajan, 2016). The major application of product gas will be the direct use for the generation of power (and heat). This can be either in stand-alone

combined heat and power (CHP) plants or by co-firing of the product gas in large-scale power plants and need additional gas cleaning and conditioning to afford a gas with the correct composition and specifications for the final application.

2.5.1 Factors affecting product gas composition

Product gas composition is mostly dependent on gasifier, gasifying agent, gasification operating parameters such as gasification temperature, pressure, feedstock and feedstock pre-treatment etc (Lucas, 2005). Narvaez *et al.* (1996) analyzed biomass gasification process variables such as equivalent ratio (from 0.20 to 0.45), temperatures of the gasifier bed (750–850 °C) and of its freeboard (500 –600 °C), H/ C ratio in the feed, use of secondary air (10% of the overall) in the freeboard, and addition (2–5 wt %) of a calcined dolomite mixed with the biomass used as the feedstock. The results revealed ER as the most important biomass gasification factor which defines the temperatures of the bed and of the freeboard, tar yield, composition and calorific value of the product gas. On increasing ER from 0.20 to 0.45, the heating value decreased about 2 MJ/ Nm³ (negative effect) but the tar yield also decreased about 50 wt % (positive effect). Tar contents were reduced the temperature of gasifier freeboard was increased by 100 °C. Good quality raw product gas with maximum heating value and minimum tar contents could be obtained when the biomass was fed near the bed bottom with ER around 0.25– 0.30, H/ C around 2.2 (Narvaez *et al.*, 1996).

2.5.1.1 Equivalence ratio (ER)

In biomass gasification with air, ER is an important operational variable (Turn *et al.*, 1998) which has a noteworthy influence on product gas composition. ER is a measure of external oxygen (or air) supplied to the gasifier and is calculated by dividing the actual oxygen (or air) to biomass molar ratio to the stoichiometric oxygen (or air) to biomass molar ratio. Both oxygen and air can be used as the gasifying and fluidizing medium. Using air instead of oxygen as the gasifying medium can be economical by avoiding the use of costly air separation unit but has the negative effect of diluting the product gas due to the presence of nitrogen in the air (Mahishi & Goswami, 2007).

Sheth and Babu (2010) determined that an optimum equivalence ratio is necessary for accelerating gasification and drying rate due to conduction and convection process which also increases the biomass consumption rate. The optimum equivalence ratio varies for different biomass due to the amount of oxygen elementally present in the biomass as well as in the ash content. The existing literature shows that equivalence ratio should be around 0.2 - 0.4 for the successful gasification as shown in Table 2.7 (Gautam, 2010). Increasing ER increases the temperature inside the gasifier but decreasing char formation inside the gasifier. All combustible products reduce with an increase in ER with the formation of a higher amount of CO₂ as well as the total gas yield greatly diminishing the heating value of the final syngas.

Table 2-7: Optimum ER values for different gasifier and biomass type (Gautam, 2010).

Gasifier Type	Feedstock	Optimum ER	Reference
Fluidized Bed	Rice Husk	0.2–0.55	Narvaez <i>et al.</i> (1946)
	Pine Woodchips	0.3	Natarajan <i>et al.</i> (1998)
	Pine Saw Dust	0.2	Gil <i>et al.</i> (1999)
Down Draft	Furniture wood + charcoal	0.38	Zainal <i>et al.</i> (2002)
	Olive kernels and olive tree cuttings	0.2	Skoulou <i>et al.</i> (2008)
	Hazelnut shells	0.28	Dogru <i>et al.</i> (2002)
	Furniture waste	0.2	Sheth & Basu (2009)

The effect of ER on the gasification of rice husk was investigated by Kook *et al.* (2016) in a bubbling fluidized bed gasifier. It was identified in this study that ER has a pivotal effect on the gas concentrations as presented in Figure 2-10. With increase in ER, the concentrations of CO, H₂ and CH₄ decreased while the concentration of CO₂ increased.

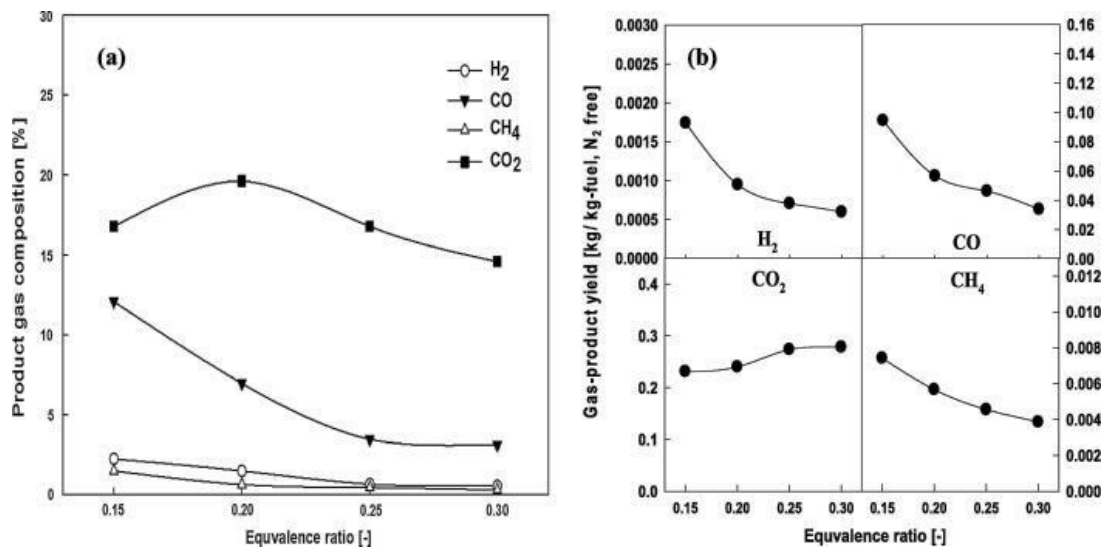


Figure 2-11: Effect of ER on gas components' concentration (Kook *et al.*, 2016).

Wan Ab Karim Ghani *et al.* (2009) found out that the equivalence ratio had the most pronounced effect on the reactor temperature, the gas composition, the gas yield, and the gas heating value as presented in Table 2-8. The selection of a suitable equivalence ratio would depend on the final use of the gas produced. As a higher equivalence ratio (ER) had complex effects on the tests results and there existed an optimal value for this factor, which was different according to different operating parameters. The influence of equivalence ratio on the performance of a gasifier could be regarded as the effect of reactor temperature as the reactor temperature was determined to be ER dependent.

Table 2-8: Comparison of product gas yield (mol /kg biomass) and gas LHV (kJ/Nm³)

(Wan Ab Karim Ghani, Moghadam et al. 2009).

Equivalence Ratio (ER)	Gas Yield (mol/kg biomass)			Gas LHV (kJ/Nm ³)		
	Coconut shell	Palm shell	Kernel	Coconut shell	Palm shell	Kernel
0.15	0.31	2.7		117	2286	
0.20	0.41	4.02		190	2863	
0.25	1.08	2.81		473	3467	
0.30	0.64	1.86		261	1812	
0.45	0.25	1.08		85	1482	

Miccio *et al.* (2009) explored the performance of the producer gas from two different raw materials i.e. beech wood and dry granulated sewage sludge in a bubbling fluidized bed gasifier with quartz bed material. Focusing the effect of process temperature and ER on the performance of the producer gas, it was found that composition of the producer gas is independent of whatever fuel was gasified. The process performance was poor for sewage sludge while the tar yield was high for both of fuels and even higher with a blend of fuels while the tar concentration for beech wood was more than that of dry sewage sludge. Gasification of beech wood at 900 °C showed no evidence of

ash accumulation in the bed while in sewage sludge ash skeletons were retrieved in the discharged materials with a change in color of sand.

2.5.1.2 Temperature

According to Mahishi and Goswami (2007), the gasification temperature not affects only the product yield but also governs the process energy input. Gasification temperature (800–850 °C) results in the production of a gas mixture that is rich in H₂ and CO, higher hydrocarbons and a small amount of CH₄. Low temperature may result in the presence of solid carbons (C) and methane (CH₄) containing product gas. It is necessary to ensure that the product gas is free of any solid carbon. As temperature increases, both carbon and methane are reformed. At about 1000K both are reduced to very small amounts and in the process get converted into CO and H₂ (Mahishi & Goswami, 2007).

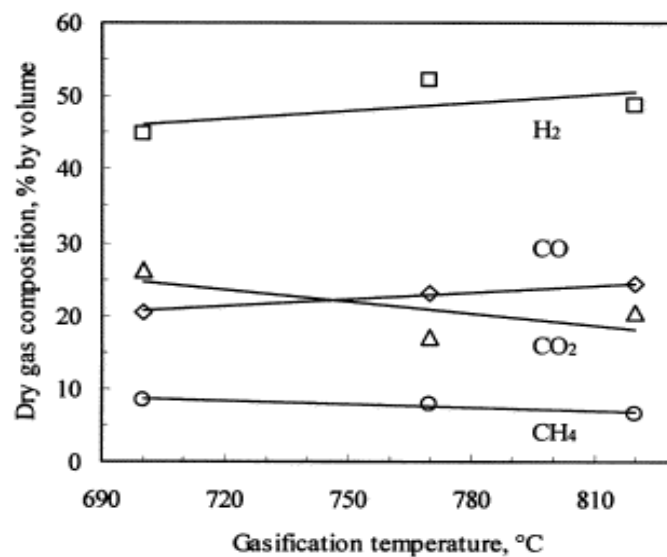


Figure 2-12: Gas yield as a function of gasification temperature (Rapagna et al., 2000).

Effect of temperature on product gas yield was also investigated by S Rapagna *et al.* (2000) in steam gasification of biomass in a fluidized bed of olivine particles as presented in Figure 2-11. The gasification temperature was examined over 700–820 °C. It was found that the dry gas yield was 1.5 times at the maximum temperature than that of the dry gas yield at 700 °C.

Boerrigter and Rauch (2005) indicated that an increase in the gasification temperature results in the reduced tar content as well as decreased char inside the gasifier which consequently increases the gas yield as more tar cracking results in more product gas yield. High temperature can be achieved by providing heat in the gasifier directly or indirectly. Optimum gasification temperature ranges ca. 600–1000 °C. One of the means of increasing temperature is by internal recirculation of syngas. The temperature of the gasifier reactor is dependent on various factors such as moisture content of the fuel, ER, heat losses from the system, and amount of steam added (Chum & Overend, 2001).

Mahishi and Goswami (2007) explored the effect of temperature on gasification and found its effects on product yield and process energy input. A gas mixture of rich H₂ and CO₂ is produced with low CH₄ and higher hydrocarbons at high gasification temperature (800–850 °C).

Hoque and Bhattacharya (2001) gasified coconut shells in a fluidized and a spouted bed to study the effects of gasification temperature on individual gas components, yield and heating values of the product gas. The results showed that the product gas quality (heating value and yield) improved with an increase in the bed temperature. In addition, fluidized bed was found to be superior over spouted bed in the gasification study.

Aigner *et al.* (2011) investigated the effect of temperature on tar component and composition in the product gas of a 100 kW dual fluidized bed gasifier. It was observed that at high temperatures, tar composition shifted to high molecular tars as polyaromatic hydrocarbons or PAHs.

2.5.1.3 Biomass elemental composition

Gautam (2010) described that biomass elemental composition has a plentiful effect on the product gas composition. Pyrolysis is vastly reliant on hydrogen/carbon ratio as well as oxygen/carbon ratio and increases when these ratios increase, especially with an increase in Hydrogen/Carbon ratio. A higher oxygen concentration in biomass needs lower ER for gasification because of its inherent oxygen that will also be available for gasification (Chum & Overend, 2001).

The ash content of the feedstock is also an important factor affecting biomass gasification (Corton *et al.*, 2017). Although the formation of clinkers can cause

problems for the gasifier operation with biomass having ash content above 5%, successful gasification with ash content up to 25% has been reported. Higher ash content causes slugging, and consequently ash agglomeration due to fusion, the rate of which is dependent upon the ash content in biomass and ash composition (Gautam, 2010).

2.5.1.4 Biomass particle size

The appropriate size of biomass particles is vital in biomass gasification (Tinaut *et al.*, 2008). The small particle size facilitates the fast rate of heat transfer and gasification by providing more surface area and pores (Kirubakaran *et al.*, 2009). Higher gas yields were observed with the smaller particle size (Lv *et al.*, 2004; Sergio Rapagna & Latif, 1997).

Hernández *et al.* (2010) inspected the effect of fuel particle size of grapevine pruning and sawdust wastes, marc of grape and a fossil fuel (a coal– coke blend) in relation to the product gas quality in an entrained flow gasifier. The results obtained in this investigation depicted that a reduction in the fuel particle size leads to a weighty increase in concentration of all the combustible components of the product gas as presented in Figure 2-12.

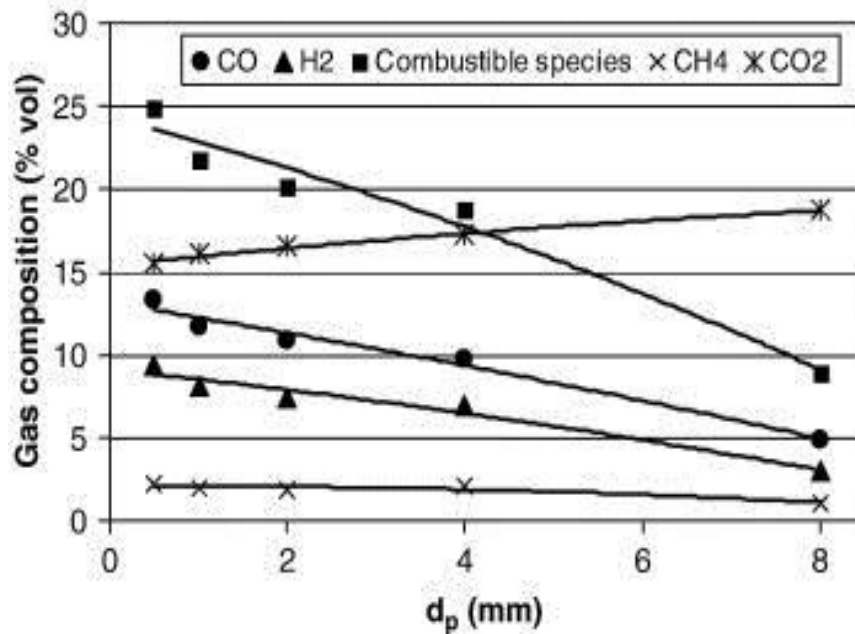


Figure 2-13: Effect of fuel particle size in relation to the product gas quality in an entrained flow gasifier (Hernández *et al.* (2010))

Moisture contents in biomass play an important role in energy consumption and high moisture contents in biomass have an adverse effect on thermal equilibrium in biomass gasification process (Jenkins *et al.*, 1998). The desired range of moisture contents must be maintained through drying biomass for higher gas yield and less energy consumption in the gasification process.

In comparison with fixed bed gasifiers, fluidized bed gasifiers have more strict requirements for particle sizes. Usually, the feed size less than 51 mm and 6 mm is recommended for fixed bed and fluidized bed, respectively (Gautam, 2010).

2.5.1.5 Gasifier pressure

Valin *et al.* (2010) investigated the effect of gasification pressure on syngas composition in a fluidized bed biomass gasifier with wood sawdust as the feedstock within the range from 2 to 10 bars. It was observed that the concentrations of CO₂, CH₄ and H₂ increased while CO decreased with an increase in the gasifier pressure. With steam and N₂ as the gasification medium, an increase of 16%, 53% and 38% of H₂, CO₂ and CH₄, respectively and a decrease of CO by 33% were found when the pressure was increased from 2 bars to 10 bars. The dry gas yield was found to increase by 20% with the increase of pressure from 2 bars to 7 bars after which the gas yield remained constant as shown in Figure 2-13.

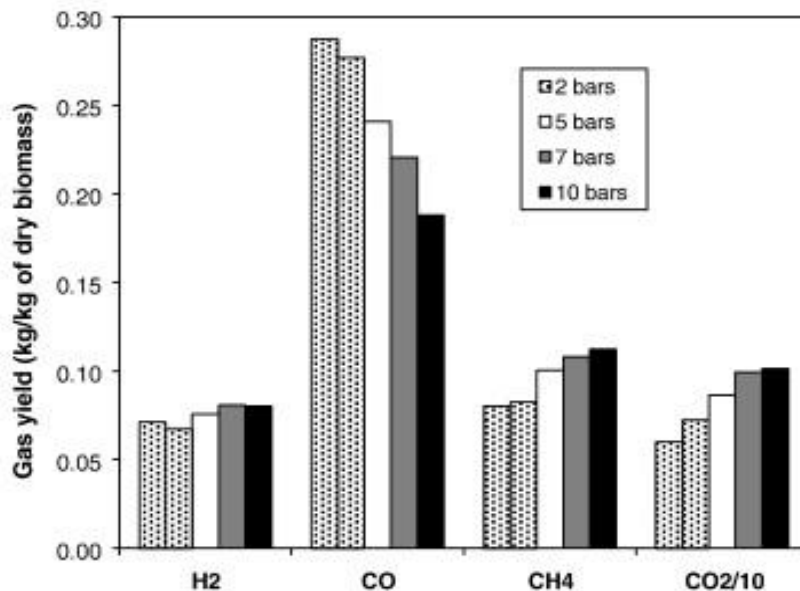


Figure 2-14: Concentrations of product gas components as a function of pressure (Valin *et al.*, 2010).

Altafini and co-workers (2003) reported that an increase in pressure resulted in reduced hydrogen and carbon monoxide concentrations. It was also established that very low pressures (10.13 kPa) leads to an increased yield of H₂, however, the increase was found to be negligible (less than 0.2%). Low pressure does not provide substantial improvements and high pressure reduces H₂ yield. They also concluded that the atmospheric pressure was the best condition for fluidized bed gasifiers (Altafini *et al.*, 2003).

2.5.1.6 Gasification medium and secondary air

Air, oxygen, steam or a combination of these can be used as a gasifying agent in biomass gasification reactor (Thanapal *et al.*, 2012). The process of gasification carries on in the presence of a gasification agent or commonly called oxidizing agent at high temperature. Gil *et al.* (1999) studied the effect of gasifying agents including air, pure steam, and steam-O₂ mixture on the composition of product gas, char and tar yields and the product gas quality in atmospheric and bubbling fluidized bed gasifiers as presented in Table 2-9.

When air is the gasifying medium, the major component of the product gas is nitrogen. The air to fuel ratio (ER) in a gasification process usually ranges from 0.20–0.4. The concentrations of CO, CO₂, H₂O, H₂, CH₄ and other gaseous hydrocarbons depend on partial oxidation of the volatile products (Safitri, 2005), and hence the air to fuel ratio used.

Table 2-9: effect of gasifying agents including air, pure steam, and steam-O₂ mixture on the composition of product gas (Gil *et al.* 1999)

Operating Conditions	Air	Steam (pure)	Steam-O ₂ mixture
ER	0.18–0.45	0	0.24–0.51
S/B (kg/kg daf)	0.08–0.66	0.53–1.10	0.48–1.11
T (°C)	780–830	750–780	785–830
Gas composition			
H ₂ (vol %, dry basis)	5.0–16.3	38–56	13.8–31.7
CO (vol %, dry basis)	9.9–22.4	17–32	42.5–52.0
CO ₂ (vol %, dry basis)	9.0–19.4	13–17	14.4–36.3
CH ₄ (vol %, dry basis)	2.2–6.2	7–12	6.0–7.5
C ₂ H _n (vol %, dry basis)	0.2–3.3	2.1–2.3	2.5–3.6
N ₂ (vol %, dry basis)	41.6–61.6	0	0
Steam (vol %, wet basis)	11–34	52–60	38–61
Yields			
Tars g/kg daf	3.7–61.9	60–95	2.2–46
Char g/kg daf	na	95–110	5–20
Gas Nm ³ /kg daf	1.25–2.45	1.3–1.6	0.86–1.14
LHV MJ/Nm ³	3.7–8.4	12.2–13.8	10.3–13.5

Sutton *et al.* (2001) reported that the high heating value (HHV) of the product gas of air gasification was low as 4–7 MJ/Nm³ due to inherent dilution with N₂ present in the air. On the contrary, gasification with oxygen produced a product gas with a heating value

of 10–12 MJ/ Nm³ and steam gasification resulted in a product gas with heating value even higher, 15–20 MJ/ Nm³. Secondary air reduced the tar content in the syngas due to partial combustion of the product gas.

2.6 Tar and biomass gasification

Tar is a highly viscous carbon as presented in Figure 2-11, containing a compound which is found from liquid to highly viscous to solid deposits by cooling of the gaseous phase to the ambient temperature (Aigner *et al.*, 2011). Tars contain oxygen, nitrogen and sulphur besides their main constituent; carbon and hydrogen. Milne and Evans (1998) stated that the organics produced under the thermal or partial oxidation regime (gasification) of any organic materials, are called tars and are generally assumed to be largely aromatic. Tar can also be defined as a complex mixture of condensable hydrocarbons including single to multiple aromatic compound rings along with other oxygen containing hydrocarbons and complex polyaromatic hydrocarbons (Devi *et al.*, 2003).

2.6.1 Tar classification

Tar classification is defined in different kinds of literature on the basis of their composition and nature. There are five major tar classes (Devi *et al.*, 2003; Milne & Evans, 1998).

Class 1- GC undetectable: Tar compounds that cannot be detected and include tar compounds heavier than coronene and are determined by subtracting GC-detectable tar fraction from the total gravimetric tar.

Class 2- Heterocyclic aromatics: These include aromatic compounds with heteroatoms (e.g. oxygen and nitrogen), and are compounds with higher water solubility. These include pyridine, phenol, cresole and quinoline.

Class 3- Light aromatics (1 ring): These tars are with 1 aromatic ring and do not contribute to tar related problems. These include xylene, styrene, and toluene.

Class 4- Light PAH compounds (2-3 rings): These include tar compounds with 2-3 aromatic rings and condense while gas is cooled down to 20 °C. Naphthalene, biphenyl, acenaphthylene, fluorine, phenanthrene, anthracene are included in this class.

Class 5- Heavy PAH compounds (4-7 rings): Tars with 4-7 aromatic rings which are condensed as gas is cooled down to 20 °C. Fluoranthene, pyrene, chrysene, benzo-fluoranthene, benzo-pyrene and perylene are classified as heavy polyaromatic compounds (PAH).

2.6.2 Tar formation in biomass gasification

The Cellulose, hemicellulose and lignin are the three basic components of a biomass (Wu *et al.*, 2017). Ideally a biomass consist of 1/3 of each type, however, wood have higher lignin content than straw (Pedersen & Larsen, 1999). The gasification starts with heating and drying of the biomass. Subsequent heating of the biomass results pyrolysis which initiates at about 230 °C, where the complex polymers in the biomass are broken down resulting in a gas consisting mainly of CO₂, H₂O, CH₄, CO, H₂, tar and char.

In the gasification systems, tar is considered as a major pollutant of the product gas (Pumiglia *et al.*, 2017). Formation and concentration of tar in the product gas also indicates the performance and efficiency of a gasification system (Asadullah, 2014). Each type of the gasifier reactor has a different effect on the tar formation, concentration and tar yield. In gasification of biomass, the feedstock composition and gasification operating parameters such as gasifier type, the composition of feedstock, gasifying agent, pressure, temperature and equivalence ratio are the main components responsible for quality and quantity of tar yield (Huang *et al.*, 2011). AV Bridgwater (1995) found that the gasification of wood shows higher tar concentrations with the higher amounts of stable aromatics in comparison to coal or peat.

The composition of a specific tar is dependent on many factors like the nature of fuel used and the gasification process itself (Abu El-Rub *et al.*, 2004).

Li and Suzuki (2009) have articulated biomass gasification for biomass utilization method, the most promising technology to produced biomass energy. They described through their research that product gas contains an unacceptable level of tars. For the successful application of product gas tar production control is a key factor.

Rabou *et al.* (2009) stated that gasification below 1300 °C yields product gas which contains different heavy hydrocarbons collectively known as tar. These tars cause fouling and blockage of their research equipment. Different tar measurement techniques including tar guideline, solid-phase adsorption (SPA) method and tar dew point analyzers were discussed and compared by Rabou *et al.* (2009). The effects of gasification operating conditions, biomass fuel composition and bed materials on tar formation and tar prevention were also been studied. They found that product gas cleaning was the best achieved by oils scrubbing. Tar reducing measures played vital roles to reduce tar formation and to simplify tar removal from product gas while the use of water was also an effective mean.

Han and Kim (2008) detailed that higher amount of tar in the product gas reduces utilization efficiency and suitability of biomass for gasification technology. They overviewed different literature related to tar reduction and tar destruction methods and classified them into five main groups i.e., mechanism methods, self-modification, plasma technique, thermal cracking and catalyst cracking. They found that mechanism methods are very effective to capture fly ash particles and to remove tar. Different

mechanism methods such as water scrubber, venturic scrubber, rotational particle separator and cyclone etc. can capture about 40-99% tars. However, the energy contained in tars is lost by using these technique. The self-modification i.e., selecting better gasifier and an optimizing operation parameters of gasification not only reduces tar but also converts them into the useful gases.

Devi *et al.* (2003) described tar formation as one of the major causes of equipment blocking and fouling such as engines and turbines. Tar condenses at the reduced temperatures. They divided tar removal into two main types, i.e. secondary and primary method. The secondary method involves hot gas cleaning after the gasifier and the primary method involves hot gas cleaning inside the gasifier, in which the gasifier is optimized to minimize tar formation which can be achieved by proper selection of an operative parameters such as temperature, gasifying agent/medium, equivalence ratio, gasification residence time etc. Bed additives/ catalysts such as dolomite, olivine, char or Ni-based catalysts were found to be effective to reduce the tar and nitrogenous compounds (such as ammonia). Gasifier reaction modifications could also improve the product gas quality.

According to Philipp Hasler and Nussbaumer (2000), tars and particulate matter were harmful components for internal combustion engine applications. They pointed out analysis of the sample and long duration sampling of the product gas should be implemented. They concluded that the heavy tars could be excellent indicators for

product gas assessments as they deposited more preferentially than poly aromatic hydrocarbons (PAH) both in engine manifolds and in cylinders.

2.6.3 Tar treatment (tar removal) from the product gas

Many researchers have described different methods of tar removal/conversion based on intensive research in the fluidized bed biomass gasification. On the basis of the locality where tars are removed/ converted, two methods are defined and known as the primary method and the secondary method (Xiao *et al.*, 2010).

In the primary method tars are treated inside the gasifier (Sikarwar *et al.*, 2016) in which the gasifier is optimized to minimize tar formation which can be achieved by proper selection of an operative parameters such as temperature, gasifying agent/medium, equivalence ratio, gasification residence time etc. itself including to select proper operational parameter, to select proper fuel characteristics, the use of catalysts or additives in the bed, and the modification of gasifier (Devi *et al.*, 2003) while in the secondary method tar treatment is carried out outside of the gasifier which is more efficient, economical and easier to control because tar will be removed by outside installed gas cleaning equipment gasifier including thermal cracking, catalytic cracking and mechanical treatments such as the use of cyclones, baffled filters, fabric filters, ceramic filters, rotating particle separators, electrostatic filters and scrubbers etc. (Wang *et al.*, 2008).

2.6.3.1 Primary (in-situ) tar removal methods

Despite the proven effectiveness of secondary methods, primary methods of tar removal have caught the most attention, since they would eliminate the need for cleaning the gas. In a primary treatment, gasification is optimized to produce a gas with the minimum concentration of tar. Primary methods can involve such factors as (1) selection of specific operational parameters, (2) the use of catalysts in the bed, and (3) modification of the gasifier (Pereira *et al.*, 2012). Operational parameters such as the temperature, gasifying agent, equivalence ratio, and gas residence time are of extreme importance for the formation and decomposition of tar.

Primary methods do not need secondary reactors and are employed inside the gasifier to achieve tar reduction by controlling operating conditions, gasifier design and by using an in-bed catalyst. Altafini *et al.* (2003) reported that these in-bed catalysts also facilitate combustion of tars into combustible gases along with increasing gasification reaction rate at low gasifier temperatures. Copious biomass gasification investigations have revealed the effect of gasification operating parameters such as gasification temperature, gasifying agent, ER, total gasifying agent to biomass ratio, and biomass feeding rate on the total tar amount in the product gas.

In the “self-modification method”, temperature, pressure, equivalence ratio (ER), gasifying medium, gas residence time, biomass type and gasifier type play key roles in product gas composition and tar fractionation, concentration and yield. Van Paasen *et*

al. (2002) investigated the gasifier operating conditions' influence on tar formation in a bubbling fluidized bed biomass gasifier. It was found that increasing the bed temperature (up to 950 °C) from 750 °C, led to the tar composition changing from alkyl substituted polyaromatic hydrocarbons (PAH) and oxygen and nitrogen containing tars to non-substitute polyaromatic hydrocarbons (PAH).

Bed additives/ catalysts such as dolomite, olivine, char or Ni-based catalysts were found to be effective to reduce tar and nitrogenous compounds (such as ammonia). Gasifier reaction modifications could also improve the product gas quality (Devi *et al.*, 2003).

Al-Dury (2009) used different carbon materials as additives for cleaning of the product gas at 70–110 °C. It was found that adsorption capacity was mainly reliant on the particle size of the carbon material as larger specific surface area and smaller particle size was beneficial in the lighter tar removal; gasification temperature also had an impact on tar removals. Activated carbon, coal char and coke with the high specific surface area and average small particle size were found to be most effective in removing the tars from the product gas. These carbon materials were proved as a cheap and effective way of cleaning product gas in biomass gasification at low temperatures.

Pereira *et al.* (2012) found that tar condenses under reduced temperatures, polymerizing in such equipment as engines and turbines. Many researchers have described different

methods of tar removal/conversion based on intensive research in fluidized bed biomass gasification. On the basis of the locality where tars are removed/ converted, two methods are defined and known as the primary method and the secondary method. In the primary method tars are treated inside the gasifier while in the secondary method tar treatment is carried out outside the gasifier (Asadullah, 2014). Wang *et al.* (2008) observed that an addition of 20% of secondary air above the biomass feeding point resulted up to 88.7% (wt) decrease in the total tar at temperatures 840–880 °C.

Thermal cracking of tar is the process of treating tars at certain temperatures for a specific residence time resulting conversion of tar into lighter gases. High gasification temperature results in low tar yield and high product gas. According to Han and Kim (2008), efficient tar cracking could be achieved at a temperature of 1250 °C and 0.5 sec of residence time. In experimentation of Myren *et al.* (2002), the gasification of raw materials from birch, miscanthus and straw at temperatures 700 °C, 850 °C and 900 °C was investigated. They observed that benzene and naphthalene increased as a result of an increase in temperature while other lighter tar compounds were found to have decreased.

Mayerhofer *et al.* (2012) investigated the effect of gasification operating conditions on the quality of fuel gas in an allothermal bubbling fluidized bed steam gasifier with a bed temperature of 750–840 °C, steam to biomass (S/B) ratio of 0.8–1.2 and pressure of 0.1–0.25 MPa. They observed that an increase in the temperature resulted in a decrease

of total tar content, specifically heterocyclic and light aromatic compounds. It was also found that as contrary to pressurized fluidized bed gasifiers, at atmospheric pressure the naphthalene content increased slightly with the increasing temperature. Increasing Steam/Biomass ratio also decreased the total tar contents while increasing pressure led to an increase in the total tar content mainly due to naphthalene as presented in Figure 2-15.

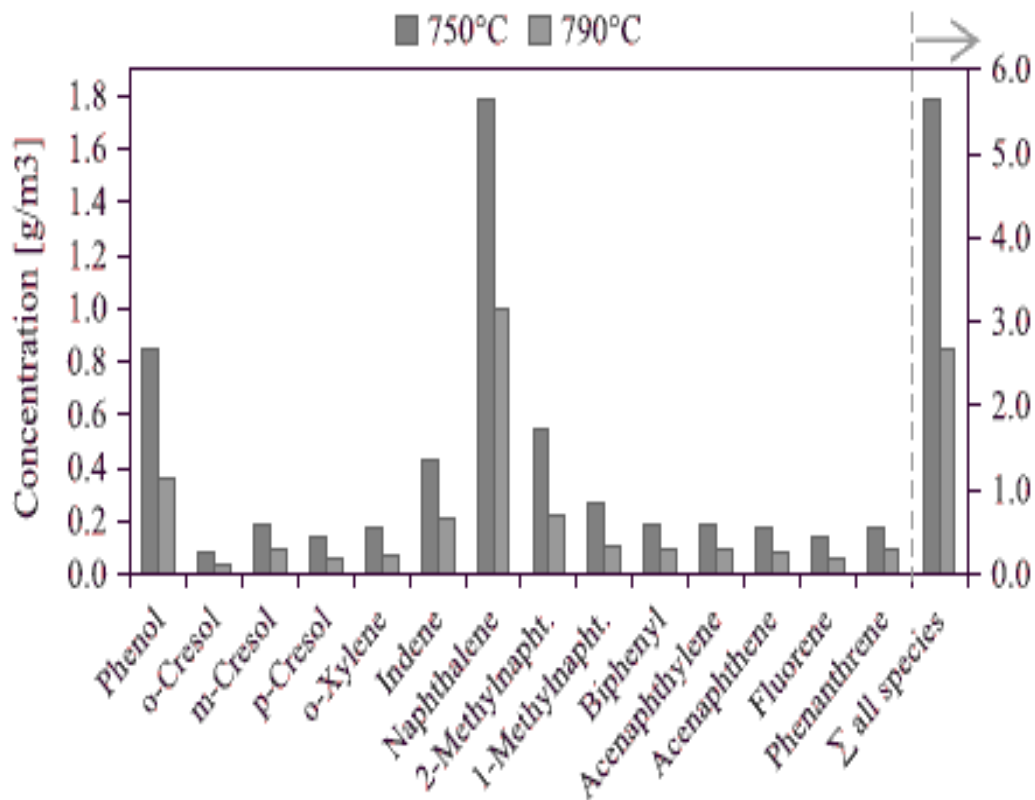


Figure 2-15: Influence of reactor temperature on tar composition in (g/m³) for S/B ratio 1.2 at 0.25 MPa (Mayerhofer *et al.*, 2012).

Aigner *et al.* (2009) studied the influence of temperature on the tar content and composition in the product gas of fluidized bed gasification and low temperature pyrolysis of straw and wood. (Figure 2-16).

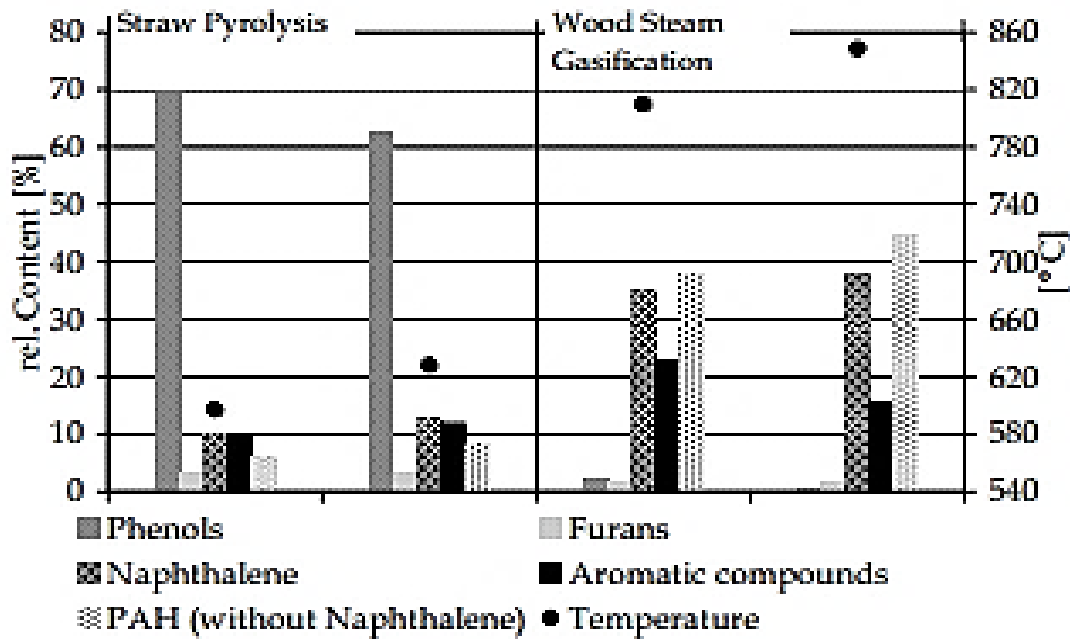


Figure 2-16: Comparison of relative tar composition of pyrolysis and steam gasification at different temperatures (Aigner *et al.*, 2009).

The experiment was carried out in 100 kW dual fluidized bed steam gasifier at a temperature range of 700–870 °C while pyrolysis experiments were conducted in a rotary kiln reactor at a temperature between 600–630 °C. They observed that at higher temperatures, high molecular tars (poly aromatic hydrocarbon (PAH)) were the main tar components, whereas phenols were the key tar components at low temperature (pyrolysis).

According to Bergman *et al.* (2002), primary tar removal methods do result in lower tar emissions, but have yet to achieve the satisfactory levels of tars in the product gas for many applications such as gas engines and gas turbines etc. In addition, they have limitations in terms of feedstock feasibility, the scale-up efficiency of cold gas and complex gasifier constructions. Therefore, primary methods are not feasible without applying secondary methods of tar removal from the product gas.

2.6.3.2 Secondary (post gasifier) tar removal methods

The secondary methods mainly consist of downstream cleaning of the hot gas. Secondary tar removal methods mainly include physical or mechanical methods and chemical methods.

- a. Physical or mechanical methods:** Physical removal of tar from the gas stream is termed as a physical method by Han and Kim (2008). According to Wang *et al.* (2008), the physical methods include scrubbers (dry scrubbers, wet scrubbers), filters (fabric filters, bag filters, ceramic filters and baffle filters), electrostatic precipitator (ESP) and cyclones. These physical methods can be operated efficiently at low temperatures. At temperatures lower than 450 °C, tars start to condense and form aerosols. These aerosols are heavier than water vapors and can easily be separated from the product gas by simple filtration. Venturi scrubbers were efficient in removing tars 51–91% from product gas in a counter-current gasifier for rice husk. Water and other wet scrubbers are also proven effective in capturing contaminants, tars and particulate matter. Salam *et al.* (2010) reported

that the tar level reduction to 20–40 mg/m³ and particulate matter reduction by 10–20 mg/m³ could be achieved by using water scrubber. The energy contained in the tars is lost when the tar was removed by wet scrubbers. Wet scrubbers are also disadvantageous as they reduce the product gas temperature during the wet scrubbing process, leading to a decrease in the efficiency of the gasification process. Further, the wastewater treatment adds extra cost to this method.

b. Chemical methods: Chemical methods include thermal cracking, catalytic cracking and plasma cracking. According to Bosmans *et al.* (2013) thermal cracking of tars involves the conversion of tars into lighter gases by subjecting the tars to a sufficiently high temperature for a certain time. Typically, temperatures between 1100 °C and 1300 °C are employed; the lower the temperature, the higher the residence time required for effective cracking while catalytic cracking use both primary and secondary methods”.

Chiang *et al.* (2013) investigated two stage fixed bed electric heated gasifier consisting of an in-situ catalytic gasifier and a hot gas cleaning system. In this research they found a significant decrease in tar yields as a result of increasing zeolite addition during in-situ catalytic gasification. The hot gas cleaning system was a multipack tower with a series of three columns to capture particles containing tar. The columns were filled with zeolite, dolomite and activated carbon respectively. As the product gas from gasification passed through the hot gas cleaning system, tar concentration was found further decreased. Major tar types found in the product gas after passing through the hot

gas cleaning system were; 1- ring and 2- ring hydrocarbons such as benzene, toluene, xylene, styrene and naphthalene. They found their product gas suitable for gas engines for the production of electricity.

Jordan and Akay (2013) investigated the effect of CaO on tar production and dew point depression during gasification of fuel cane bagasse in a novel downdraft gasifier. Granular CaO was used to study its effects on the product gas yield, tar composition, concentration and dew point. It was found that 2,3 and 6wt% in-bed CaO promoted the conversion of class 1,4 and 5 tars to be converted into class 3 tars and overall this resulted in a decrease of 16-35% tar yield, 44-80% in tar concentration, 17–37% increase in the product gas. The tar dew point was decreased by 37–60 °C with an increase of CaO concentration from 2–6 wt%.

An extensive literature was reviewed by Sutton et al. (2001) on the efficiency of different catalysts used to eliminate condensable organic compounds (hydrocarbons) which are produced during biomass gasification and considered as the main hurdle in applications of biomass gasification technology in different fields.

Miccio *et al.* (2009) studied biomass gasification in a catalytic fluidized reactor focusing the effect of four different materials as catalysts on the product gas composition and tar concentration. Four bed materials were used in this experimental work: inert quartzite as the reference case, olivine and dolomite as the natural catalysts

and Ni-alumina as the artificial catalyst under typical operating conditions in a bubbling fluidized bed biomass gasifier. Ni-alumina, the artificial catalyst was found to be more effective in reducing tar concentration up to 50% as compared to the reference catalyst; its presence also had an effect on the nature of tar. The effect of olivine was found to have slightly increased H₂ concentration in the product gas and contribute to the tar conversion to lighter hydrocarbons. Ni-alumina was the most stable catalyst investigated by this study.

Anis and Zainal (2011) explained that the successful application of producer gas depends not only on the quantity of tar which is associated with the dew-point of tar components, but also on its properties and compositions. After reviewing the literature on tar reduction processes, they concluded that different methods applied in tar removal had different pros and cons.

The equilibrium and semi-equilibrium models can predict the qualitative assessment of gasifier performance under different operating parameters. The kinetic model provides physically more representative comprehension into the different aspects of the gasification process and divulges relative influence of a number of operating and design considerations on the gasification process.

Three equilibrium modelling methods of the biomass gasification process have been discussed in the literature viz. kinetic modelling, semi equilibrium modelling and equilibrium modelling.

The kinetic models of a biomass gasifier mainly defines the char reduction process on the basis of kinetic rate expressions obtained from the experiments for the simulation of the experimental data for the gas of short residence time. The kinetic equilibrium model divulges the biomass conversion process and is helpful in designing and evaluation of the gasifier modelling. Many researchers have focused on kinetic modelling of biomass gasification. In a thermodynamic and kinetic modelling for char reduction reactions in the reduction zone of a down draft gasifier presented by Sharma 2008 focused on the chemical kinetics of this zone followed by the finite rate of reactions. Kinetic rate models always contain parameters that limit their applicability to different plants (Sharma, 2008).

Fakhim and Farhanieh (2011) introduced an equilibrium model for biomass waste gasification in a bubbling fluidized bed. It was anticipated that the idealized fluidized bed gasifier model is used with the following assumptions: (i) The chemical equilibrium between gasifier products is reached, (ii) the ashes are not considered and (iii) heat losses in the gasifier are neglected and found that the higher moisture contents can decrease higher heating value and cold gas efficiency whereas the exergetic efficiency of the product gas was increased. It was also determined that higher

temperature and higher gasification relative fuel/air ratio would increase both the product gas higher heating value, cold gas efficiency and the exergetic efficiency. It was also proposed in this study that in bubbling fluidized bed the bed, temperature will be in the range of 900-1200oK by which the equilibrium constants will be calculated.

Chapter 3 Experimental Setup

3.1 Gasification

Gasification of SRC willow woodchips (size: 3–10 mm) was scrutinized in a bubbling fluidized bed biomass gasifier (BFBBG) under controlled conditions of temperature, pressure, feeding rate and air flow rates. Biomass gasification, product gas composition, gas cleaning technologies and tar arrest techniques were main focuses of this research.

3.1.1 Gasifier description

The bubbling fluidized bed biomass gasifier (BFBBG) as schematically shown in Figure 3-1 consists of a fluidized bed gasification reactor, a cyclone, biomass hopper feeder, screw feeder, a gas cooling unit, a tar removal unit (a mop fan unit, a biomass/char bed), an electrically heated combustor, an air supply/ preheating system and data acquisition devices.

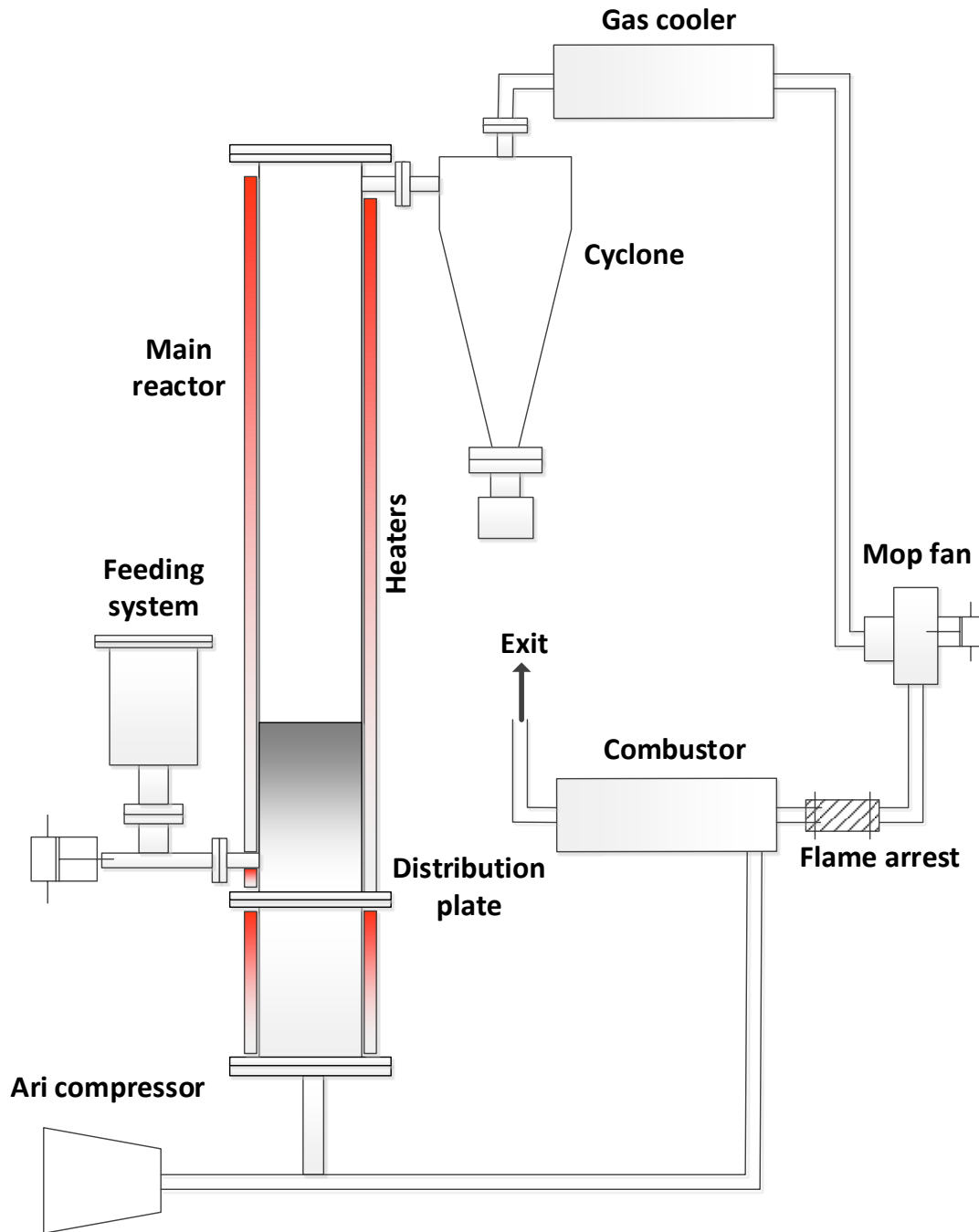


Figure 3-1: Schematic of bubbling fluidized bed biomass gasifier.

3.1.2 Biomass feeding unit

The biomass feeding unit consisted of a cylindrical shaped hopper; a screw auger connected to a geared motor, a timed stirrer is connected to the gasifier reactor to feed biomass in the reactor at controlled and desired feeding rate.



Figure 3-2: Stirrer and pressure gauge installed at woodchips hopper

The auger and stirrer facilitated the continuous and reliable feeding and prevent the channeling of biomass in the hopper. Initially a pyramid shaped biomass hopper was installed for feeding woodchips to gasifier reactor as shown in Figure 3-2, but it did not provide constant flow of woodchips as woodchips were sticking with walls of feeder. To overcome this serious feeding issue, a cylindrical shaped feeder was designed and installed which provided reliable constant flow of woodchips to gasifier reactor.



Figure 3-3: Rectangle shaped woodchip feeder hopper.



Figure 3-4: Cylindrical shaped woodchips feeder hopper.

3.1.3. Auger

The auger mechanism was attached with the woodchips hopper and powered by a geared electric motor controlled by an inverter to carry woodchips from the hopper to the gasifier reactor at desired feeding rates.



Figure 3-5: Auger feeding wood chips to the gasification reactor from the feeder hopper.

3.1.4 Gasifier reactor

A stainless steel bubbling fluidized bed gasifier reactor was installed as shown in Figure 3-6.



Figure 3-6: Bubbling fluidized bed gasifier reactor and cyclone.

Internal diameter of the reactor is 108 mm and the height is 1.8 m. A stainless steel porous plate with pore size of 100 μm and thickness 10 mm was installed at the base of the reactor which served as the air distributor. Three independently controlled heating elements which surround the reactor were used to pre-heat the reactor to reach the required gasification temperature (700–800 $^{\circ}\text{C}$). Thermocouples and pressure sensors are also installed along the reactor to monitor the fluidization and gasification process. Compressed air at ambient temperature is used as the fluidization and gasification medium.

3.1.5 Cyclone

A high efficiency cyclone was installed at the exit of the fluidized bed gasifier reactor for the primary removal of particulates. Particles are collected in the ash pot of cyclone as the product gas passes from the cyclone.

3.1.6 Gas cooler and combustor

The product gas was cooled by the cooler before being introduced into combustor in the electrically heated combustor before being released to the atmosphere.

3.1.7 Mop fan (the gas cleaning unit)

A mop fan as schematically shown in Figure 3-7 operates as a gas filter as well as a gas moving device. It utilizes a brush disk, instead of traditional bladed impellers within a centrifugal fan casing. The mop fan cleaning unit is a multifunctional device which can be used for gas circulation, de-dusting of gas stream and efficient removal of gaseous contaminants.

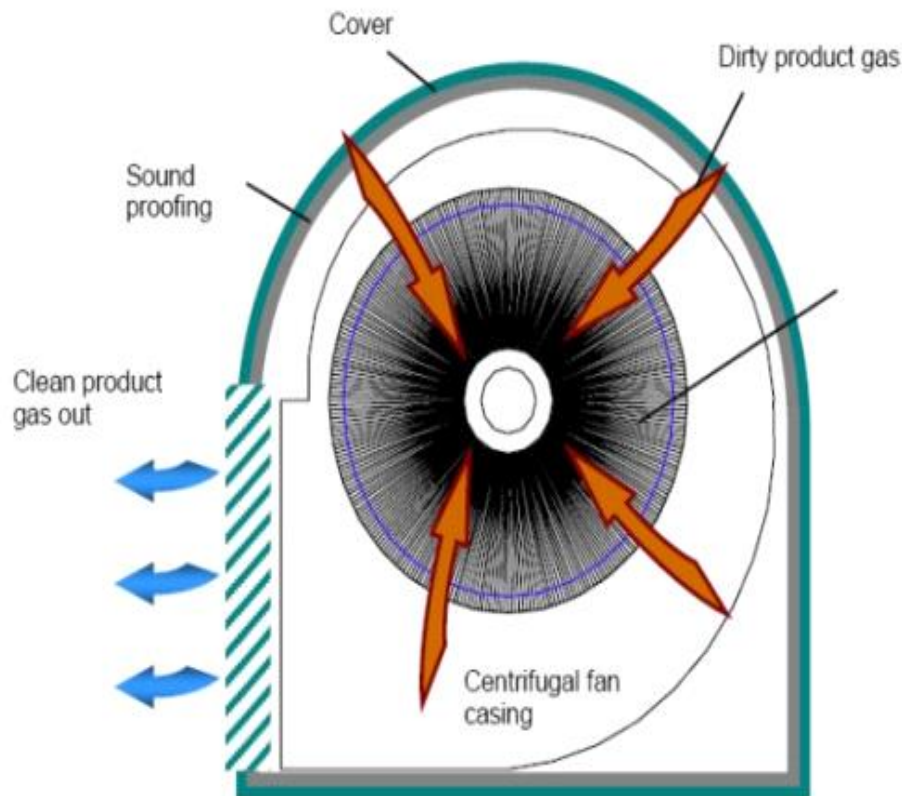


Figure 3-7: Schematic diagram of mop fan and its operation process.

For this research, the mop fan gas cleaning was proposed as an innovative method to clean the product gas from a BFBBG. As schematically shown in Figure 3-7, the

contaminated product gas containing particular matters, tar and chemical compounds enters the mop fan case, makes contact with the rotating mop fibers and is cleaned by the fibers within the case. A small amount of water was sprayed on the surface of the mop fibers to facilitate the particle and chemicals' removals. Figure 3-8 shows a real image of the mop fan used in this investigation. The fiber length of this mop fan is 70 mm and the diameter of each fiber is 0.4–0.6 mm. The performance of a mop fan in gas cleaning depends on many factors such as the fiber number, fiber diameter, fiber arrangement on the shaft, and the quantity and quality of the liquid spray.

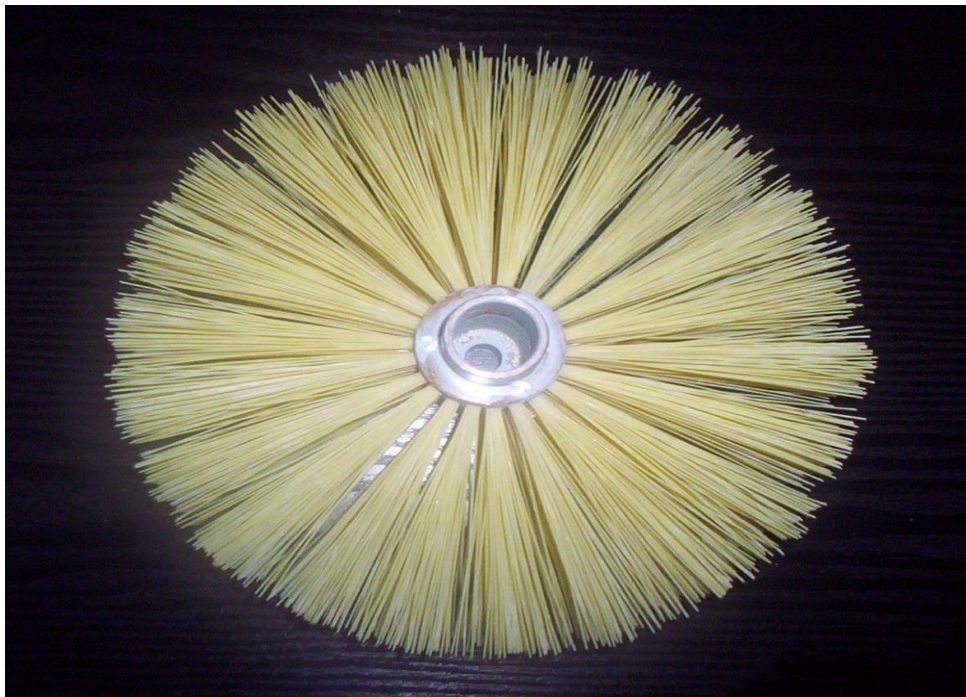


Figure 3-8: The mop fan used for product gas cleaning.

Product gas cleaning by use of the mop fan gas cleaning unit has a significant potential advantage in terms of wastewater treatment cost over conventional liquid scrubbers. The large surface areas provided by the mop fibers can ensure high removal efficiencies of particulates, tars and chemicals, while the use of smaller amount of water compared to liquid scrubbers results in a much smaller amount of wastewater which needs to be treated before disposal.

3.2 Gasification operating conditions

The gasification operating parameters such as gasifier type, bed material, gasification temperature, ER, biomass feedstock type have significant influence on the product gas composition and hence the product gas composition varies in different gasifying circumstances.

3.2.1 Bed material and fluidization

Silica sand within the size range of 212–300 μm was used as the bed material as presented in Figure 3-8. Fluidization tests under ambient conditions confirm that the bed material belongs to Geldart B particles. The bubble initiation, rising and burst can be clearly seen when the fluidization air is gradually increased as shown in Figure 3-9–3-11.

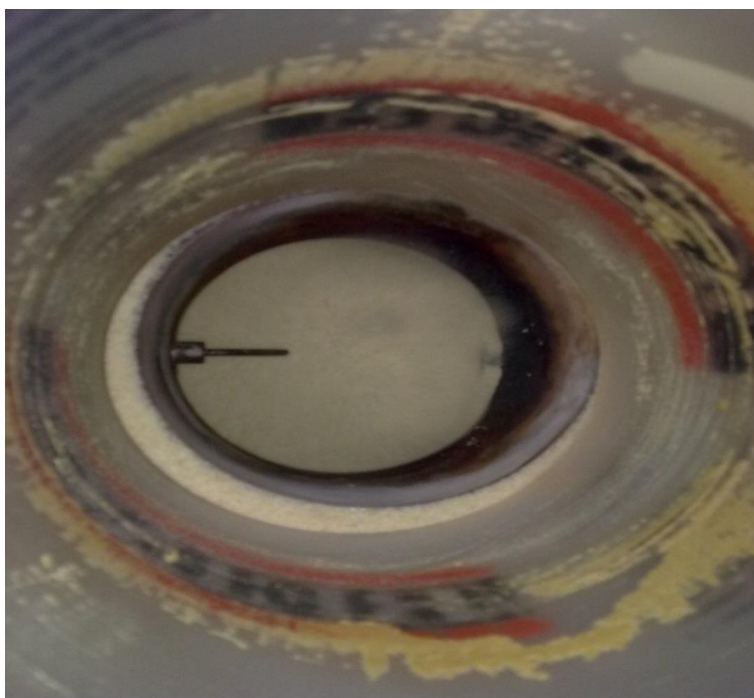


Figure 3-9: Bed material in the reactor.

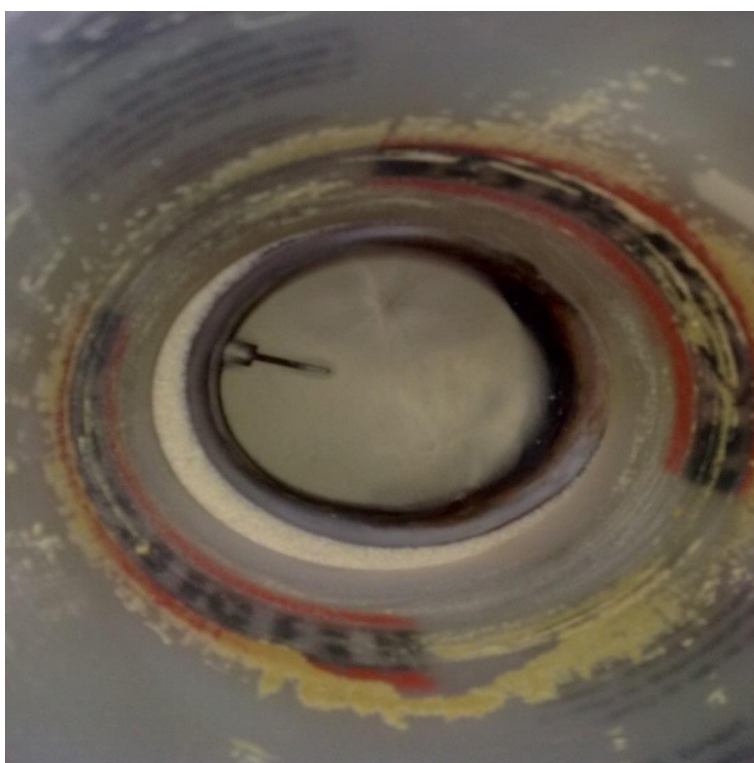


Figure 3-10: Bubble initiation in the reactor.



Figure 3-11: Air bubble rising in the reactor.

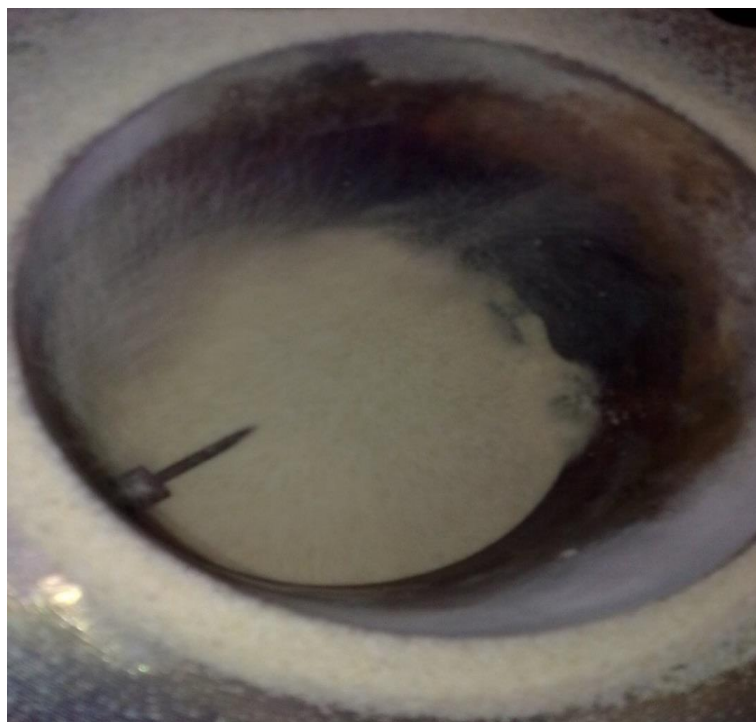


Figure 3-12: Air bubble burst in the reactor.

3.2.2 Gasifier operating conditions

Table 3-1 shows the operating conditions used in the gasification and product gas cleaning tests.

Table 3-1: Gasification operating conditions used in gasification and product gas cleaning.

Equivalent Ratio (ER)	0.319, 0.464, 0.567		
Gasification air flow rate (L/m)	45, 65, 80		
Combustion air flow rate (L/m)	150, 128, 112		
Hopper air flow rate (L/m)	3		
Heater temperature setup (°C)	Upper Heater	Lower Heater	Combuster
	660	800	850
Screw feeder motor frequency (rpm)	10, 15, 20		
Mop fan motor frequency (rpm)	10, 15, 20		
Mop fan spray water flow rate (L/m)	0.0, 0.5, 0.75		

The Equivalent ratio (ER) of the gasification was 0.328 to investigate the effect of ER on the product gas composition and heating value. The flow rate of the combustion air

supplied to the combustor was varied according to ER to ensure the total amount of air supplied into the whole system to remain constant. A small amount of air (3 lit/min, 1 atm, 15 °C) was injected into the sealed hopper to prevent the backward flowing of hot gas into the hopper. The biomass feeding rate was calibrated when the auger motor frequency was set to 10 Hz (50 rpm) and 12.5 Hz (62.5 rpm). Different mop fan rotational speeds and different spray water flow rates were tested to evaluate the performance in terms of removing particulate matters and certain chemical compounds presented in the product gas.

3.3 Product gas composition analyzers

In this study, particle loadings at the inlet and outlet of the mop fan unit were measured by a dust monitor TSI DustTrak as shown in Figure 3-13, to evaluate the particle removal efficiency of the selected mop.



Figure 3-13: TSI DustTrak used to measure the concentration of dust particles

(<http://www.jiahuazhongxin.com/>).

A water trap bottle was also used to capture the particulate matters in the sampling product gas. The dirty water containing particles was then filtered by filter paper. The net weight of particles captured was determined by drying the filter paper at room temperature.

The composition of the product gas from the gasifier was determined by an off-line gas chromatography (GC) method, whereas the gas composition at the exit of the combustor was continuously measured by on-line ABB EasyLine analyzer as shown in Figure 3-14, for CO, CO₂ and O₂, Horiba NO/NO_x analyzer for NO/Nox is shown in Figure 3-15.



Figure 3-14: ABB online gas analysers equipped with sampling unit.



Figure 3-15: HORIBA NOx analyser.

3.4 Determination of carbon conversion

Determination of carbon conversion is an important aspect of this research investigation. Carbon conversion was determined by the help of air flow rates for fluidization, hopper feeder and combustor. The stoichiometric air flow rate was determined by the data from ultimate analysis of woodchips and calculated and analyzed.

Chapter 4 Biomass Gasification and Product Gas Composition Analyses

In this research investigation, SRC willow woodchips were gasified in the bubbling fluidized bed biomass gasifier. These woodchips were within the size range of 3–10 mm and supplied by a local SRC willow grower. The woodchips were analysed for proximate and ultimate analysis for their properties before subjecting them to the gasification. These properties are listed in Table 4-1.

Table 4-1: Ultimate analyses of SRC willow woodchips.

Component	Weight (%)
Carbon	45.4
Moisture	10.0
Ash	0.5
Volatiles	
Hydrogen	5.7
Nitrogen	0.8
Sulphur	0.1
Oxygen	37.5

Table 4- 2: Proximate analyses of SRC willow woodchips.

Component	Weight (%)	
	As received(wet)	Dry basis
Fixed carbon	12.5	12.90
Moisture	2.95	-
Ash	1.23	1.26
Volatiles	83.32	85.84

4.2 Biomass feeding calibration

Constant feeding of biomass woodchips is one of the foremost parameters of biomass gasification as it is very important to have a stable biomass feeding to produce steady product gas flow for reliable sampling and analysis of product gas. Biomass particle shape, size, moisture content, density and feeder design (hopper size and shape, auger design) are the main factors affecting the feeding process.

Repeated feeding rate calibrations were carried out by weighing the amount of woodchips in a specific time after regular intervals to check the consistency of biomass flow from the hopper to the gasification reactor through auger. In addition, a timed stirrer was added to the cylindrical hopper. The stirrer was programmed to stir for 5 sec/min. The feeder with cylindrical hopper and the timed stirrer ensured woodchips

were fed from feeder to the gasifier at a stable feeding rate for up to 2-3 hours to achieve stable gasifier temperature profiles and product gas compositions.

Table 4-3: Biomass feeding rate calibration.

	Biomass feed rate (g/h)					
	Auger speed (50 rmp)		Auger speed (55 rmp)		Auger speed (62.5 rmp)	
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
0	0	0	0	0	0	0
2	66	61.1	69.2	68.8	78.6	76.4
4	132.4	123.2	139.5	140.3	164.9	161.8
6	196.5	186.8	211.6	210.8	246.8	245.7
8	263.2	251	282.5	283.8	332.5	330.9
10	328.4	316.4	356	358.5	415.3	414.5
12	394.7	383.1	430.6	429.3	500.6	501.3
14	459.2	448.1	501.8	503	586.4	588.1
16	524.4	512.6	572.5	574.7	672.6	671.2
18	590.7	578.8	642.3	645.1	758.3	757.9
20	655.9	646.2	714.8	715.4	843.9	842.3
22	722.2	713.1	785.2	787.3	928.2	925.6
24	789.9	778.7	856.5	855.9	1008.3	1004.8

Biomass Gasification and Product Gas Composition Analyses

26	855.3	839.1	925	927.8	1090.8	1087.1
28	923	906.2	994.4	997.1	1172.4	1169.3
30	986.7	973	1064.6	1067.4	1251.4	1247.7
32	1053.1	1040.8	1135.7	1137.6	1333.2	1328.8
34	1116.7	1106	1207.2	1209.5	1411.7	1408.6
36	1179.6	1173.9	1274	1276.8	1488.9	1483.5
38	1243.4	1237.3	1341.3	1344.4	1567.9	1561.4
40	1306.7	1301.7	1414.2	1418.6	1647.1	1641.8
42	1369.8	1364.3	1488.8	1493.2	1725.6	1719.7
44	1432.3	1428.5	1562.6	1566.6	1807.1	1800.5
46	1493.4	1490.9	1633.6	1638.3	1890	1883.4
48	1555.5	1555.7	1706	1711.7	1973.7	1967
50	1616.8	1617.4	1777.6	1784.3	2055.3	2047.1
52	1677.8	1680.3	1847	1855.8	2139.5	2131.8
54	1737.7	1743.2	1915.8	1924.1	2224.9	2212.6
56	1798.9	1806	1987.4	1995.6	2308.8	2296.3
58	1859.4	1870.4	2057.4	2069.9	2391.5	2377.9
60	1920.9	1933.4	2126.8	2135.7	2469.6	2453.3
Avg (g/h)	1927.50		2131.25		2461.45	

Three different auger speeds rpm i.e., 50 rpm, 55rpm and 62.5 rpm were measured repeatedly to ensure the constant flow of the woodchips for reproducible results of product gas composition.

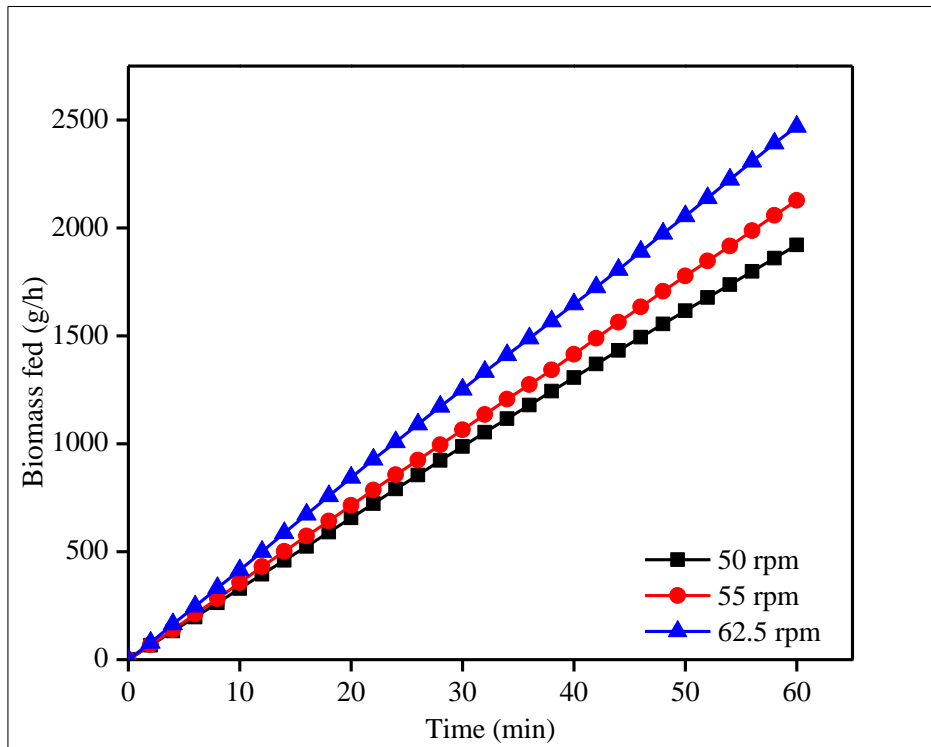


Figure 4-1: Biomass feeding calibration at different screw feeder speeds.

The rotation speed of the auger determines the amount of biomass fed to the gasifier. The rotation speed of the auger was controlled by the inverter of the gear motor. Table 4-3 and Figure 4-2 show that the feeding rate was stable under each screw rotation speed and the increased auger rotation speed increased the feeding rate. As auger rotation speed was increased from 50 rpm to 55 rpm and then 62.5 rpm, the amount of biomass fed also increased from 1920.9 g/h to 2126.8 g/h and then to 2469.6 g/h respectively.

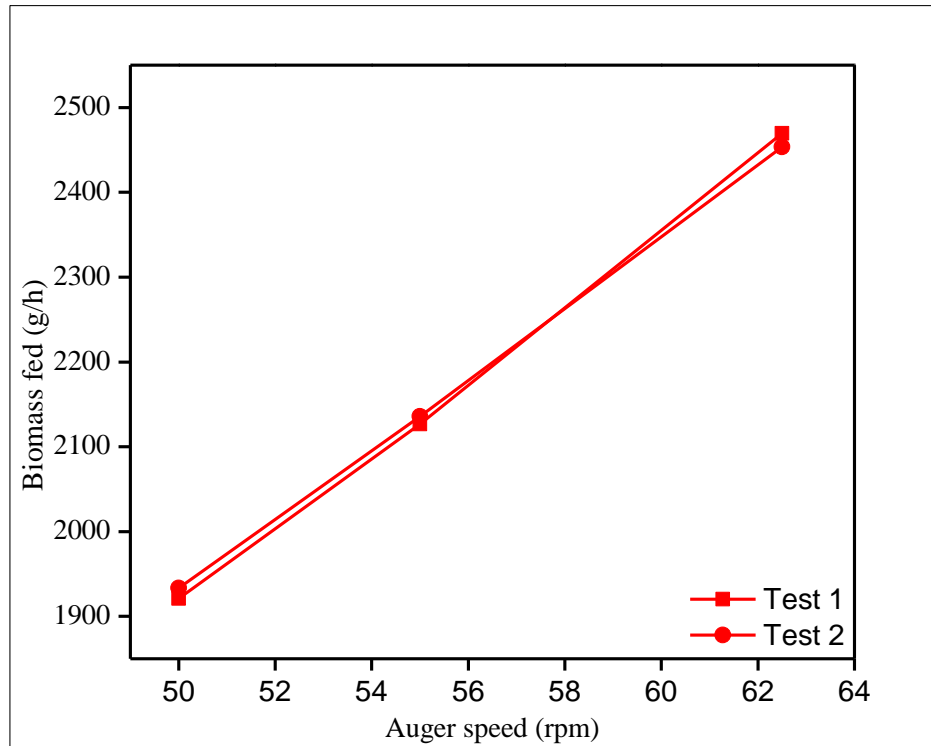


Figure 4-2: Biomass feeding rate (g/h) comparison at different auger speeds.

4.2 Gasification temperature profile and equivalence ratio (ER)

The gasification temperature is one of the most important parameters in determining the composition and yield of the product gas. However, biomass gasification temperature is not an independent parameter in practical gasification applications. Partial combustion of the gasification fuel (biomass) is usually used to achieve the intended gasification temperature. Very high temperatures may lead to ash sintering

and slugging. The temperature profile was observed by installing thermocouples at different heights from the distribution plate (Table 4-3).

Table 4 -4: Distances of thermocouples from the distribution plate in the reaction tower.

Thermocouple	Distance from distribution plate (cm)
T1	-5
T2	9
T3	17
T4	25
T5	45
T6	74
T7	105
T8	150

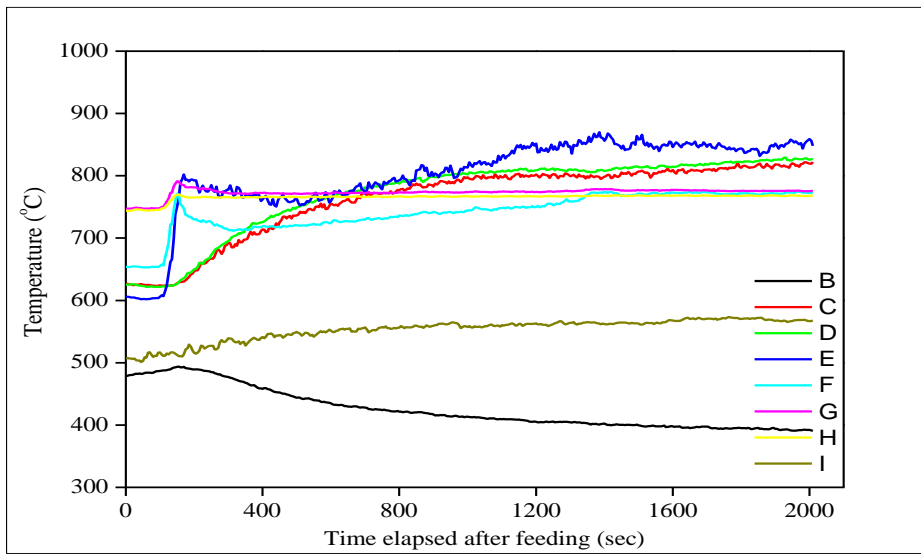


Figure 4-3: Temperature profiles at different heights from main distribution plate in the gasifier reactor at ER 0.319.

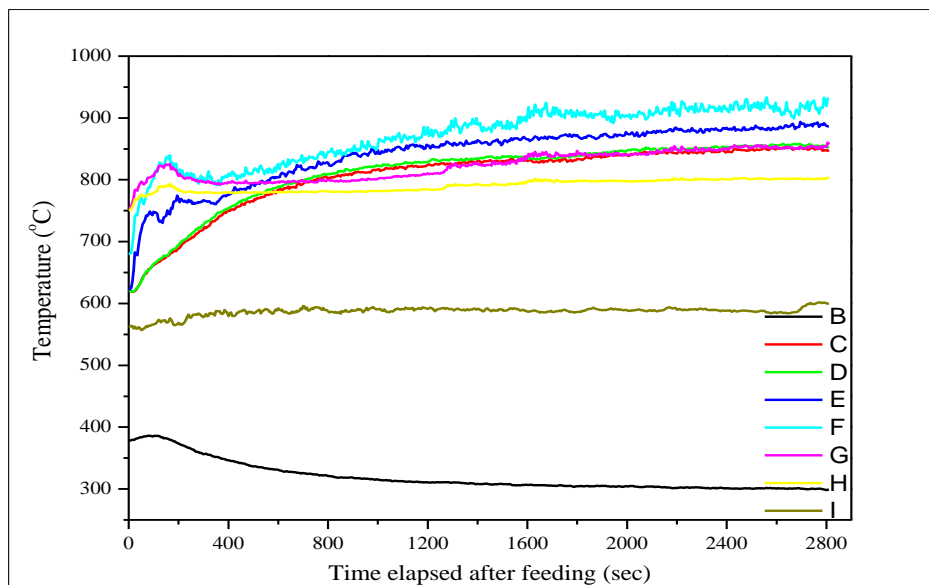


Figure 4-4: Temperature profiles at different heights from main distribution plate in the gasifier reactor at ER 0.464.

Figure 4-3 and 4-4 shows the variations in temperatures at different heights from the distribution plate and at different ER values (0.328 and 0.464). These figures clearly show that the stable temperature profile was achieved at approximately 20 minutes after the feeding of biomass started. The highest temperature was found in the dense bed zone of the gasifier between 9 cm and 45 cm height from the distributor plate where most of the biomass partial combustion occurred. Comparing Figure 4-3 and 4-4, it can be seen that higher temperatures above the distribution plate were achieved with ER=0.464 than those with ER=0.319. This is as expected that at higher ER, more partial combustion of biomass occurs in the gasifier and hence higher temperatures are resulted.

This is further illustrated in Figure 4.5. In this case, the temperatures of the gasifier reactor were seen to be changing with ER from 0.319 to 0.464. In a single continuous gasification test, the temperature at location of -5cm (below the distribution plate) decreased at higher ER is mainly due to the fact that additional primary air without adequate preheating was brought into the gasifier underneath the distributor plate. The temperatures in the main reaction zone, at heights between 9cm and 105cm, had achieved fairly stable and homogeneous distributions. The average temperature in the reaction zone increased from ca 800–850 °C when ER was increased from 0.328 to 0.587.

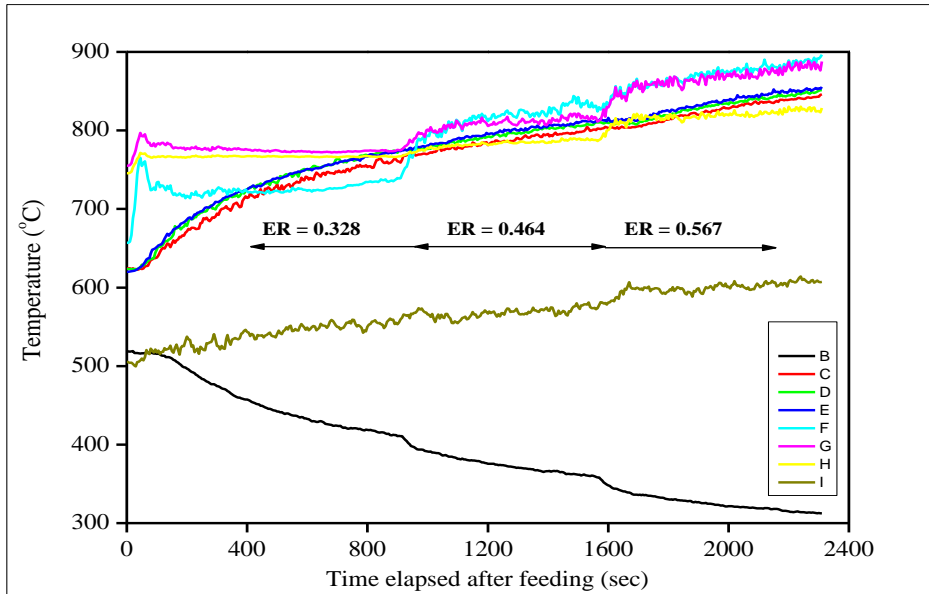


Figure 4-5: Temperature profile comparison at different ERs.

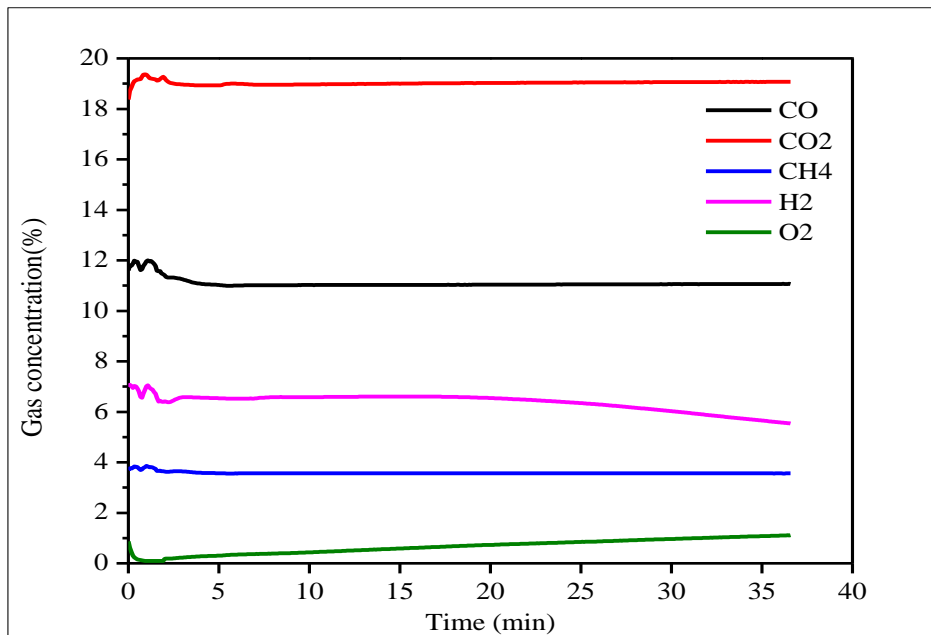


Figure 4-6: Product gas profile during biomass feeding at 1920.9 g/h.

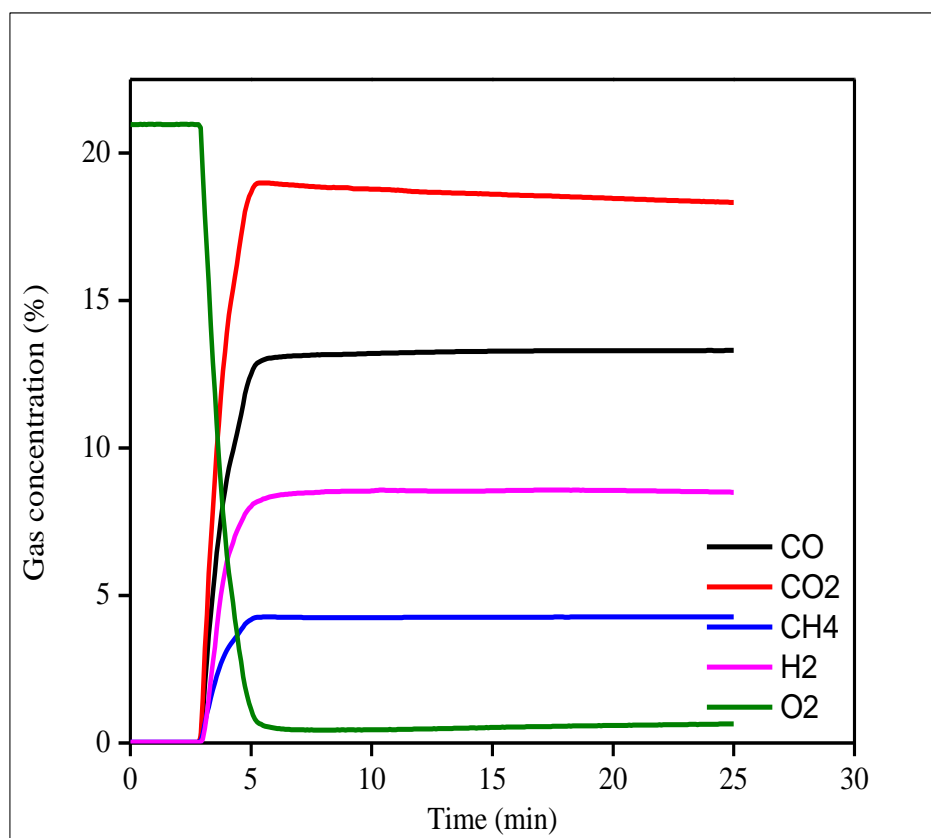


Figure 4-7: Product gas profile during feeding biomass at 2469.6 g/h.

4.3 Product Gas Composition Analysis

Gas composition was continuously analyzed at the inlet or the outlet of the combustor by using online gas analyzer. The gas composition at the inlet of the combustor represents the composition of the product gas from the gasifier. Very low concentration of CO (~100 ppm) was measured at the exit of combustor suggested nearly complete combustion of product gas before its exit to the air. The product gas composition was

also determined by offline gas chromatograph. Figure 4-6 and 4-7 show the gas composition profiles with auger speed 50 rpm and 62.5 rpm (biomass feeding rates 1920.9 g/h and 2469.6 g/h respectively).

4.3.1 Online analysis

The main components of the product gas (CO, CO₂, CH₄, and H₂) were continuously monitored by online gas analyzers. These analyzers were calibrated with standard gas samples after regular intervals.

Figures 4-8 – 4-10 show the effect of ER on the product gas composition measured by the on-line gas analyzer. Four repeated testing results were included in these Figures. Very small differences measured in compositions of product gas components indicate the gasification tests were very reproducible and hence reliable. As expected, concentrations of CO, CH₄, and H₂ in the product gas increase with the biomass feeding rate (decreasing ER value) while the concentration of the CO₂ in the product gas decrease with the biomass feeding rate.

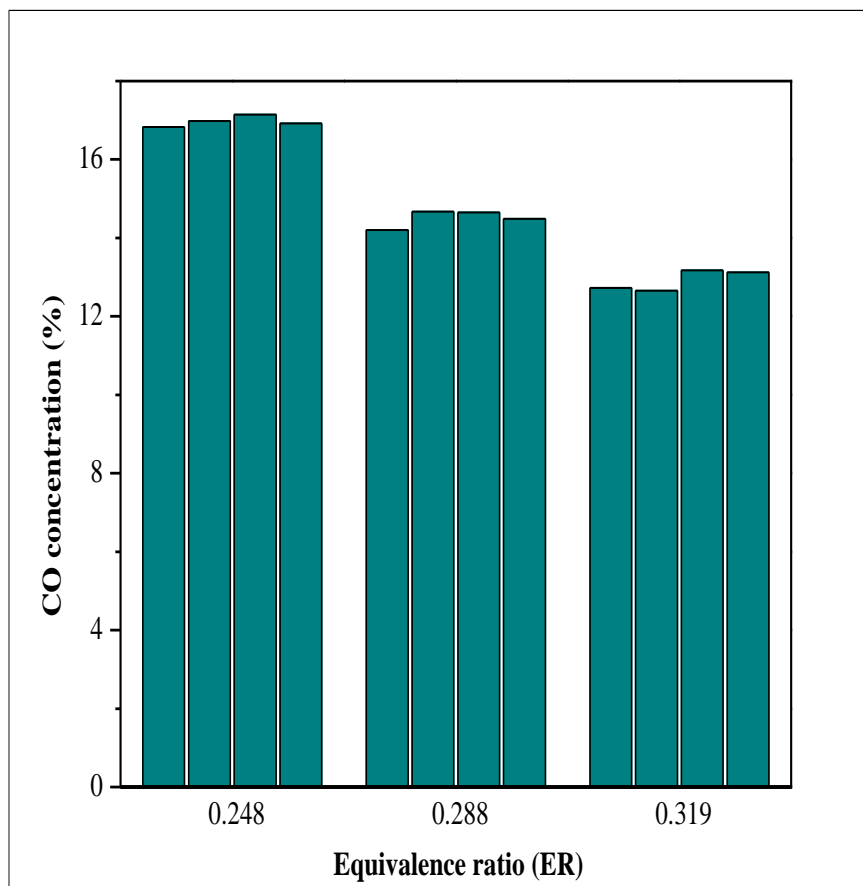


Figure 4-8: CO concentrations at different biomass feeding rates.

As Figure 4-8 illustrates that increase in the biomass feeding rate or with decreasing ER, the concentration of CO increased as a result of lack of oxygen. Similar findings were also presented by (Lv *et al.*, 2004) while gasifying the pine sawdust for different gasification parameters. Similarly the findings of Kinoshita *et al.* (1994) described that the ER is very crucial because its higher value results in lower concentration of H₂, CO and higher CO₂ content in the product gas.

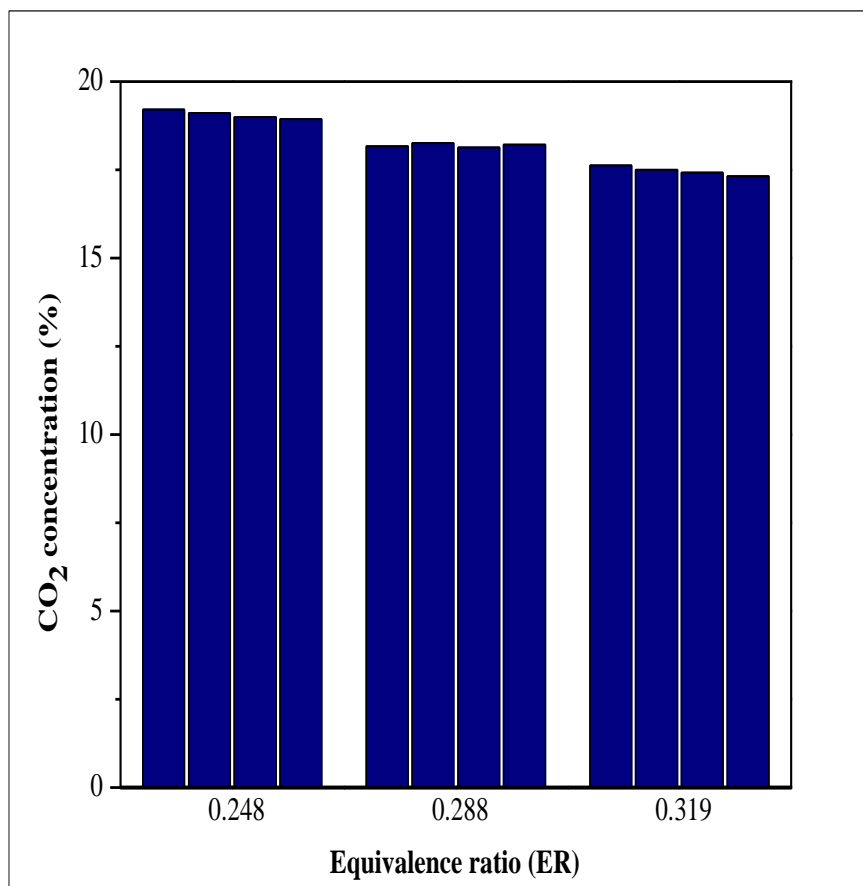


Figure 4-9: CO₂ concentrations at different ER values.

As depicted by the Figure 4-9, the concentration of CO₂ in the product gas decreased with the increase in the biomass mass feeding rate and vice versa with the ER. This result is in agreement with the findings of Skoulou *et al.* (2008) which presented that with increase in ER from 0.2–0.4, a significant decrease was observed in the concentration of CO₂.

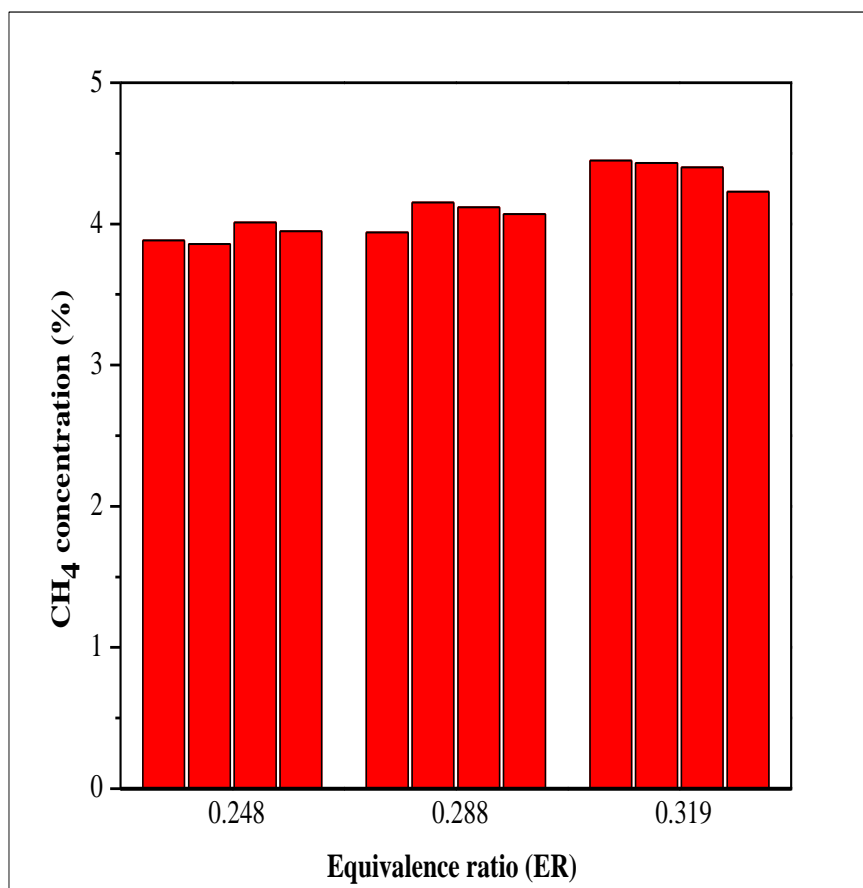


Figure 4-10: CH₄ concentrations at different ER values.

As illustrated by Figure 4-10, the concentration of methane (CH₄) was found increasing with decreased ER. This decrease can be explained as a result of exothermic methanoation reaction or steam methane reforming reaction which results in decrease of CH₄ and H₂O and liberates more H₂ and CO. Same findings were observed by Doherty *et al.* (2009) for their investigation of effect of air preheating in a biomass

circulating fluidized bed gasifier. It was found that to a certain increase in ER value, H₂ and CO was found maximum because of endothermic water-gas shift reaction. Similar tendencies in concentration of gas components are also presented by Kim *et al.* (2013).

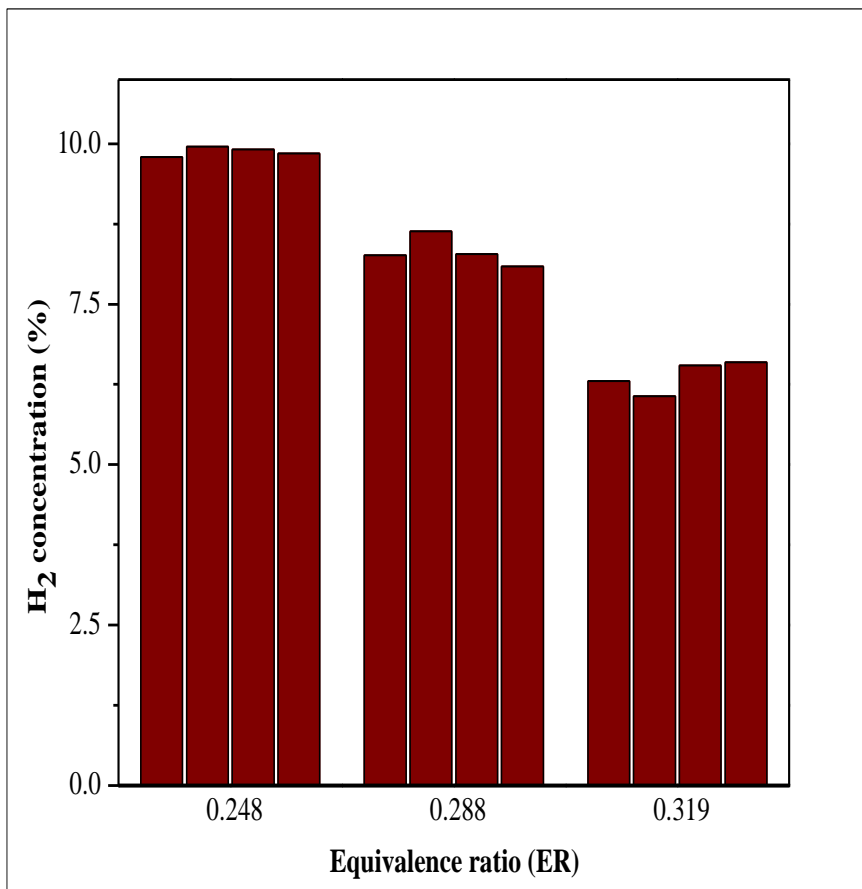


Figure 4-11: H₂ concentrations at different ER values.

From the Figure it can be seen that with decrease in the ER from 0.319 to 0.248 increasing the biomass feeding rate from 1920.9 g/h to 2469.6 g/h, the concentration of

H₂ also increased almost from 6% to 9% in the product gas. This increase in H₂ is in accordance with the findings of S Rapagna *et al.* (2000) where they found that with increased ER, the concentration of H₂ was decreased at increased temperatures. This decrease in H₂ can be regarded as with increasing ER, the Oxidation reactions dominate and H₂ contents in the product gas decreases. Similar tendencies in H₂ concentration have been found by (Narvaez *et al.*, 1996).

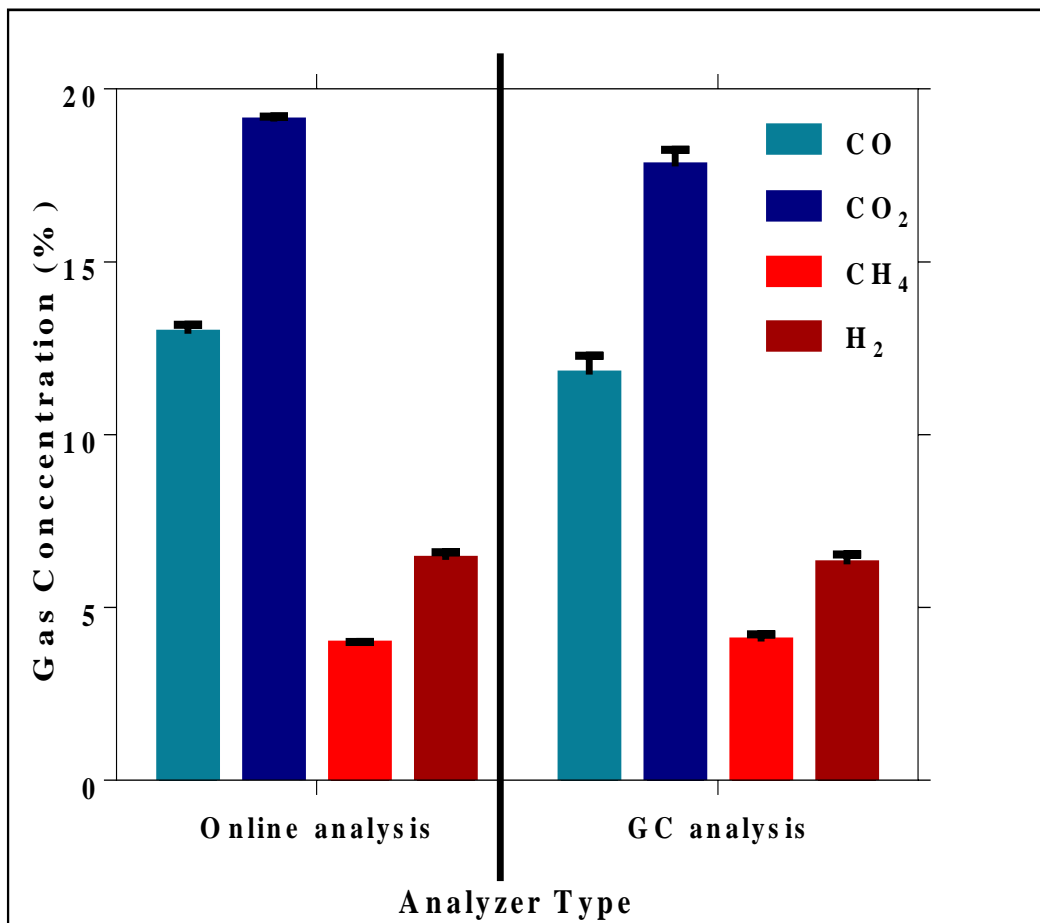


Figure 4-12: Product gas compositions with GC and online analyser at 1920.9 g/h biomass feeding rate.

Figure 4-12 compares the efficiency of the analysers in measuring the concentration of product gas components. This observation is made confirm the proper working of the analysers i.e. online analyser and offline (GC analyser) used in this research investigation.

It can be seen clearly from these Figures (4-8 – 4-11) that the product gas composition becomes very stable after about 10 minutes of gasification. Figures 4-3 and 4-4 already showed the stability of gasification temperatures after about 10 minutes of gasification. Stable biomass feeding rates throughout the whole experiment ensured product gas samples and tar samples obtained at different times were representative of their averages during the whole testing period.

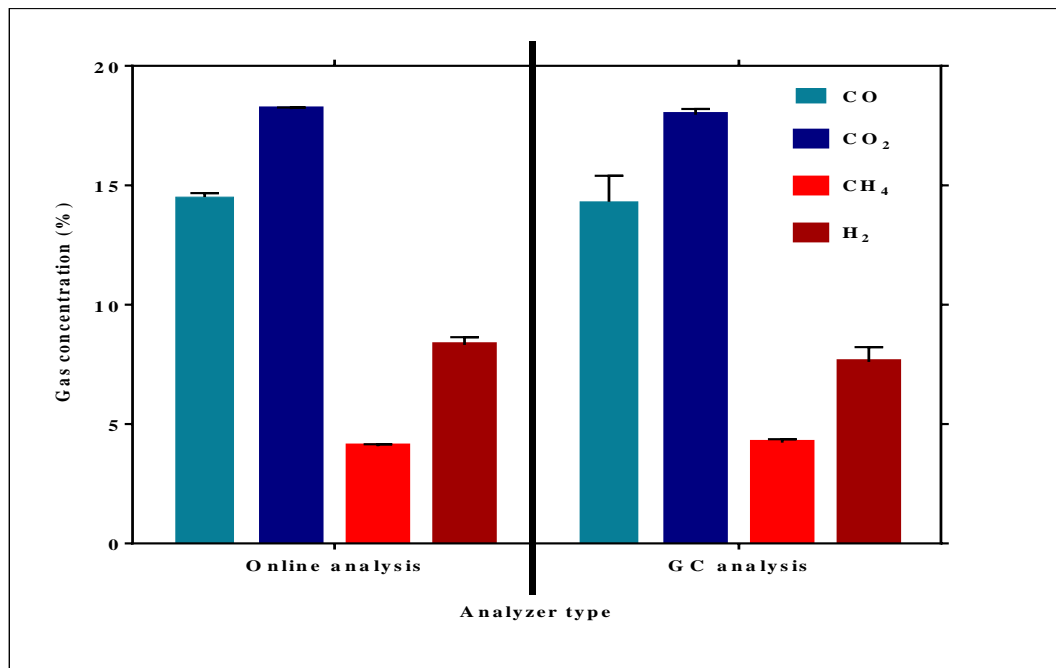


Figure 4-13: Product gas composition with GC and online analyser at 2126.8 g/h biomass feeding rate.

4.3.2 Gas Chromatography (GC) analysis

Gas chromatography was also used to analyze the product gas components analysis such as CO, CO₂, CH₄ and H₂. The results of GC analysis were used to check reliability of the online gas analyzer installed with the gasifier reactor. During each test, once the gasification process was confirmed to be stable through the gas temperature profile and gas composition profile (measured by the on-line-ABB gas analyzer), the product gas was sampled into sampling bags. Usually four product gas sampling bags (0.5 lit) were prepared with each gasification test. Biomass feeding at 1920.9 g/h, 2126.8 g/h and 2469.6 g/h was investigated.

It can be seen that the repeatability of GC sampling and analysis under each gasification condition is very good. The effects of biomass feeding rate on the product gas composition is shown in Figure 4-15 are in agreement with those shown in Figure 4-15 – 4-18. Quantitative compositions of the gas composition determined by the online gas analyzer and by the GC analysis shown in Figures 4-12 – 4-14. It can be seen clearly that the gas compositions determined by the online gas analyzer are in excellent agreement with those determined by the GC analysis.

4.4 Gasifier performance evaluation

The performance of the laboratory scale bubbling fluidized bed biomass gasifier at University of Nottingham was evaluated in aggregation with the effectiveness of tar reduction methods, product gas cleaning and particulate matter arrest techniques.

In order to thoroughly evaluate the performance of the biomass gasification system under the operating conditions of interest a set of efficiency metrics are applied which consider the efficiency of the gasifier in converting both input mass and energy into a desirable synthesis gas product. While certain primary methods may promote low tar production, this is typically accomplished at the expense of increased energy input or decreased synthesis gas production. Therefore, the reduction of tar should be balanced with the cost of cleaner synthesis gas. The following are descriptions of the metrics which are used to evaluate the performance of the biomass gasification system.

4.4.1 Determination of carbon conversion

In order to come across the fuel engrossments of the end-use devices of the product gas, an economically feasible technique is vital to convert the original feedstock into an appropriate energy form. In an ideal condition, 100% of the feedstock is to be converted to the product gas, or to a desired mixture of product gas and secondary products. In biomass gasification of the woodchips, carbon, hydrogen and oxygen in the feedstock are converted to synthesis gas, secondary products (e.g. carbon dioxide, methane and higher gaseous hydrocarbons), and undesirable products (e.g. sulfur species, tars and particulate matter).

Table 4-5: Carbon conversion calculated at different biomass feeding rates.

Gear motor speed (rpm)	50	55	62.5
Room temp (°C)	20	20	20
Fluidization air flow rate (Litre/min)	45	45	45
Hopper air flow rate	3	3	3
Combustion air flow rate	165	165	165
Stoichiometric air flow rate @273K,1atm	4375.8	4375.8	4375.8
Gasification air flow rate @273K,1atm	44.72	44.72	44.72
ER	0.319	0.288	0.248
Feeding time	60	60	60
Biomass fed into bed	1920.9	2126.8	2469.6
Carbon element in biomass	45.4	45.4	45.4
Carbon fed into bed	877.58	965.57	1120.93
Integrated CO ₂ during feeding	49463.5	49712.25	49458.2
Integrated CO during feeding	1637.94	352.5	1651.48
Integrated CO ₂ during burnout	2125.72	4950.12	2209.5
Integrated CO during burnout	131.59	190.6	208.68
Total flue gas flow rate at combustor exit @ RT, 1atm	213	213	213
CO ₂ volume during feeding @ 273K, 1atm, exit of combustor	1637.02	1645.25	1636.85
CO volume during feeding @ 273K, 1atm, exit of	54.21	11.67	54.66

combustor			
Total gasified carbon	906.02	887.64	906.16
CO ₂ volume during burnout @ 273K, 1atm, exit of combustor	70.35	63.83	73.12
combustor			
CO volume during burnout @ 273K, 1atm, exit of combustor	4.36	6.31	6.91
combustor			
Total residue carbon	40.02	41.14	42.87
Total carbon detected by analyser	946.04	978.78	949.04
Relative error between fed carbon by calibrated feeding rate	8	8	8
<hr/>			
Carbon conversion	93.48	92.69	93.21
<hr/>			

These results shown in the table depict that at ER 0.319 (biomass feeding rate of 1920.9 g/h), the carbon conversion is highest i.e. 93.48% as compared to ER 0.288 (biomass feeding rate of 2126.8 g/h) and ER 0.248 (biomass feeding rates 2469.6 g/h) where carbon conversion is 92.69% and 93.21% respectively. It is concluded from these results that ER has very minute effect on carbon conversion efficiency in this investigation. Similar results are presented by Hernández *et al.* (2010) where they found that higher carbon conversion efficiency is mainly due to greater extension of oxidation reactions of carbon fines.

4.4.2 Estimation of higher heating value (HHV), lower heating value and cold gas efficiency at different ERs

The heating values of the product gas such as higher heating values (HHV), lower heating values (LHV) and cold gas efficiencies (CGE) from the SRC willow woodchips gasification in a bubbling fluidized bed gasifier were examined to investigate the gasification process and gasifier performance comparison under the influence of different ER values such as 0.319, 0.288 and 0.248.

4.4.2.1 Estimation of higher heating value, lower heating value and cold gas efficiency at ER 0.319

a. Estimation of higher heating value (HHV)

$$\text{HHV} = (\text{H}_2 \text{ conc. in product gas} * \text{HHV of H}_2) + (\text{CO conc. in product gas} + \text{HHV of CO}) + (\text{CH}_4 \text{ conc. in product gas} * \text{HHV CH}_4)$$

$$\begin{aligned} \text{HHV} &= ((6.2 * 12.08) + (13.2 + 11.97) + (4.3 * 37.74))/100 \\ &= (74.90 + 158 + 162.28)/100 \end{aligned}$$

$$\text{HHV} = 3.95 \text{ MJ/m}^3$$

b. Estimation of lower heating value (LHV)

$$\text{LHV}_{\text{gas}} = \sum V_i * \text{LHV}_i$$

Where V_i = % composition of gas component in product gas

LHV_i = lower heating value of individual gas component

Thus

$$\begin{aligned}\text{LHV}_{\text{gas}} &= (\text{V}_{\text{H}_2} * \text{LHV}_{\text{H}_2} + \text{V}_{\text{CO}} * \text{LHV}_{\text{CO}} + \text{V}_{\text{CH}_4} * \text{LHV}_{\text{CH}_4}) / 100 \\ &= (6.2 * 10.2 + 13.2 * 11.97 + 4.3 * 34) / 100 \\ &= (63.24 + 158 + 146.2) / 100 \\ &= 367.44 / 100\end{aligned}$$

$$\text{LHV}_{\text{gas}} = \mathbf{3.67 \text{ MJ/m}^3}$$

c. Estimation of gas yield

$$\begin{aligned}\text{Total gas yield} &= \text{Amount of N}_2 \text{ fed to the gasifier} * \text{N}_2 \text{ conc in} \\ &\quad \text{product gas} \\ &= \text{N}_2 \text{ (m}^3/\text{h)} * (100 - \sum \text{V}_{\text{gi}})\end{aligned}$$

Where

$$\text{V}_{\text{gi}} =$$

$$\text{N}_2 = \text{Air fed into gasifier (m}^3/\text{h)} * \text{N}_2 \text{ conc. in product gas}$$

Thus

Total gas yield at ER 0.319

$$\begin{aligned}\text{Total gas yield} &= 2.27 / 57.7 * 100 \\ &= \mathbf{3.93 \text{ m}^3/\text{h}}\end{aligned}$$

d. Estimation of cold gas efficiency (CGE)

Cold gas efficiency can be calculated by the following equation

$$\begin{aligned}\text{CGE}(\eta) &= \frac{\text{Gas yield} * \text{LHV}_{\text{gas}}}{\text{Biomass feeding rate} * \text{LHV}_{\text{biomass}}} * 100 \\ &= \frac{3.94 * 3.67}{1.92 * 16.22} * 100 \\ &= \frac{14.46}{31.14} * 100\end{aligned}$$

$$\text{CGE} (\eta) = 46.43\%$$

4.4.2.2 Estimation of higher heating value, lower heating value and cold gas efficiency at ER 0.288

a. Estimation of higher heating value (HHV)

HHV = (H₂ conc. in product gas * HHV of H₂) + (CO conc. in product gas + HHV of CO) + (CH₄ conc. in product gas * HHV CH₄)

$$\begin{aligned}\text{HHV} &= ((8.2 * 12.08) + (14.4 + 11.97) + (4.1 * 37.74))/100 \\ &= (99.06 + 172.37 + 154.7)/100\end{aligned}$$

$$\text{HHV} = 4.26 \text{ MJ/m}^3$$

b. Estimation of lower heating value (LHV)

$$\text{LHV}_{\text{gas}} = \sum V_i * \text{LHV}_i$$

Where V_i = % composition of gas component in product gas

LHV_i = lower heating value of individual gas component

Thus

$$\text{LHV}_{\text{gas}} = (V_{\text{H}_2} * \text{LHV}_{\text{H}_2} + V_{\text{CO}} * \text{LHV}_{\text{CO}} + V_{\text{CH}_4} * \text{LHV}_{\text{CH}_4}) / 100$$

$$= (8.2 * 10.2 + 14.4 * 11.97 + 3.9 * 34) / 100$$

$$= (83.64 + 172.37 + 132.6) / 100$$

$$= 388.61 / 100$$

$$\text{LHV}_{\text{gas}} = \mathbf{3.89 \text{ MJ/m}^3}$$

c. Estimation of gas yield

$$\begin{aligned} \text{Total gas yield} &= \text{Amount of } \text{N}_2 \text{ fed to the gasifier} * \text{N}_2 \text{ conc in} \\ &\text{product gas} \\ &= \text{N}_2 (\text{m}^3/\text{h}) * (100 - \sum V_{\text{gi}}) \end{aligned}$$

Where

V_{gi} = Volume conc. of individual component in the product gas

N_2 = Air fed into gasifier (m^3/h) * N_2 conc. in product gas

Thus

Total gas yield at ER 0.288

$$= 2.27 / 54.5 * 100$$

$$\text{Total gas yield} = \mathbf{4.17 \text{ m}^3/\text{h}}$$

d. Estimation of cold gas efficiency (CGE)

Cold gas efficiency can be calculated by the following equation

$$\begin{aligned} \text{CGE } (\eta) &= \frac{\text{Gas yield} \cdot \text{LHV}_{\text{gas}}}{\text{Biomass feeding rate} \cdot \text{LHV}_{\text{biomass}}} * 100 \\ &= \frac{4.17 \cdot 3.95}{2.12 \cdot 16.22} * 100 \\ &= \frac{16.47}{34.39} * 100 \end{aligned}$$

$$\text{CGE } (\eta) = 47.89\%$$

4.4.2.3 Estimation of higher heating value, lower heating value and cold gas efficiency at ER 0.248

a. Estimation of higher heating value (HHV)

HHV = (H₂ conc. in product gas * HHV of H₂) + (CO conc. in product gas + HHV of CO) + (CH₄ conc. in product gas * HHV CH₄)

$$\begin{aligned} \text{HHV} &= ((9.8 * 12.08) + (17.1 * 11.97) + (3.9 * 37.74))/100 \\ &= (118.38 + 204.68 + 147.19)/100 \end{aligned}$$

$$\text{HHV} = 4.7 \text{ MJ/m}^3$$

b. Estimation of lower heating value (LHV)

$$\text{LHV}_{\text{gas}} = \sum V_i * \text{LHV}_i$$

Where V_i = % composition of gas component in product gas

LHV_i = lower heating value of individual gas component

Thus

$$\text{LHV}_{\text{gas}} = (\text{V}_{\text{H}_2} * \text{LHV}_{\text{H}_2} + \text{V}_{\text{CO}} * \text{LHV}_{\text{CO}} + \text{V}_{\text{CH}_4} * \text{LHV}_{\text{CH}_4}) / 100$$

$$= (9.8 * 10.2 + 17.1 * 11.97 + 3.9 * 34) / 100$$

$$= (99.96 + 204.69 + 132.6) / 100$$

$$= 437.25 / 100$$

$$\text{LHV}_{\text{gas}} = 4.37 \text{ MJ/m}^3$$

c. Estimation of gas yield

$$\begin{aligned} \text{Total gas yield} &= \text{Amount of N}_2 \text{ fed to the gasifier} * \text{N}_2 \text{ conc in product gas} \\ &= \text{N}_2 \text{ (m}^3/\text{h)} * (100 - \sum \text{V}_{\text{gi}}) \end{aligned}$$

Where

$$\text{N}_2 = \text{Air fed into gasifier (m}^3/\text{h)} * \text{N}_2 \text{ conc. in product gas}$$

Thus

Total gas yield at ER 0.319

$$= 2.27 / 49.9 * 100$$

$$\text{Total gas yield} = 4.55 \text{ m}^3/\text{h}$$

d. Estimation of cold gas efficiency CGE

Cold gas efficiency can be calculated by the following equation

$$\begin{aligned} H &= \frac{\text{Gas yield} * \text{LHV}_{\text{gas}}}{\text{Biomass feeding rate} * \text{LHV}_{\text{biomass}}} * 100 = \frac{4.55 * 4.37}{2.47 * 16.22} * 100 \\ &= \frac{19.88}{40.06} * 100 \end{aligned}$$

CGE = 49.63%

The comparison of high heating values, lower heating values and cold gas efficiency at different ER values are calculated and compared in the table 4-6.

Table 4- 6: Effect of ER on the product gas higher heating values (HHV), lower heating values (LHV) and cold gas efficiency (CGE) and total gas yield.

ER	HHV MJ/m³	LHV MJ/m³	Gas yield	CGE %
0.248	4.7	4.37	4.55	49.63
0.288	4.26	3.89	4.17	47.89
0.319	3.95	3.67	3.93	46.43

From the results presented in table 4-5, the values of HHV, LHV, and CGE of the product gas determined at different ER values found in this research investigation are in accordance with the findings of Z. Ma *et al.* (2015), where they reported decrease in LHV and CGE of the gasifier with the increasing ER values. F. Guo *et al.* (2014) reported the same effect of ER on the product gas. Hamad *et al.* (2016) also reported from their research investigation of hydrogen rich gas production from catalytic gasification of biomass. It was presented in this research that the increasing ER reduced the heating values and cold gas efficiency of the gasifier. AS higher ER value results in high N₂ supply to the gasifier which results in dilution of the product gas. Hence the

HHV, LHV, and CGE are decreased at higher ER. Similar findings were also reported by Timmer (2008), Ahmed *et al.* (2014), F. Guo *et al.* (2014) and many others.

Consequences of ER on the gas yield in gasification of biomass were observed by Yu *et al.* (2014). It was found that with the increase of ER, the total combustible gas yield was decreased. Higher ER value results in more active oxidized reactions which results in higher CO₂ and H₂O concentration on the expense of CO and H₂. The decrease in total gas yield is in contradiction to the many previous literatures which demonstrate increase in the gas yield with increasing ER, but decrease in gas yield also seems logical in view that higher ER as described by H. Yu *et al.* (2014). Another hypothesis in this scenario is that at more higher ER values the product gas becomes a mixture of air and combustible gases and hence the performance of the gasifier decreases which results in less combustible gas yield as suggested by (Sheeba *et al.*, 2009).

Chapter 5 Product Gas Cleaning Strategies for Particles

The gasification of biomass yields not only the combustible product gas but also produces some undesired by-products which are known as contaminants. These contaminants in the product gas include fine and coarse particles (e.g., fly ash, fragmented non-volatilized material), volatilized components and tars. The contaminants which are resulted from the organic and inorganic constituents of the carbonaceous biomass raw materials include tars (condensable organic compounds), nitrogen compounds (which include NO_x, hydrogen cyanide HCN and ammonia NH₃), sulphur compounds (such as hydrogen sulfide H₂S, carbonyl sulfide COS, carbon disulfide CS₂). Hydrogen chloride (HCl), chlorine (Cl), trace metals like sodium (Na) and potassium (K) can also be found as trace contaminants in the product gas (Asadullah, 2014). The presence of these deleterious compounds and elements in the product gas causes different problematic issues including technical as well as operational. For example, H₂S may result in corrosion of the end use equipment and tars have higher tendency of fouling the equipment (Chan & Tanksale, 2014).

The application of biomass gasification as a potential technology as a biomass energy production system is much more dependent on the composition and the quality of the product gas. The product gas can be used in variety of applications such as large-scale combined heat and power generation, domestic and other commercial applications

where heat generation may be the prime focus (Wang *et al.*, 2008). For the successful application of the product gas in heat and/or power generation, the contaminants in the product gas should be within threshold limit according to the requirement of the end use equipment (Albrecht *et al.*, 2016). In this chapter, the removal of particulate matter and NO_x is investigated by adopting different approaches. The removal of particulate matter from the product gas was examined by application of mop fan cleaning unit, with water spray and the conjoint effect of mop fan with water spray was also inspected.

5.1 Product gas cleaning strategies

As mentioned above, the raw product gas from biomass gasification contains variety of contaminants and pollutants which are needed to be cleaned prior to its domestic and/or commercial application for energy production. In particular, particulate matter can cause severe problems for end-uses. The mop fan cleaning unit with and without water spray methods are investigated in terms of their efficiency in capturing pollutants from the contaminated product gas.

5.1.1 Particulate matter capture

The particulate matter from the raw product gas is captured by using three different techniques i.e. particulate capture with mop fan cleaning unit, particulate capture with water spray and particulate capture with mop fan and water spray combined effect.

5.1.1.1 Particulate matter capture with mop fan cleaning unit

As discussed in chapter 3, the mop fan unit is being used to evaluate its effect in capturing the particulate matter from the product gas. Desired rotational speeds for the mop fan were achieved by using a geared motor. The effectiveness of mop fan in capturing the particulate matter was investigated in two conditions i.e. mop fan running without water spray and with water spray over the passing product gas.



Figure 5-1: Mop fan unit installed on the gasifier.

To determine the particle concentration in the contaminated product gas and the efficiency of mop fan unit in capturing the particles from the polluted product gas, a

dust monitor (TSI DustTrak) was used to measure the particle loading at two different points at the inlet (before the mop fan cleaning unit) and at the outlet (after the mop fan cleaning unit). Since, the device is sensitive to moisture contents in the sampling gas hence no water spray was used in these sets of measurements. Mop fan testing in these observations was carried out by running it at different rotation speeds to find the particulate capture efficiency of different mop fan rotational speeds. Rotation of the mop fan was controlled by the inverter frequencies of its geared motor.

Two samples of the product gas were taken and analysed for each mop fan rotational speed. Sample A of the product gas was taken just before entering the mop fan cleaning unit for a measured time and the concentration of the particulate matter was measured using the dust monitor. Sample B of the product gas was taken at the exit of the mop fan cleaning unit and the concentration of the particulate matter was again measured using the dust monitor. Difference in concentrations of the particulate matter was calculated and tabulated as particulate capture efficiency of the mop fan cleaning unit. Same procedure was repeated for different mop fan rotational speeds to investigate the efficiency of the mop fan rotational speeds in capturing particulate matter from the product gas.



Figure 5-2: Mop fan installed in mop fan unit.

The mop fan unit was installed before the combustor as illustrated in Figure 5-2. A flame arrestor was also installed between the mop fan and combustor to avoid the burning product gas backflow into the gas carrier pipe towards the mop fan. The mop fan tested in this section of product gas cleaning strategies consisted of a central shaft with mop fan threads which is connected to the motor. Different desired mop fan rotational speeds were achieved with controlled motor speed. The tars and contaminants in the product gas are captured by the mop fan threads and accumulate on the surface of the threads (Figure 5-2). Three different mop fan rotational speeds were investigated i.e. 60 rpm, 90 rpm and 120 rpm. The effect of mop fan rotational speed is evaluated as the efficiency in capturing tar from the product gas.

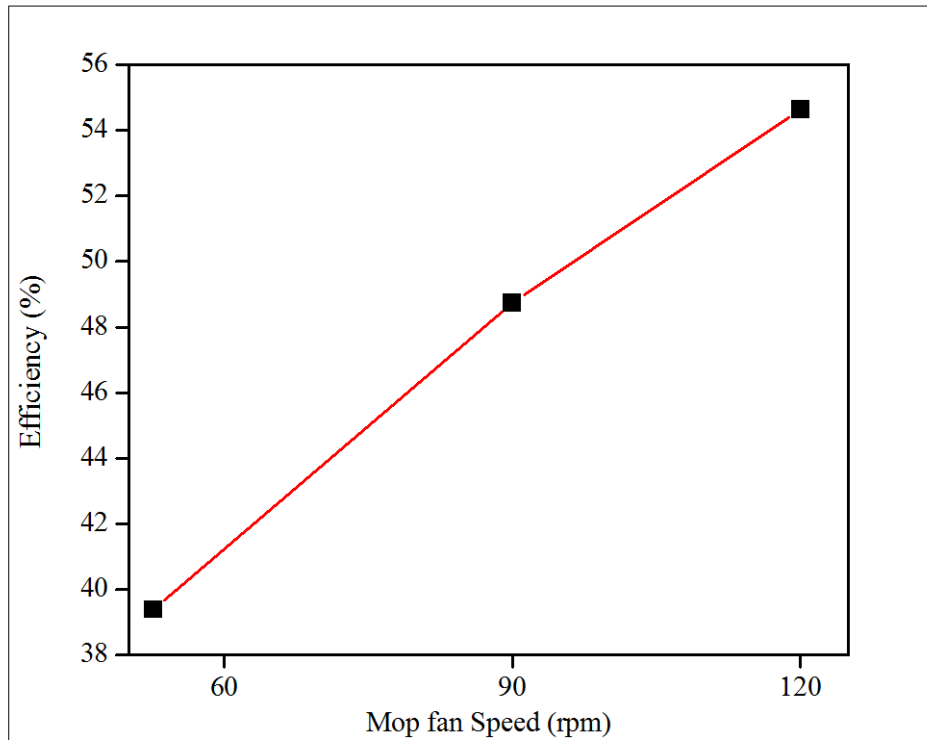


Figure 5-3: Particle capture efficiency comparison of mop at different rotational speeds.

Figure 5-3 represents the efficiency of the mop fan in capturing particulates at different mop fan running speeds. As expected, by increasing mop fan speed the particulate capture efficiency is also improved. The mop fan rotating at a higher speed is making more contacts with the passing product gas and hence more particulate matter is being captured at high mop fan rotational speed. Figure 5-3 also shows that the particle removal efficiency was 39.4%, 48.8%, and 54.5% with the mop fan rotation speed at 60 rpm, 90 rpm and 120 rpm respectively. Riffat *et al.* (1995) studied the use of mop fan running at different speeds for livestock buildings and found its efficiency 30% in removing dust from the air. It was also noted that increasing the mop fan speed resulted

in increased particle removal. X. Ma *et al.* (2008) studied the effectiveness of a photocatalytic mop fan for cleaning the air and described it as an effective technique to reduce contaminants from 656 mg/m³ to 593 mg/m³. Hence the mop fan cleaning unit in this research proved to be more efficient method for product gas cleaning as compared to other research work done where the mop fan was used in different scenarios for cleaning air by reducing the contaminants.

5.1.1.2 Particulate capture with water spray

Water scrubbing has been found an efficient technique to remove particulates including tars (Karmakar *et al.*, 2015). The efficiency of particulate removal by water scrubbing can be very high but it also generates waste water that needs to be treated (Elliott *et al.*, 2015). In this section, small amounts of water sprays i.e., 0.5 L/min and 0.75 L/min were used to observe the effect of water spray on particulate capture.

The operating conditions are described as follows:

Biomass Feeding Rate: 1920.6 g/h

ER: 0.319

Water Spray: 0.0 L/min, 0.5 L/min and 0.75 L/min

Table 5-1: Potentials of water spray in capturing particulate matter from the product gas.

	Inlet	Outlet: Water Spray		
		0.0 L/min	0.5 L/min	0.75 L/min
Filter paper initial weight (g)	1.4286	1.4542	1.3896	1.4825
Filter paper final weight (g)	1.4474	1.4727	1.3971	1.4882
Particulate mass captured (g)	0.0188	0.0185	0.0075	0.0057
Particulate removal efficiency (%)		1.6	60.1	69.7

In this technique, particulates present in the product gas make contact with water droplets. As the product gas approaches water droplets, particles in the product gas are arrested by the surface tension of the water droplets and collected with the waste water. Table 5-1 illustrates the effect of water spray on the particulate capturer from the product gas. Water was sprayed at 0.5 L/min and 0.75 L/min and compared against no water spray. Although no water spray also showed small amount of capture efficiency, this was mainly due to some experimental uncertainties, for example, sticking to the walls of sampling tubes and devices. An increase in particulate capture efficiency was observed as 60% and 70% with increasing water spray from 0.5 L/min to 0.75 L/min. As the amount of water spray increased, more water droplets were available for making contact with suspended contaminants/ particulate matter in the product gas. Higher amount of the surface area of water droplets contacted the particulate matter and water surface tension came in action in capturing higher amount of particulate matter from the product gas. Han and Kim (2008) found 60%-70% of particle removal by using

wash towers. Laurence and Ashenafi (2012) also studied the water scrubbing method in syngas treatment unit for small scale gasification-application to IC engine gas quality requirement. They found that the particulates with diameter between 0.1 and 1 μ m are the most difficult to capture either by diffusion or inertial mechanism. Jansen *et al.* (2002) presented the effect of water scrubbing and found that the contaminant level up to 10-20 mg/m³ was achieved in a tar water cleaning study. Water quenching of the syngas was also investigated by PH Hasler and Nussbaumer (1999) and found it an effective method for cleaning the particulate matter from the product gas as up to 98%. Schiffner and Hesketh (1996) stated that the spray scrubbing can achieve up to 90% removal particulate matter size > 5 μ m and around 40% for the submicron particles. The experimental work of present research for removal of particulate matter from the product gas (up to 70%) by water scrubbing (wet method) are in agreement with the achievements of other researchers in the same senario where a prominent reduction of contaminants was achieved using water scrubbing or wet method.

5.1.1.3 Particulate capture by mop fan unit with water spray

In this approach the synergic effect of mop fan cleaning unit and water spray was studied in context of product gas cleaning. The particle removal efficiency of a mop fan also depends on the mop fan threads density. In this case, the mop fan's threads are denser than that of the mop fan used in previous investigation and results are presented in Table 5.2.

The operating conditions are as follows:

Biomass Feeding Rate: 1920.6 g/h

ER: 0.319

Water Spray: 0.0 L/min, 0.5 L/min and 0.75 L/min

When combining the spray water with the mop fan to capture particles from product gas, the efficiency of particulate removal was noticed higher than using mop fan and spray water separately as presented in Table 5.2. Without water spray, the mop fan particulate removal efficiency was measured as 52.6%, which is about 13% higher than the value shown in Figure 5-3. This is perhaps due to different mop fan with denser threads was tested and results presented in Table 5.2.

Table 5-2: Particulate capture efficiency comparison of spray water and spray water and mop fan.

	Inlet	Outlet (Mop Fan: 60 rpm)		
		Water Spray		
		0.0 L/min	0.5 L/min	0.75 L/min
Filter paper initial weight (g)	1.428	1.4467	1.3981	1.4358
Filter paper final weight (g)	1.4474	1.4556	1.4027	1.4382
Particulate captured (g)	0.0188	0.0089	0.0046	0.0024
Particle removal efficiency (%)		52.6	75.5	87.2

The synergic effect of mop fan and water spray in capturing particulate matter from the product gas can be seen from Figure 5-4. The mop fan was run at 60

rpm speed while the water spray was exercised at 0.0 L/min, 0.5 L/min and 0.75 L/min respectively. A small amount of water spray (0.5 L/min) is seen enough to increase particulate capture efficiency to 75%. Further increase in spray water could increase the capture efficiency but also leads to more waste water that needs to be treated.

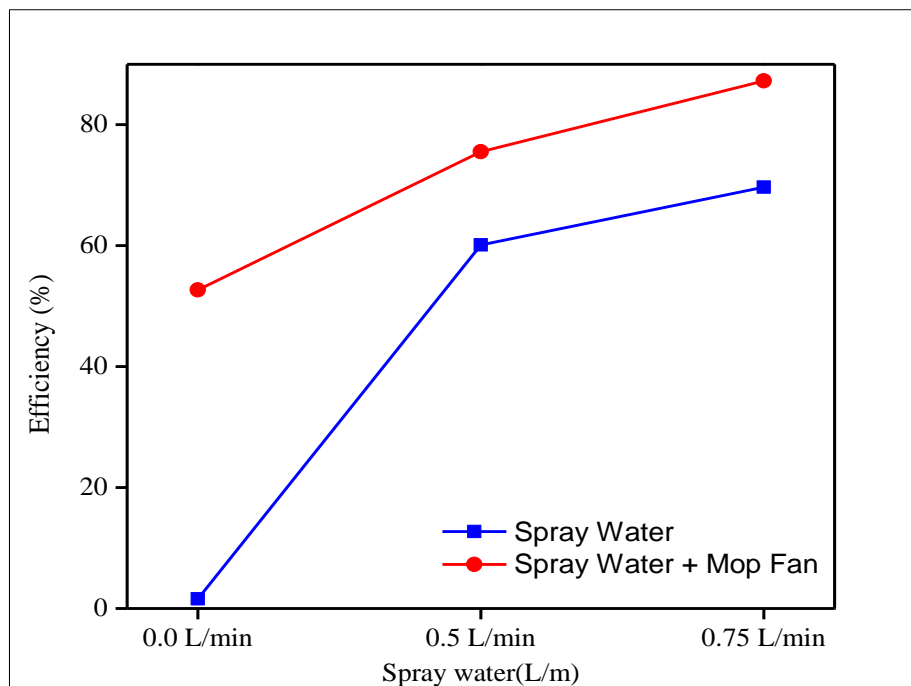


Figure 5-4: Particulate captures efficiency of spray water and mop fan.

The performance of the mop fan cleaning unit in particle removal is evaluated by measuring particle loadings at both the inlet and the outlet. When the mop fan ran without spraying water, the particle removal efficiency was in the range of 50 – 60%. When a small amount of spray water 0.5 L/min is used, the

particle removal efficiency was found to be improved up to 90%. These results present the efficiency of water spray and mop fan in removing the particulate matter from the product gas. Water scrubbing has been reported as an effective medium for particle removal from the product gas in different literatures. Kurella *et al.* (2017) used water scrubbing in removal of H₂S from the syngas in a multistage dual-flow sieve plate column wet scrubber. In present investigation, the maximum of 78.88% removal of H₂S was observed at 27.65×10^{-4} Nm³/s gas flow rate and 48.183×10^{-6} m³/s liquid flow rate for 300 ppm inlet concentration of H₂S. Lien *et al.* (2017) also studied the removal of hydrogen sulphide from biogas biomaterial using water scrubbing. It was found that the performance of hydrogen sulphide removal decreases as a result of increasing scrubbing time. The removal efficiency could be maintained at 47.7% with adequate additional fresh water of 10 L/min. According to Riffat *et al.* (1995), fan speed with doubled water spray proved more effective in capturing > 90% particles as compared to 75% particle capture while using only mop fan in the study of mop fan application in livestock buildings.

5.1.2 Removal of NO_x, HCN and NH₃ and other nitrogen species from the product gas

Major source of nitrogen in the product gas is the fuel bound nitrogen. The gasification of woody biomass releases nitrogen from the biomass at pyrolysis stage. The nitrogen is mainly in the form of NH₃, HCN and NO as contaminants in the product gas. As the

temperature increases from feedstock conversion, secondary reactions increase HCN concentration as well as NH_3 . However increased availability of H_2 and residence time will convert the HCN to NH_3 (Q. Yu *et al.*, 2007). Up to approximately 90% of the fuel bound nitrogen can be converted into nitrogenous compounds in the process of biomass gasification (Zhou *et al.*, 2000). However, the concentration of nitrogenous contaminants in the product gas is mainly dependent on fuel type, gasifier type and gasification parameters (Gustafsson, 2011). Removal of nitrogen compounds is also an important task for the successful commercial implementation of the product gas for energy production.

In this section, the average NO_x emission was measured at the exit of the combustor by using online nitrogen compounds analyzer which was installed and connected with the gasifier. Mop fan with and without water spray was tested in capturing the nitrogenous contaminants from the product gas. Figure 5-5 indicates that the use of the mop fan cleaning unit with or without spray water resulted in a reduction in NO_x , which is believed to be due to trapping of NO_x , HCN and NH_3 by mop fan threads and/or NO_x , HCN and NH_3 absorption in water spray. By using the mop fan but without the spray water, an efficiency of 44.3% in removing nitrogen species in the product gas was observed. With a small amount of spray water i.e., 0.5L/min, the efficiency in removing nitrogen compounds was achieved about 83% as shown in Figure 5-5.

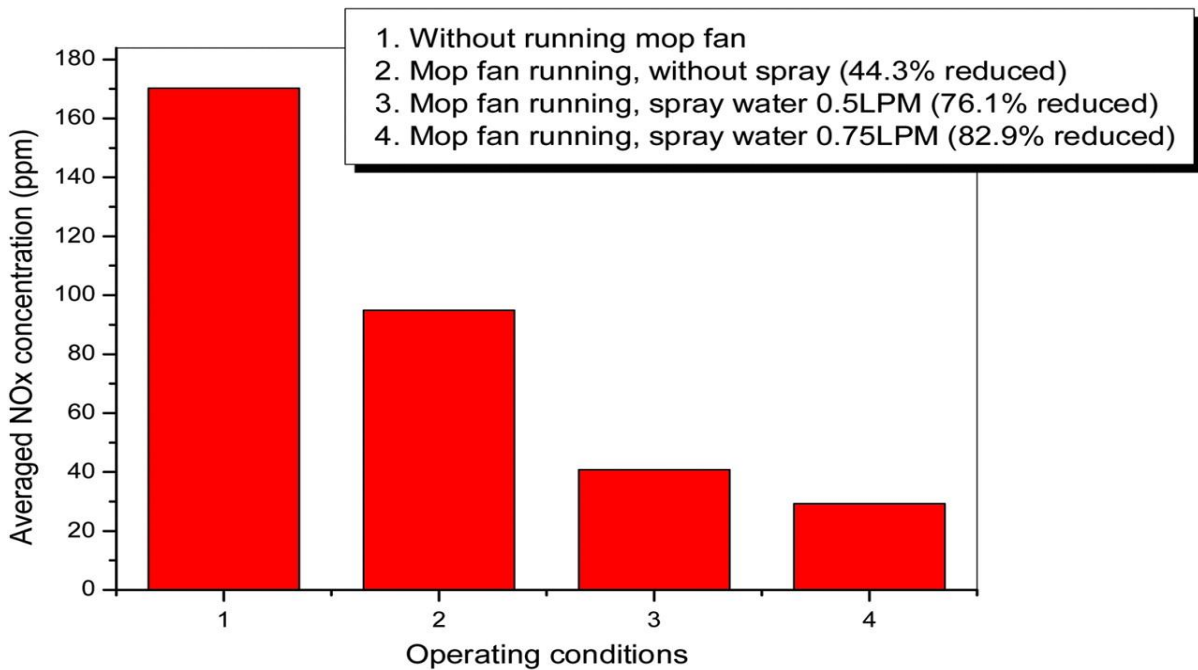


Figure 5-5: Average NOx concentration in different gas cleaning scenarios.

The results in this section using a mop fan with and without water spray as NOx/Nitrogen species capture technique from the product gas resulting from the gasification of woodchips show the effectiveness of this novel technique as product gas cleaning strategy. Water spray behaving as wet scrubbing, is also proven as an influential medium in capturing the nitrogen compounds from the product gas. Baker *et al.* (1986) explained that water spray over the gas stream can remove 95-99% of the particles. These water droplets capture the particles suspended in the gas flow through impaction, interception and diffusion (Mussatti & Hemmer, 2002). In comparison to the mop fan technique used by Riffat and Zhao (2007) in determination of the performance and operating characteristics of a mop-fan air cleaning system for buildings, the use of mop fan also found an effective technique in capturing the particles from the product gas in this research investigation. The reduction in the NOx

emissions from the product gas combustion is believed to be the result of absorption of nitrogen compounds in water.

5.2 Summary

Raw product gas from the biomass gasification is loaded with impurities such as particulate matter such as ash, tars, NO_x and other fuel nitrogen compounds which are collectively known as contaminants. Removing of particulate matter from the product gas is of utmost importance for the potential use of the product gas for its domestic or commercial application in power generation. Different applications of the product gas for power generation need a specific gas quality/ standard. As the contaminants or pollutants present in the raw product gas have tendency to clog, corrode and fouling the end use equipment, these are required to be removed prior the product gas end use. In this chapter three different approaches were tested in removing the particulate matter from the raw product gas i.e. mop fan, water spray and mop fan joint with water spray. For mop fan, the particle removal efficiency was tested at three different mop fan rotational speeds i.e. 60 rpm, 90 rpm and 120 rpm. The particle removal by mop fan rotation was found to be increased with the increased rotational speed of the mop fan. A gradual increase in mop fan efficiency for particulate matter removal was noticed as 39.4%, 48.8% and 54.5%. As the mop fan rotational speed was increased from 60 rpm to 90 rpm, the efficiency increased by almost 10% in capturing the particulate matter from the product gas. In the next step, by increasing the mop fan rotational speed from 90 rpm to 120 rpm, an increase in efficiency was noted as about 6%. This decrease in

the efficiency increase rate at the higher rotational speeds could be due to the fact that higher rpm speed exerted higher centrifugal forces to some of the particulates when they came in contact with the mop fan threads which could have sent these particulates back to the product gas stream.

The particulate matter captured by water spray was studied in three different scenarios i.e. no water spray, 0.5 L/min and 0.75 L/min. The product gas was sampled at two points i.e. before the water spray and after the water spray and denoted as inlet point and outlet point respectively. Particulate matter capture efficiency was noted as 1.6%, 60.1% and 69.7% with no water spray, 0.5 L/min water spray and 0.75 L/min water spray respectively. The reduction in particulate matter in this technique is the result of water spray which worked as wet scrubber and held some of the impurities from the raw product gas in the collected spray water which required to be disposed-off safely. Increasing the water spray amount resulted in the higher particulate matter capture as expected. Higher amount of spray water provided more surface for the contact with the raw product gas and hence higher amount of the particulate matter and other impurities trapped by higher amount of water spray.

Investigating the combined effect of mop fan and tar removal revealed synergic effect as it produced the highest efficiency in capturing particulate matter from the raw product gas amongst all of the product gas cleaning strategies studied in this observation. The highest efficiency of mop fan (120 rpm) in capturing particulate

matter was 54.5%, efficiency of water spray (0.75 L/min) is noted as 69.7% and mop fan (60 rpm) conjoint with water spray (0.75 L/min) was found 87.2% efficient in capturing particulate matter from the raw product gas.

Nitrogen compounds such as NO_x, HCN and NH₃ and other nitrogen species' arrest from the raw product gas was also studied using different. Water spray (0.5 L/min) removal efficiency was noted 47.6% while mop fan (60 rpm) without spray water was found efficiently removing 44.3% of the nitrogen compounds. While testing the mop fan (60 rpm) with water spray (0.5 L/min), it was capable of 76.1% nitrogen compounds removing from the raw product gas. The mop fan (60 rpm) with higher amount of water spray (0.75 L/min) effectively abated 82.9% of nitrogen compounds from the product gas. Hence the synergic effect proved more acceptable method in product gas cleaning.

Chapter 6 Tar Arrest from the Product Gas

6.1 Tar and Biomass Gasification

Tar is regarded as one of the most problematic and unpleasant component of the product gas. Tar formation during the gasification of biomass is considered as a universal challenge of gasification because of its tendency to deposit in the end use equipment which utilizes the product gas. Tar has high potential to foul filters, lines, and engines, as well as deactivate catalysts in clean up systems or downstream processes (Torres *et al.*, 2007).

Kumar *et al.* (2009) describes that the primary organic compounds in tar can be grouped as mixed oxygenates, phenolic ethers, alkyl phenolic, heterocyclic ethers, poly-aromatic hydrocarbons (PAH) and larger PAH. The composition shifts from larger molecules (e.g., larger PAH) to smaller molecules (e.g., mixed oxygenates) with increased reaction severity. During gasification, reaction severity can be increased by increasing the temperature, flow of oxidizing agents or amount of catalysts. Tar is less problematic for combustion of product gas because tar also can combust and add to the calorific value of the fuel, although less readily and at higher temperatures. Other applications, wherein the gas stream is cooled, result in condensation of the tar.

6.2 Major contaminants of biomass gasification

Gasification of biomass results in not only product gas yield, but also some unwanted by-product like ash, HCN, NH₃, NO_x and tar are also formed which can cause annoyance in applications of the product gas in industry. The tar formation in biomass gasification is very much dependent on the operational parameters of the gasification conditions such as gasification temperature, equivalence ratio and gasifying agent used such as air, steam, oxygen or a combination of these. The carbonaceous material in biomass breaks down and form long chain molecules such as permanent gases (hydrogen, carbon monoxide and methane etc.) and larger molecules of tars (long chain hydrocarbons) when heated at certain temperatures.

Tar is one of the main contaminants in the product gas and is the focus of many research investigations in gasification of biomass for the production of alternative energy. Commercial success of the biomass gasification is in fact more or less reliant on achieving lower tar contents in the product gas as tars can condense and accumulate in the gasification system and the end use equipment as well and lead to slagging, clogging and corrosion of the system. Therefore, the removal of tars from the product gas is an important task for the production of producing low tar syngas.



Figure 6-1: Tar in spray water drainage pipe.

To reduce tar formation in the product gas, a post-treatment, maintenance, and complex cleaning of the syngas is required for its successful application at commercial, industrial and domestic level utilizations. However, the minimum allowable limit for tar is highly dependent on the kind of process and the end user application. Bui *et al.* (1994) mentioned that the preferable tar and dust loads in gases for engines must be lower than 10mg/m^3 . The allowable tar levels are about 50, 5, 1 mg/Nm^3 for gas engines, gas turbines and fuel cells respectively according to(Iversen & Gøbel, 2004). Milne and Evans (1998) also tabulated the tar tolerance limit for various end use devices, suggested by different researchers. The biomass tar is a harmful outgrowth of the biomass process, usually left without being further utilized, despite its potential added value if it is professionally processed (Li & Suzuki, 2009). Tar is not a crucial problem for gas turbines if the syngas is not cooled down before entering the gas

turbines, because tars can be combusted in the high-temperature combustion chambers of the turbines.

6.3 Importance of tar removal from the product gas

Tars produced in gasification through thermochemical conversion can be collected on the surface of the condenser or in small aerosols, which are vaporized tar travelling with the moving product gas through the chamber. Exploitation of the product gas for consumption in gas turbines or engines can only be made possible by restricting the vaporized tar movements as their deposition on the surface wall of gas turbines or engines causes mechanical problems.

6.4 Experimental set up for tar removal from the product gas

Tar sampling was started after achieving a constant feeding rate and having the same product gas composition throughout the experiment and continued for 15-20 minutes. Tar sampling could be carried out at different sampling points (at different distances from main gasifier reactor) depending on the testing conditions and purposes.

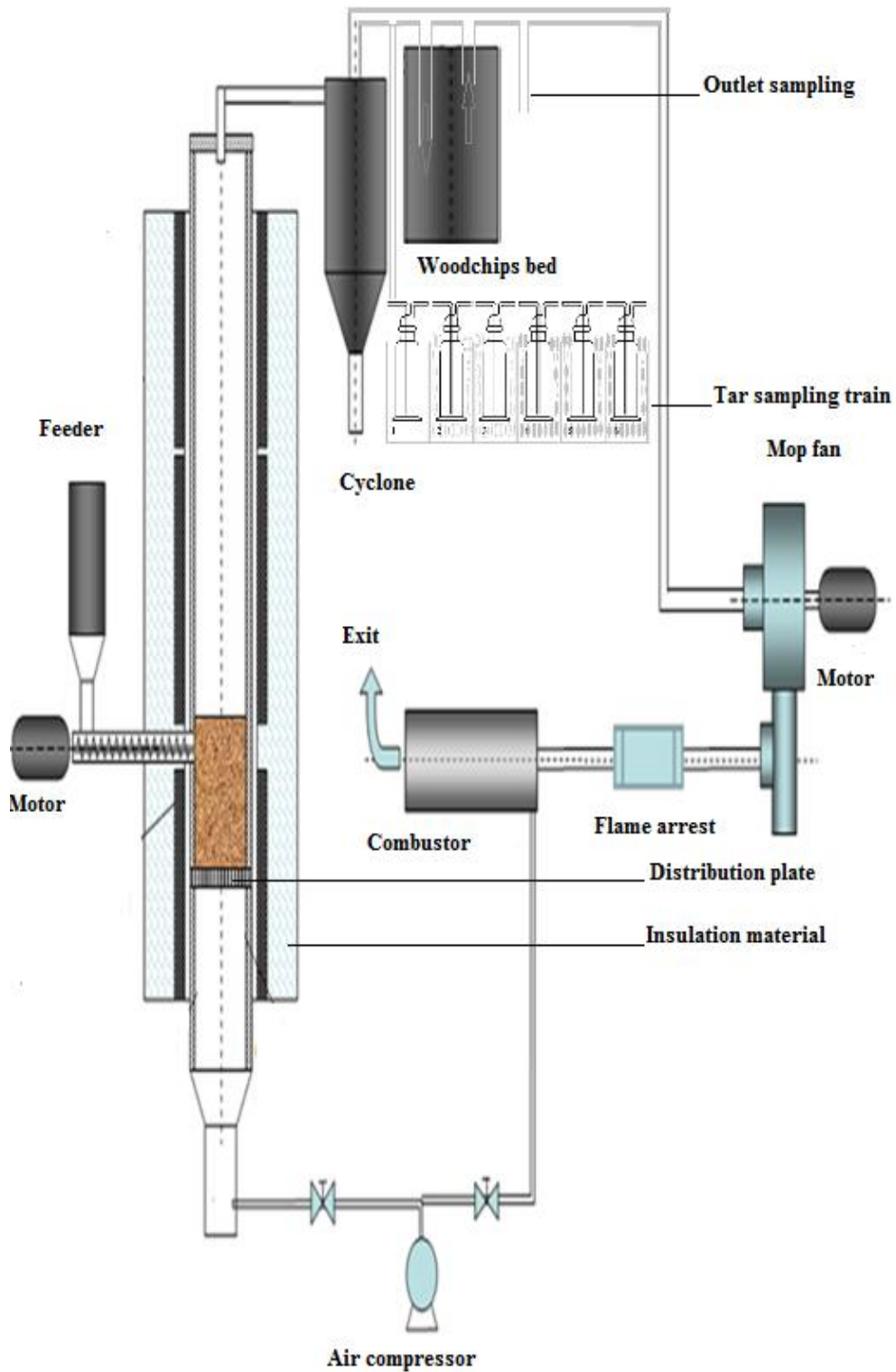


Figure 6-2: Tar sampling schematic.

6.4.1 Product gas sampling for tar collection

Product gas was collected at different designated sampling ports for offline GC analysis. Continuous gas sampling was also used by the online gas analyzers at the exit of the cyclone (for product gas analysis) or at the exit of the combustor (for combustor exhaust gas analysis).



Figure 6-3: Tar sampling train.

Tar sampling was carried out at the selected tar sampling points (Figure 6-3). The product gas in the sampling stream was cooled down using a series of dreschel bottles cooled with ice and dry ice (solid form of CO₂).

The product gas in the sampling stream was cooled down using ice and dry ice (solid form of CO₂). Eight dreschel bottles were connected in the tar collection sampling stream. First dreschel bottle directly attached to the sampling point, contained glass wool to filter the particulates. The next three bottles in the beaker were cooled using cold water and ice to condense the moisture contents in the product gas. The next three bottles were surrounded by dry ice in beakers to condense tars. Last dreschel bottle contained glass wool to filter the particulates. The gas flow was maintained at a constant flow rate by use of a suction pump at the end of sampling stream and monitored by a mass flow control meter (Figure 6-4).

6.4.2 Tar sampling and collection

Tar sampling was started after achieving a constant feeding rate and having the same product gas composition throughout the experiment and continued for 15–20 minutes. Tar sampling could be carried out at different sampling points (at different distances from main gasifier reactor) depending on the testing conditions and purposes. Wood chips of size 3–10 mm were gasified in a bubbling fluidized bed biomass gasifier at specific operating conditions for tar sampling and product gas analysis. Tars and particulates' samples were taken at designated sampling ports in order to investigate the

effectiveness of the tar removal devices, i.e. woodchips bed and mop fan (as shown in Figure 6-2 and 6-3). Sampling ports were ensured to be gas tight so that neither can gas escape from the system nor can enter it. The volatile tars were trapped in six dreschel bottles connected in series and chilled by using ice and dry ice as shown in Figure 6-5. The sampled gas volume is measured under dry conditions by means of a mass flow meter (as shown in Figure 6-4).

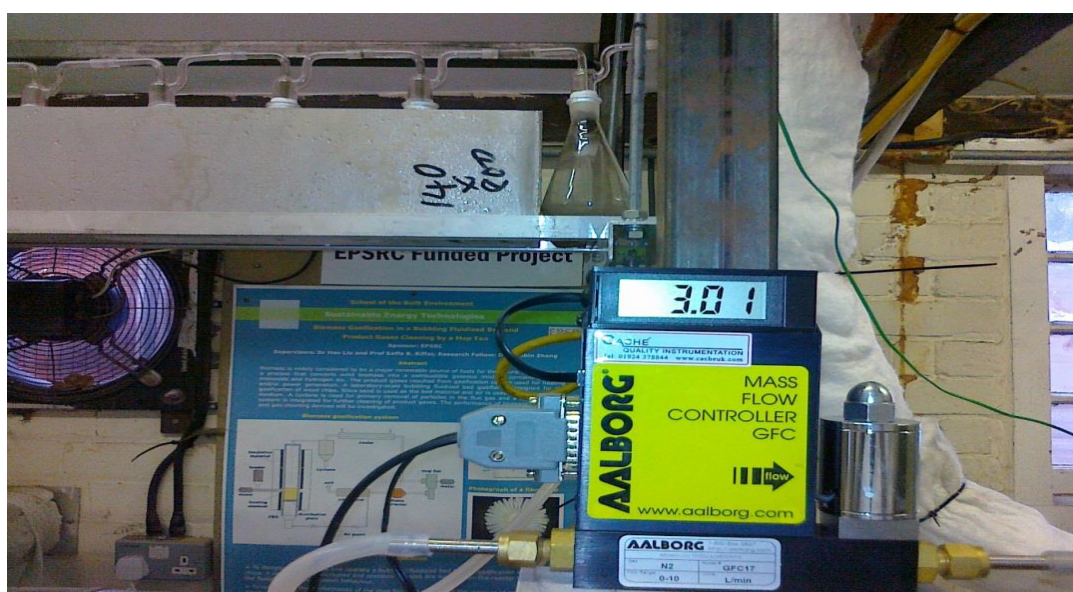


Figure 6-4: Gas flow control meter.

After achieving a constant feeding rate and steady product gas composition, tar sampling started and lasted for 15~20 minutes. During each tar sampling period, the product gas was continuously sampled to the online gas analyzer so that the product gas composition could be continuously monitored. Wood chips of size 3–10 mm were gasified in a bubbling fluidized bed biomass gasifier at specific operating conditions.

The sampling stream was connected to a main product gas stream at different sampling points (at different distances from main gasifier reactor).

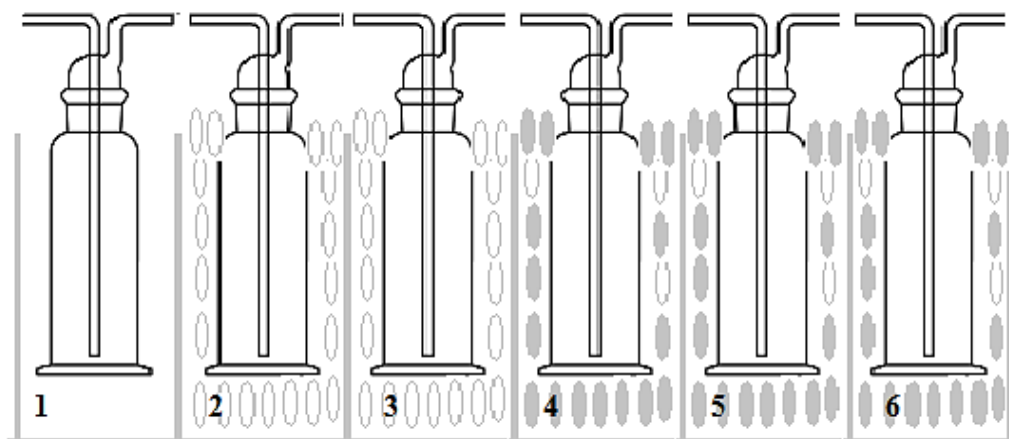


Figure 6-5: Schematic of tar sampling train of connected dreschel bottles.

As shown in Figure 6-5, the tar sampling train consists of six dreschel bottles connected to each other and placed in separate beakers in an aluminium container divided into six parts. The inlet and the outlet of sampling train were fitted with filters to minimize the particulate level in the tar samples. The first dreschel bottle beaker was filled with cold water; the second and the third beaker were filled with ice while fourth-sixth beakers contained dry ice in order to gradually condense tars in the sampling train. During each tar sampling period, the sampling gas flow was maintained at a constant flow rate of 3.0 L/ min by a vacuum suction pump and a mass flow controller.

6.5 Tar removal techniques from the product gas

The tar removal from the product gas was one of the main focuses of this research consideration. As tars are the major problematic components found in the product gas, which can get condensed and cause fouling and blocking in the devices and equipment, hence they are needed to be removed or lowered up to a tolerable level in the product gas for domestic and commercial application of the product gas for energy generation (Han & Kim, 2008). Primarily, the tar removal and product gas cleaning techniques are divided into two methods i.e. primary method (tar treatment inside the gasifier reactor) and secondary method (hot gas cleaning after the gasifier reactor). In this study, three techniques (secondary method) were adopted for tar removal from the product gas and hence categorized as dry scrubbing method, wet scrubbing method, dry and wet mix scrubbing method. Dry method does not involve any liquid (e.g., water or oil etc.). Wet scrubbing involves the use of liquid materials as scrubber. Wet scrubbing (when using water) needs waste water treatment.

6.5.1 Dry scrubbing

Dry scrubbing tar removal is performed after the gasifier reactor and involves physical tar removal from the product gas (Mastellone & Arena, 2008). Dry scrubbing method adopted in this investigation involved three tar scrubbing techniques i.e., secondary woodchips bed, secondary biochar bed and mop fan cleaning unit. The effectiveness of each of the methods in tar capturing was studied and compared against each other for their efficiency analysis.

6.5.1.1 Secondary woodchips bed

The concept of installing a secondary bed for removing the tars from the product gas is based on the model of dual bed gasifiers used to investigate the catalytic effect in gasification and product gas clean-up by different researchers (Corella *et al.*, 2007; Larsson *et al.*, 2014; Pfeifer *et al.*, 2004; Xu *et al.*, 2006). Instead of using a catalyst, a simple technique is used to present a surface area for the product gas contact and to achieve tar capture in this study. To achieve the tar arrest goal, a woodchips bed was constructed and installed next to the cyclone exit at this gasification reactor and examined for its effectiveness in arresting tar from the biomass product gas.

Small wood chips of size 3-10 mm and large willow woodchips of size 10-25 mm were tested for their tar capture efficiency. Product gas samples were collected at two points i.e.; before entering into the woodchips bed (inlet) and just after leaving the woodchips bed (outlet). Selection of wood chips proven to be an easily available, low cost and easy disposable material used as tar arrest technique in this method.



Figure 6-6: Small wood chips (3-10 mm) bed for tar arrest experiment.

a. Small wood chips bed

Small wood chips of SRC willow (size 3-10 mm) weighing 350 g were used as a bed material as shown in Figure 6-6, to capture tar from the product gas as the gas passed through this bed installed near the exit of the cyclone. The woodchips bed revealed its effectiveness in capturing tar from the product gas.

Figure 6-7 shows the deposited tar on the woodchips.



Figure 6-7: Image of tar trapped by small woodchips (3-10 mm).

Figure 6-7 illustrates the image of tar deposited on the small woodchips (3-10 mm) used as product gas cleaning substance. Two product gas samples were taken for the major tar components' concentration at two points i.e. before entering the woodchips bed (inlet) and at the exit of woodchips bed (outlet). The concentration of each component is measured at inlet and outlet sampling points and the difference in their concentrations is calculated and denoted as the efficiency of woodchips in capturing tar components. Average tar capture efficiency is also calculated and presented in Table 6-1.

Table 6-1: Tar component capture efficiency of small wood chips bed (3–10 mm).

Tar Component	Inlet (mg/L)	Outlet (mg/L)	Efficiency (%)
1,1Binaphthalene	0.002786	0.002557	8.22
Indene	0.001584	0.001435	9.41
Naphthalene	0.004126	0.003632	11.97
2-Methyl Naphthalene	0.001229	0.001061	13.67
1-Methyl Naphthalene	0.000919	0.00077	16.21
Acenaphthalene	0.001513	0.001351	10.71
Biphenyl	0.000447	0.000378	15.44
2-Ethanyl Naphthalene	0.000459	0.000378	17.65
Fluorene	0.000441	0.000373	15.42
Phenanthrene	0.000304	0.000208	31.58
Fluoranthene	0.000244	0.000136	44.26
Toluene	0.000948	0.000372	60.76
Phenol	0.000362	0.000176	51.38
Styrene	0.000949	0.000867	8.64
Avg. tar components' capture efficiency (%)			22.5

Table 6.1 represents the efficiency of tar capture using small woodchips bed installed at the exit of the gasifier reactor. Tar samples were collected before and after the product gas entering the woodchips bed. The efficiency of woodchips in capturing the tar components such as Toluene, Phenol,

Fluoranthene and Phenanthrene was observed as 60.76, 51.38, 44.26 and 31.58 respectively which are found significantly higher than the other tar components found in the product gas. The average total components' removal efficiency of small wood chips is noted as 22.5% (calculated by arithmetic mean). Phuphuakrat, Nipattummakul, *et al.* (2010) investigated the sawdust as tar absorbent and a reduction in 14-36% (by weight). Paethanom *et al.* (2012) also inspected the rice husk and vegetable oil for tar absorption from the product gas.

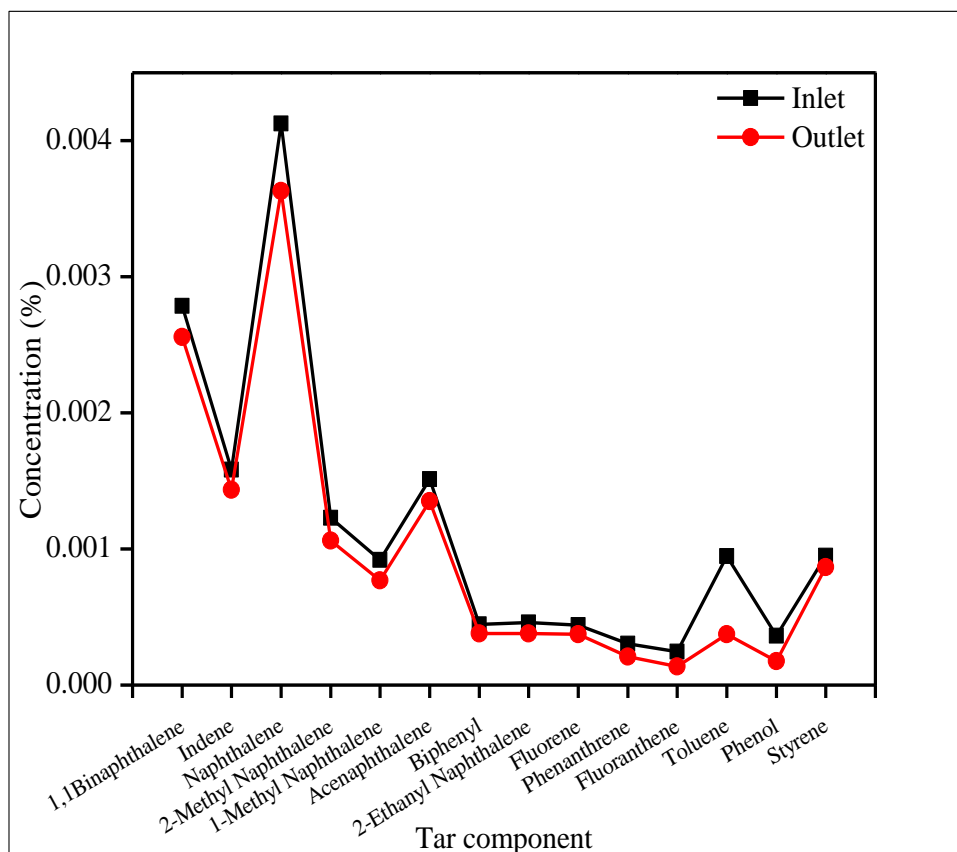


Figure 6-8: Concentration comparison of tar components at inlet and outlet using small woodchips bed at 1926.9 g/h biomass feeding.

Table 6.1 and Figure 6-8 demonstrate the tar components' concentrations and tar capture efficiency of the small woodchips bed. The major decrease was observed in the concentration of toluene, phenol, fluoranthene and phenanthrene. Mainly this reduction in concentrations of these tar components is supposed to be due to adsorption by the woodchips as described by Al-Dury (2009) in their research while using different biomass materials as a filter for tar components from the product gas where a decrease was noted in tar components. Zaitan *et al.* (2016) used clay for adsorption of volatile organic compounds from the gas stream and found the affinity of toluene, methanol and benzaldehyde to be absorbed by the clay.

b. Large wood chips bed

The large woodchips (10–25 mm) were also investigated for tar capturing from the product gas in comparison to the small woodchips. The effectiveness of different sized wood chips in a secondary bed in capturing tar from the product gas was investigated and results are presented to determine the best tar capture technique/material to be selected.

Table 6-2: Tar component capture efficiency of large wood chips (10–25 mm) bed.

Tar Component	Inlet (mg/L)	Outlet (mg/L)	Efficiency (%)
1,1 Binaphthalene	0.00272	0.00256	5.89
Indene	0.0023	0.000829	63.93
Naphthalene	0.00458	0.00277	39.59
2-Methyl Naphthalene	0.00124	0.00081	34.84
1-Methyl Naphthalene	0.000873	0.000655	24.97
Acenaphthalene	0.00151	0.0012	20.45
Biphenyl	0.000394	0.000326	17.26
2-Ethanyl Naphthalene	0.000403	0.000331	17.87
Fluorene	0.000488	0.000406	16.80
Phenanthrene	0.000299	0.000209	30.10
Fluoranthene	0.000271	0.000121	55.35
Dibenzofuran	0.000228	0.00017	25.44
Avg tar component capture efficiency (%)			29.4

Table 6-2 denotes the efficiency of large wood chips (size 10-25 mm) in capturing tar from the product gas. The concentration of individual tar components before entering woodchips bed and after leaving the woodchips bed is tabulated and the difference in their concentrations calculated as the efficiency of woodchips in capturing tar components. Average total tar capture efficiency is also calculated and presented as 29.4%. Efficiency in capturing the individual tar component captured by large woodchips was noted higher for

Indene (63.93%) and Fluoranthene (55.35%) as compared to rest of the tar components. Phuphuakrat, Namioka, *et al.* (2010) also investigated the absorption of Indene on woodchips and found it absorbed higher (0.0027 g/g absorbent) amongst all other individual tar components absorbed by woodchips. The total tar absorption was noted higher by woodchips (0.1557 g/g absorbent) in comparison with activated carbon (0.0975 g/g absorbent) and Synthetic porous cordierite (0.0128 g/g absorbent). Hence the wood chips scrubbing could have been the more suitable option for tar removal from the product gas as they are available in abundance, low cost and easily replaceable/ disposable as compared to wastewater generated during product gas cleaning in wet scrubbing method.

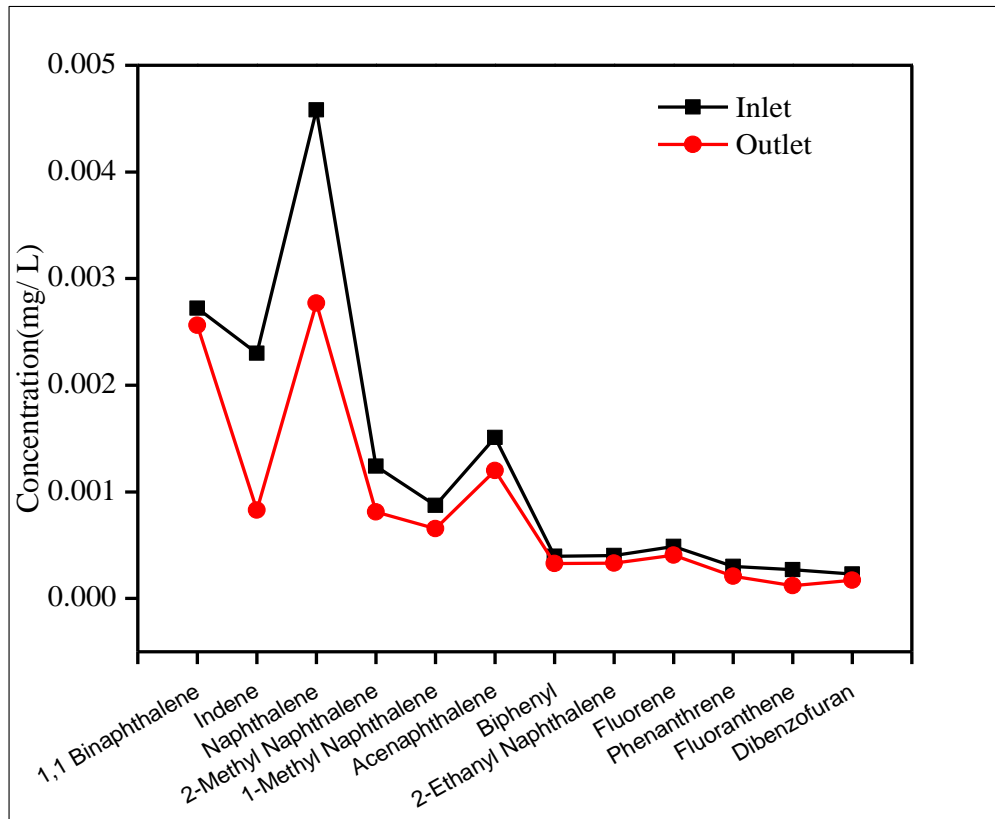


Figure 6-9: Tar components comparison at inlet and outlet using large woodchips (10–25 mm) bed.

As shown in Figure 6-9 and Table 6.2, large woodchips bed was also found an effective method for removal of tar components from the product gas. Comparison of tar components' concentration at inlet and outlet of the woodchips bed shows the decrease in the concentration of tar components efficiently.

Table 6-3: Tar component capture efficiency comparison of small wood chips bed (3–10 mm) and large woodchips bed (10–25mm).

Tar Component	Small wood chips bed's efficiency (%)	Large wood chips bed's efficiency (%)
1,1 Binaphthaene	8.22	5.89
Indene	9.41	63.93
Naphthalene	11.97	39.59
2-Methyl Naphthalene	13.67	34.84
1-Methyl Naphthalene	16.21	24.97
Acenaphthalene	10.71	20.45
Biphenyl	15.44	17.26
2-Ethanyl Naphthalene	17.65	17.87
Fluorene	15.42	16.80
Phenanthrene	31.58	30.10
Fluoranthene	44.26	55.35
1,1 Binaphthaene	8.22	5.89

The installed woodchips bed has been found to be an effective technique in capturing tar from the product gas. The average tar content capture was found as 29.4% with larger wood chips and 22.5% with small wood chips bed. A similar method was also adopted by Thapa *et al.* (2017) for tar abatement from

the product gas and found 10% tar reduction using corn woodchips shavings of size up to 2mm.

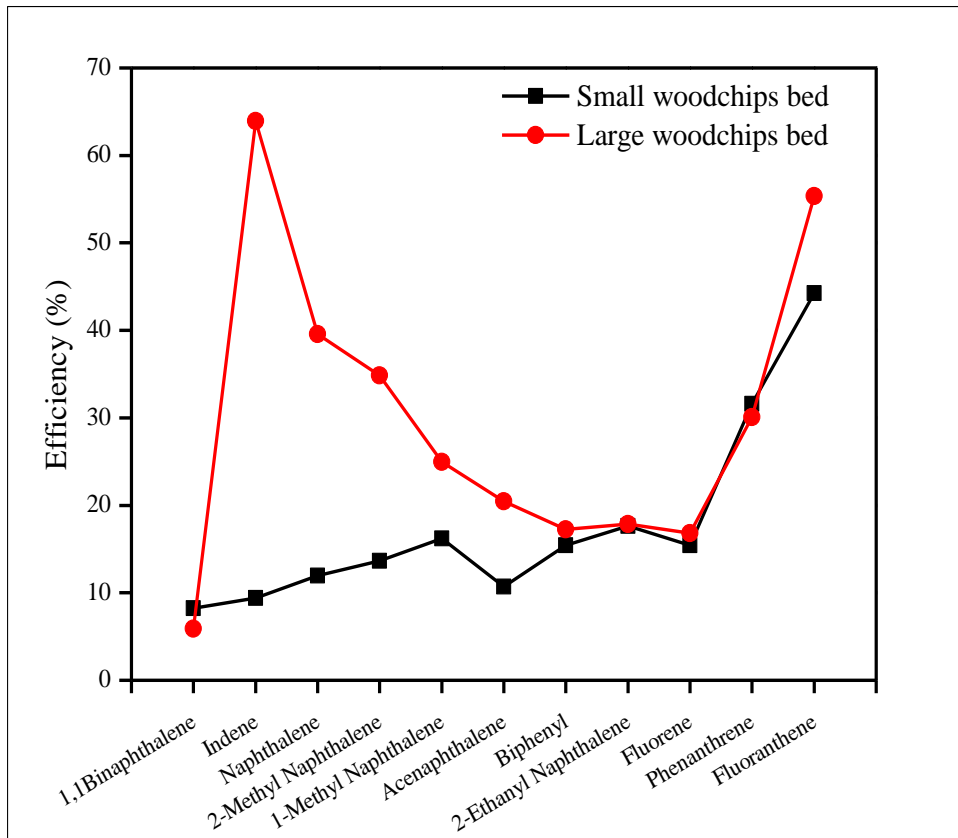


Figure 6-10: Tar component capture efficiency comparison of small wood chips (3-10 mm) bed and large wood chips (10-25 mm) bed.

Results showed in Table 6.3 and Figure 6-10 that large wood chips (10-25 mm) bed is more efficient in capturing tar from the product gas. This is because they have a large size and more bulk mass is available as compared to small woodchips (3-10 mm) exposing the more surface area for product gas to

contact. As the product gas containing tar and particulate matter entered in the secondary bed, the bed material containing larger wood chips provide more surface area to the contaminated product gas as compared to the small woodchips which are more compactly packed, hence the particle capture with the large woodchips bed material is more than that of the smaller woodchips bed material.

As the wood chips have a hydrophilic nature, the stream from the product gas accumulates at the surface of the woodchips; the water soluble tars are captured at the surface of the woodchips. As the larger wood chips provide more surface area exposed to the passing by contaminated product gas, hence they are found to be more effective in capturing tar from the product gas as compared to the small woodchips.

Bio-char bed

A biochar bed was tested in arresting the tar contents from the product gas samples. Carbonaceous materials have been focus of many research investigations in the context with particulate and tar removal from biomass product gas. As biochar is easily available, cheap and easy to install as bed material, biochar was tested for its tar removal efficiency from the product gas. Biochar provides more porous surface as compared to wood material, hence it is expected more efficient.



Figure 6-11: Biochar bed as an unsuccessful attempt in tar capture.

As shown in Figure 6-11, the biochar used to arrest the tars from the product gas was unsuccessful due to burning of biochar in the bed. As the hot product gas passed through the biochar bed, the unreacted carbon present in the biochar started ignition and hence leads a failure in using biochar as tar arrest material in this research study. Shen (2015) successfully used biochar as tar absorbent but also suggested that char has less tar absorbing ability than that of highly porous activated carbon. Biochar has higher closed pores in comparison with activated carbon and woodchips (Nakamura *et al.*, 2016). Char is also more suitable for absorbing light tars. Tarnpradab *et al.* (2016) also investigated waste char as tar absorbent for rice husk gasification and found it effective in capturing 76% of naphthalene. Nakamura *et al.* (2016) reported 81% tar reduction while noting the efficiency of char as tar scrubber.

Mop fan cleaning unit

The efficiency of mop fan was investigated in capturing tar and other particles at different parameters (such as mop fan with and water spray over the passing product gas through mop fan unit). The tar samples were taken before the mop fan (inlet) and after the mop fan (outlet). Concentrations of the individual tar components were measured and tabulated in Table 6-4.

Table 6-4: Tar capture by mop fan without water spray.

Tar Component	Inlet (mg/L)	Outlet (mg/L)	Efficiency (%)
1,1 Binaphthalene	0.00271	0.00203	25.01
Indene	0.00339	0.00314	7.41
Naphthalene	0.0181	0.0057	68.52
2-Methyl Naphthalene	0.00319	0.00127	60.24
1-Methyl Naphthalene	0.00232	0.000882	62.05
Biphenyl	0.00141	0.00113	20.24
2-Ethenyl naphthalene	0.00111	0.000377	66.05
Acenaphthalene	0.00391	0.000341	91.29
Fluorene	0.0009	0.000301	66.54
Phenanthrene	0.00409	0.000175	95.72
Fluoranthene	0.000852	0.000151	82.29
Triphenylene	0.000624	0.000118	81.09
Average tar component capture efficiency (%)			60.54

Table 6-4 describes the effectiveness of mop fan in arresting tar components from the product gas. The mop fan was run at 60 rpm for this experiment. The highest reduction in concentration was found in Phenanthrene which was reduced by 96%.

6.5.2 Mop fan with water spray

In this method, a measured amount of water was sprayed over the gas stream conjoint with the rotating mop fan to find out the tar abatement from the product gas.

6.5.2.1 Tar capture by mop fan with water spray

For wet system, many gasification plants commonly utilize a variety of water scrubber structure to remove tar and other gas contaminants such as spray tower, impingement scrubber, packed bed scrubber and venturi scrubber. Among all these kind of structures, water spray tower is the simplest and economical scrubber structure (Paethanom *et al.*, 2012).

The solubility of most tar components in water is low (except for heterocyclic compounds which include Pyridine, phenol, cresols, quinoline, isoquinoline, dibenzophenol). Absorption by pure water eliminates heterocyclic compounds and highest PAH, especially. Polycyclic hydrocarbons with two to three rings remain in the gas and their concentrations allow for subsequent condensation. Separate liquid phase

is either driven by water or leaves with gas in the form of aerosol. Water supplied to real-life equipment is assumed to be partially saturated with tar. Tar scrubbing is therefore based on elimination of aerosol. The disadvantage of gas scrubbing using water is a transfer of applicable heat of the gas into low-potential production of environmentally unfriendly waste water; another disadvantage is the need to have a source of cool water or equipment for its production. During summer, facilities may utilize spray tower, sprinkled cooler or chiller. Chiller is very expensive method of scrubbing while using water is relatively cheap (Balas *et al.*, 2014).

Table 6-5: Efficiency of mop fan with water spray in capturing tar.

Tar Component	Inlet (mg/L)	Outlet (mg/L)	Efficiency (%)
1,1 Binaphthalene	0.00271	0.00203	25.01
Indene	0.00339	0.000149	95.60
Naphthalene	0.0181	0.000641	96.46
2-Methyl Naphthalene	0.00319	0.000109	96.59
1-Methyl Naphthalene	0.00232	0.0000822	96.46
Biphenyl	0.00141	0.000173	87.76
2-Ethenyl naphthalene	0.00111	0.000049	95.59
Acenaphthalene	0.00391	0.0000435	98.89
Fluorene	0.0009	0.0000558	93.80
Phenanthrene	0.00409	0.00003	99.27
Fluoranthene	0.000852	0.0000376	95.59
Triphenylene	0.000624	0.0000356	94.30

Table 6-5 presents the efficiency of mop fan conjoint with spray water in capturing tar from the product gas. The efficiency %age in capturing the tar particles can be seen up to 95% for most of the tar components. These results are in agreement with the outcomes of the experiments performed by Rabou *et al.* (2009) at the Energy Research Centre of The Netherlands (ECN) in which water scrubbing was found as an effective technique in water-based GASREIP method to reduce tar contents from the product gas and noted tar reduction from 8 g/Nm³ to 4.5 g/Nm³. This efficiency in tar contents' reduction seems mainly because of the tar contents scrubbed with water and mop fan blades. Water droplets suspended in the stream contact with the tar contents from the gas stream and the surface tension of water droplets holds the tar and contaminants from the gas and accumulated at the water drainage section of the mop fan cleaning unit.

Figure 6-12 presents the concentrations of individual tar components in the product gas before and after its scrubbing with mop fan combined with water spray. The higher decrease of the tar components in the product gas is achieved by using mop fan and water spray together. As seen from the previous results, use of mop fan and water spray separately proved less effective in capturing the tar from the product gas as compared to use of mop fan and water spray in a synergic way.

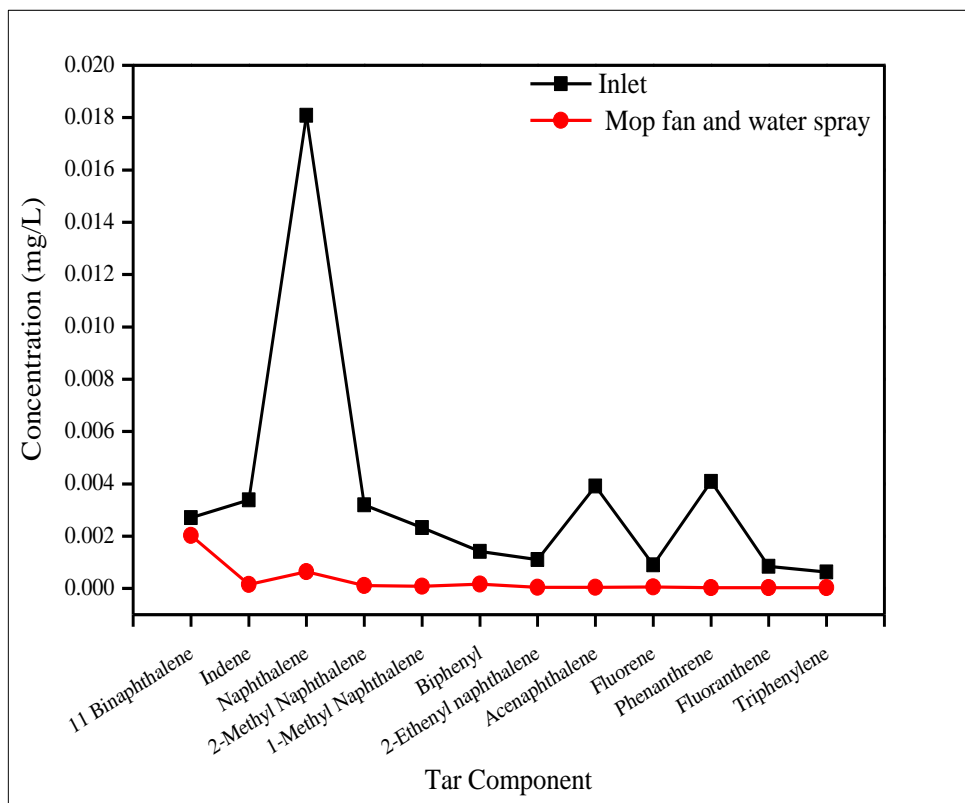


Figure 6-12: Concentration of tar components at inlet and mop fan and spray water outlet sampling points.

The tar component naphthalene was found decreased major as compared to other tar components. This could be result of affinity of naphthalene group with char and unreacted carbonaceous material as reported by W. Guo *et al.* (2017). Also, the water spray has the ability adhere the tar components and particulate matter from the product gas due to the surface tension of the water droplets. The total decrease in the tar components could also have been the result of water soluble components of the tar

which could have been dissolved in the spray water and tar condensation over the surface of water (Phuphuakrat, Namioka, *et al.*, 2010).

Table 6-6: Efficiency comparisons of mop fan and mop fan with water spray.

Tar Component	Mop fan	Mop fan with water spray
1,1 Binaphthalene	25.01	25.01
Indene	7.41	95.60
Naphthalene	68.52	96.46
2-Methyl Naphthalene	60.24	96.59
1-Methyl Naphthalene	62.05	96.46
Biphenyl	20.24	87.76
2-Ethenyl naphthalene	66.05	95.59
Acenaphthalene	91.29	98.89
Fluorene	66.54	93.80
Phenanthrene	95.72	99.27
Fluoranthene	82.29	95.59
Triphenylene	81.09	94.30

Table 6-6 compares the efficiency of mop fan with mop fan and water spray for capturing tar from the product gas. The results depicted that other than indene and biphenyl, mop fan was found very consistent in capturing tar particles from the product gas. As indene and biphenyl are not soluble in water, so this is assumed that some indene and biphenyl rich part from the surface of the mop fan blown away with the product gas stream and during the sampling at outlet, the concentration of indene and

biphenyl noted high and consequently resulted in low mop fan efficiency in capturing these tar components.

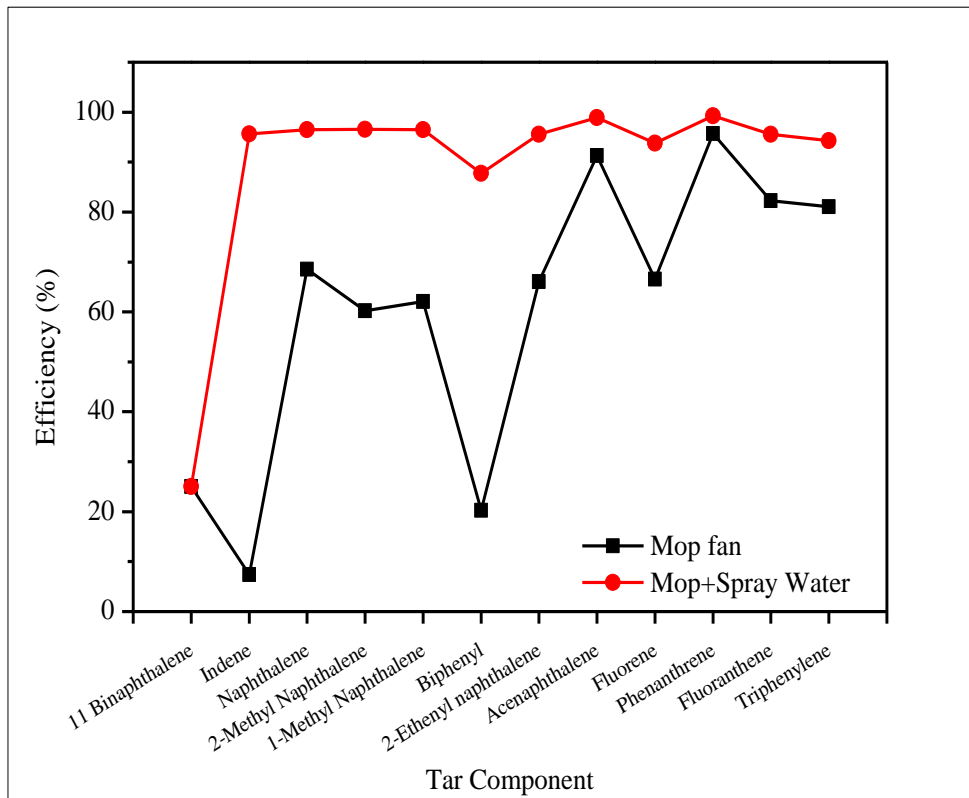


Figure 6-13: Comparison of tar component capture efficiency using mop fan and mop fan with water spray.

Figure 6-13 represents the efficiency comparison in capturing tar components by mop fan with no water spray against the mop fan with water spray 0.5 L/min. Mop fan running at 60 rpm with water spray noted as more effectual in capturing tar components from the product gas as compared to mop fan running with no water spray. Riffat *et al.* (1995) presented their research findings using mop fan for livestock

buildings and concluded that mop fan with water spray increased from 30% to 70% in capturing the particles from the air. Without water sprays its particle capture was around 30%. Nakamura *et al.* (2016) also presented the conjoint effect of bio-oil and char scrubber for tar cleaning of product gas and found this method for removing tar up to 98.0% in comparison with individual tar removal efficiency of bio-oil (64.5%) and char scrubber (81.5%).

Table 6-7: Total tar capture in different tar arrest techniques at 1920.6 g/h biomass feeding rates.

	Tar reduction (mg/L)		Avg tar reduction (mg/L)
	Test1	Test 2	
Woodchips bed	0.444	0.589	0.517
Mop fan	0.37	0.547	0.459
Mop fan + water spray	1	0.974	0.987

These results in Table 6-7 depict the efficiency of different techniques in capturing tar from the product gas. Mop fan with spray water is found to be the most effective method for removing tar components from the product gas i.e., 0.987 mg/L as compared to 0.517 mg/L and 0.459 mg/L tar removal efficiency by use of woodchips bed and mop fan without water spray respectively. These results recommend the use of mop fan with water spray for tar removal as a most efficient method. Mop fan has been found effective in capturing tar from the product gas in this research while water spray

has been used as wet scrubber in many research investigations for gas cleaning. The results presenting tar capture efficiency by different techniques in this investigation are in agreement with previous researchers' findings in achieving the same goal that also successfully removed/ abated tar and particulate matter from the product gas.

Summary

In this chapter, tar capture from the product gas was investigated by employing secondary tar removal methods (physical tar removal). The secondary tar removal method is examined in two different scenarios: dry scrubbing, dry and wet mixed scrubbing. Dry scrubbing was done by three methods i.e. woodchips bed, char bed and mop fan. In woodchips bed, small wood chips (3-10 mm) and large wood chips (10-25 mm) were tested. Average tar removal efficiency of large woodchips was noted as 29% while small wood chips were found efficient in removing 22% of tar from the product gas. Mop fan achieved about 60% tar removal efficiency while char bed was found as an unsuccessful technique for tar capture as due to high temperature of the product gas, char got ignited and burnt in the secondary bed. Tar removal by dry and wet mixed scrubbing proved higher tar capture from the product gas and achieved 89.61% efficiency by applying mop fan (60 rpm) and water spray (0.5 L/min) conjointly. This method could be applied successfully in product gas cleaning and tar removal but the drawback with this technique is generation of waste water which can add additional cost for its disposal.

Chapter 7 Conclusions and Future Work Recommendations

7.1 Conclusions

In this research investigation, a bubbling fluidized bed biomass gasifier was used to gasify short rotational crop (SRC) willow woodchips. For the first time, a novel product gas cleaning strategy with a mop fan cleaning unit for the product gas was investigated in this study. The compositions of the product gas samples were analyzed and validated by an online ABB gas analyzer installed with the gasifier and an offline analysis of the product gas samples using gas chromatographs. The analyzed product gas composition profiles confirmed the smooth running of the gasifier and the whole gasification process. The reliability of the gasifier was evidenced by the reproducible results of the product gas composition. In this research, different biomass feeding rates were tested with the carbon conversion rates within the range of approximately 92%~94%. The effect of ER on the product gas heating values and cold gas efficiency of the gasifier were also investigated and it was identified that the ER has a direct effect on the gas heating values and cold gas efficiency of the gasifier as presented in the chapter 4 and found in agreement with the different researchers.

The gasifier performance was evaluated by measuring the carbon conversion rate, high heating values, lower heating values, cold gas efficiency and gas yield against the different ER values. The carbon conversion was measured as 93.48%, 92.69% and

93.21% against the ER values 0.319, 0.288 and 0.248 respectively as presented in Table 4-5. The achieved carbon conversion is found to be in agreement with the previous gasification research work and found as acceptable carbon conversion in gasifier performance evaluation parameter. The gas heating values, cold gas efficiency and gas yield are considered as renounced parameters for the performance evaluation for the biomass gasifier. The higher and lower heating values were calculated at ER values 0.319, 0.288 and 0.248. The calculated HHV, LHV, CGE and gas yield determined in this investigation and presented in Table 4-6, are congruent to the past gasification studies regarding the product gas analyses and gas quality. It was concluded that with increasing ER, the HHV, LHV, CGE and gas yield were negatively impacted in this research of biomass gasification in laboratory scale bubbling fluidized bed gasifier.

Product gas cleaning technologies were the major focus of this study which incorporated a water spray technique and a mop fan gas cleaning unit with and without water spray. The mop fan cleaning efficiency was measured against different mop fan rotation speeds. The mop fan cleaning unit was also tested with and without spray water in particulate capture from the product gas. Without water spray, the mop fan rotation speed had a great impact on particles capturing efficiency at 10Hz (60rpm), 15Hz (90rpm) and 20Hz (120rpm). The efficiency was 39%, 49% and 55% respectively.

Spray water was another technique experimented for capturing the particulates from the product gas and found to be effective at different spray water amounts. In this method, water was sprayed over the passing product gas at 0.5L/min and 0.75L/min. By spraying water at amounts of 0.5L/min and 0.75L/min were found in capturing approximately 60% and 70% in the product gas respectively.

The combined mop fan and spray water was found to be more effective than the mop fan and spray water application separately and showed significantly high efficiency in particle capture of 76% and 87% at 0.5L/min and 0.75L/min spray water respectively with 10Hz (60rpm) mop fan rotation speeds.

Tar arrest techniques were under keen observation in this exploration. The primary tar capture methods by means of woodchips bed, bio-char bed and the mop fan with and without spray water were investigated for their tar capture performance.

The woodchips bed was installed next to the cyclone and the product gas was sampled at the entrance and the exit of woodchips bed. Two types of woodchips were used to study tar capture efficiency i.e. large woodchips and small woodchips. The same mass of large woodchips and small woodchips was used for the woodchips bed tar capture tests. Large woodchips showed higher tar capture efficiency as compared to small woodchips bed. This is due to large woodchips have bigger bulk volume and hence have bigger contact area for the tar containing product gas and woodchips.

The bio-char bed was also tested but did not prove effective as the hot product gas entered the bio-char bed, it led to the partial combustion of the very reactive bio-char and hence this technique was not successful. The mop fan with water spray was recognized to be most successful technique amongst these investigated in arresting tar components. For example, Naphthalene's concentration was reduced by 96% when using mop fan with water spray, comparing a reduction of 69%, 40% and 12% while using mop fan without spray water, large woodchips bed and small woodchips bed respectively. Similarly reduction in the concentration of Fluorene was found for these tar arrest techniques as 96%, 82%, 30% and 32 % with mop fan with spray water, mop fan without spray water, large woodchips bed and small woodchips bed respectively.

7.2 Future work and recommendations

The future work in this research is recommended as follows:

- Different biomass feedstock testing for gasification.
- Longer operation times.
- Change in gasification operating conditions.
- Different gasification medium (steam, air/steam mixture).
- Different bed materials and their effects on gasification performance (product gas composition, yield and tar contents etc.).
- Product gas cleaning performance of different mop fans.

References

- Abu El-Rub, Z., Bramer, E., & Brem, G. (2004). Review of catalysts for tar elimination in biomass gasification processes. *Industrial & engineering chemistry research*, 43(22), 6911-6919.
- Ahmed, R., Sinnathambi, C. M., Eldmerdash, U., & Subbarao, D. (2014). Thermodynamics analysis of refinery sludge gasification in adiabatic updraft gasifier. *The Scientific World Journal*, 2014.
- Aigner, I., Pfeifer, C., & Hofbauer, H. (2011). Co-gasification of coal and wood in a dual fluidized bed gasifier. *Fuel*, 90(7), 2404-2412.
- Aigner, I., Wolfesberger, U., & Hofbauer, H. (2009). *Tar content and composition in producer gas of fluidized bed gasification and low temperature pyrolysis of straw and wood-influence of temperature*: na.
- Akudo, C. O. (2008). *Quantification of Tars and Particulates from a Pilot Scale, Downdraft Biomass Gasifier*. Citeseer.
- Al-Dury, S. (2009). Removal of tar in biomass gasification process using carbon materials. *Chem Eng Trans*, 18, 665.
- Albrecht, F. G., König, D. H., & Dietrich, R.-U. (2016). Selecting the appropriate gasification technology and system design for Power and Biomass-to-Liquid concepts: A case study.
- Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., & Meinshausen, N. (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, 458(7242), 1163-1166.
- Altafini, C. R., Wander, P. R., & Barreto, R. M. (2003). Prediction of the working parameters of a wood waste gasifier through an equilibrium model. *Energy Conversion and Management*, 44(17), 2763-2777.
- Anis, S., & Zainal, Z. (2011). Tar reduction in biomass producer gas via mechanical, catalytic and thermal methods: A review. *Renewable and Sustainable Energy Reviews*, 15(5), 2355-2377.
- Asadullah, M. (2014). Barriers of commercial power generation using biomass gasification gas: a review. *Renewable and Sustainable Energy Reviews*, 29, 201-215.
- Baker, E., Brown, M., Moore, R., Mudge, L., & Elliott, D. (1986). Engineering analysis of biomass gasifier product gas cleaning technology: Pacific Northwest Lab., Richland, WA (USA).
- Balas, M., Lisy, M., Skala, Z., & Pospisil, J. (2014). Wet scrubber for cleaning of syngas from biomass gasification. *Advances in Environmental Sciences, Development and Chemistry*, 195-201.

- Balat, M. (2008). Mechanisms of thermochemical biomass conversion processes. Part 1: reactions of pyrolysis. *Energy Sources, Part A*, 30(7), 620-635.
- Basu, P. (2006). *Combustion and gasification in fluidized beds*: CRC press.
- Beenackers, A., & Maniatis, K. (1998). *Gasification technologies for heat and power from biomass*. Paper presented at the Fuel and Energy Abstracts.
- Belgiorno, V., De Feo, G., Della Rocca, C., & Napoli, R. (2003). Energy from gasification of solid wastes. *Waste management*, 23(1), 1-15.
- Bergman, P. C., van Paasen, S. V., & Boerrigter, H. (2002). *The novel "OLGA" technology for complete tar removal from biomass producer gas*. Paper presented at the Pyrolysis and gasification of biomass and waste, expert meeting, Strasbourg, France.
- Boerrigter, H., Calis, H. P., Slort, D. J., & Bodenstaff, H. (2004). *Gas cleaning for integrated biomass gasification (BG) and Fischer-Tropsch (FT) systems; experimental demonstration of two BG-FT systems*. Paper presented at the Proceedings of the 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection.
- Boerrigter, H., & Rauch, R. (2005). *Syngas production and utilisation*: na.
- Boléo, S. M. T. (2011). *Environmental impact assessment of energy crops cultivation in the Mediterranean Europe*. Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa.
- Bosmans, A., Wasan, S., & Helsen, L. (2013). *Waste-to-clean syngas: avoiding tar problems*. Paper presented at the Proceedings of the 2nd International Academic Symposium on Enhanced Landfill Mining.
- Bridgwater, A. (1995). The technical and economic feasibility of biomass gasification for power generation. *Fuel*, 74(5), 631-653.
- Bridgwater, A. (2008). *Progress in thermochemical biomass conversion*: John Wiley & Sons.
- Bui, T., Loof, R., & Bhattacharya, S. (1994). Multi-stage reactor for thermal gasification of wood. *Energy*, 19(4), 397-404.
- Caballero, M. A., Corella, J., Aznar, M.-P., & Gil, J. (2000). Biomass gasification with air in fluidized bed. Hot gas cleanup with selected commercial and full-size nickel-based catalysts. *Industrial & engineering chemistry research*, 39(5), 1143-1154.
- Casper, J. K. (2010). *Fossil fuels and pollution: the future of air quality*: Infobase Publishing.
- Chan, F. L., & Tanksale, A. (2014). Review of recent developments in Ni-based catalysts for biomass gasification. *Renewable and Sustainable Energy Reviews*, 38, 428-438.

- Chen, H. (2014). Chemical composition and structure of natural lignocellulose *Biotechnology of lignocellulose* (pp. 25-71): Springer.
- Chen, J., Yin, W., Wang, S., Meng, C., Yu, G., Hu, T., & Lin, F. (2016). Analysis of biomass gasification in bubbling fluidized bed with two-fluid model. *Journal of Renewable and Sustainable Energy*, 8(6), 063105.
- Chiang, K.-Y., Lu, C.-H., Lin, M.-H., & Chien, K.-L. (2013). Reducing tar yield in gasification of paper-reject sludge by using a hot-gas cleaning system. *Energy*, 50, 47-53.
- Chum, H. L., & Overend, R. P. (2001). Biomass and renewable fuels. *Fuel Processing Technology*, 71(1), 187-195.
- Ciferno, J. P., & Marano, J. J. (2002). Benchmarking biomass gasification technologies for fuels, chemicals and hydrogen production. *US Department of Energy. National Energy Technology Laboratory*.
- Corella, J., Toledo, J. M., & Molina, G. (2007). A review on dual fluidized-bed biomass gasifiers. *Industrial & engineering chemistry research*, 46(21), 6831-6839.
- Corton, J., Iain, D., McCalmont, J., Watson, I., Khan, Z., Blanco-Sanchez, P., Yu, X., Fletcher, G., Croxton, S., & Paul, M. (2017). The impact of biomass feedstock composition and pre-treatments on tar formation during biomass gasification.
- Couto, N., Rouboa, A., Silva, V., Monteiro, E., & Bouziane, K. (2013). Influence of the biomass gasification processes on the final composition of syngas. *Energy Procedia*, 36, 596-606.
- Dayton, D. C., & Milne, T. A. (1996). Laboratory measurements of alkali metal containing vapors released during biomass combustion *Applications of Advanced Technology to Ash-Related Problems in Boilers* (pp. 161-185): Springer.
- Demirbas, A. (2008). Biofuels sources, biofuel policy, biofuel economy and global biofuel projections. *Energy Conversion and Management*, 49(8), 2106-2116.
- Demirbaş, A. (2001). Biomass resource facilities and biomass conversion processing for fuels and chemicals. *Energy Conversion and Management*, 42(11), 1357-1378.
- Devi, L., Ptasiński, K. J., & Janssen, F. J. (2003). A review of the primary measures for tar elimination in biomass gasification processes. *Biomass and Bioenergy*, 24(2), 125-140.
- Dogru, M., Howarth, C., Akay, G., Keskinler, B., & Malik, A. (2002). Gasification of hazelnut shells in a downdraft gasifier. *Energy*, 27(5), 415-427.
- Doherty, W., Reynolds, A., & Kennedy, D. (2009). The effect of air preheating in a biomass CFB gasifier using ASPEN Plus simulation. *Biomass and bioenergy*, 33(9), 1158-1167.

- Dong, L., Liu, H., & Riffat, S. (2009). Development of small-scale and micro-scale biomass-fuelled CHP systems—A literature review. *Applied thermal engineering*, 29(11), 2119-2126.
- Đurišić-Mladenović, N., Škrbić, B. D., & Zabaniotou, A. (2016). Chemometric interpretation of different biomass gasification processes based on the syngas quality: Assessment of crude glycerol co-gasification with lignocellulosic biomass. *Renewable and Sustainable Energy Reviews*, 59, 649-661.
- Elliott, D. C., Biller, P., Ross, A. B., Schmidt, A. J., & Jones, S. B. (2015). Hydrothermal liquefaction of biomass: developments from batch to continuous process. *Bioresource Technology*, 178, 147-156.
- Feldman, D. L. (1995). Revisiting the energy crisis: How far have we come. *Environment: Science and Policy for Sustainable Development*, 37(4), 16-44.
- Gani, A., & Naruse, I. (2007). Effect of cellulose and lignin content on pyrolysis and combustion characteristics for several types of biomass. *Renewable Energy*, 32(4), 649-661.
- García, R., Pizarro, C., Lavín, A. G., & Bueno, J. L. (2013). Biomass proximate analysis using thermogravimetry. *Bioresource Technology*, 139, 1-4.
- Gautam, G. (2010). *Parametric study of a commercial-scale biomass downdraft gasifier: experiments and equilibrium modeling*. Auburn University.
- Gil, J., Corella, J., Aznar, M. a. P., & Caballero, M. A. (1999). Biomass gasification in atmospheric and bubbling fluidized bed: effect of the type of gasifying agent on the product distribution. *Biomass and Bioenergy*, 17(5), 389-403.
- Gómez-Barea, A., Arjona, R., & Ollero, P. (2005). Pilot-plant gasification of olive stone: a technical assessment. *Energy & fuels*, 19(2), 598-605.
- Gómez-Barea, A., & Leckner, B. (2010). Modeling of biomass gasification in fluidized bed. *Progress in Energy and Combustion Science*, 36(4), 444-509.
- Goyal, H., Seal, D., & Saxena, R. (2008). Bio-fuels from thermochemical conversion of renewable resources: a review. *Renewable and Sustainable Energy Reviews*, 12(2), 504-517.
- Gungor, A., & Yildirim, U. (2013). Two dimensional numerical computation of a circulating fluidized bed biomass gasifier. *Computers & Chemical Engineering*, 48, 234-250.
- Guo, F., Dong, Y., Dong, L., & Guo, C. (2014). Effect of design and operating parameters on the gasification process of biomass in a downdraft fixed bed: An experimental study. *International Journal of Hydrogen Energy*, 39(11), 5625-5633.
- Guo, W., Ai, Y., Men, B., & Wang, S. (2017). Adsorption of phenanthrene and pyrene by biochar produced from the excess sludge: experimental studies and theoretical analysis. *International Journal of Environmental Science and Technology*, 1-8.

- Gustafsson, E. (2011). *Characterization of particulate matter from atmospheric fluidized bed biomass gasifiers*. Linnaeus University Press.
- Hamad, M. A., Radwan, A. M., Heggo, D. A., & Moustafa, T. (2016). Hydrogen rich gas production from catalytic gasification of biomass. *Renewable Energy*, 85, 1290-1300.
- Han, J., & Kim, H. (2008). The reduction and control technology of tar during biomass gasification/pyrolysis: an overview. *Renewable and Sustainable Energy Reviews*, 12(2), 397-416.
- Hasler, P., & Nussbaumer, T. (1999). Gas cleaning for IC engine applications from fixed bed biomass gasification. *Biomass and Bioenergy*, 16(6), 385-395.
- Hasler, P., & Nussbaumer, T. (2000). Sampling and analysis of particles and tars from biomass gasifiers. *Biomass and Bioenergy*, 18(1), 61-66.
- Haykırı-Açma, H. (2003). Combustion characteristics of different biomass materials. *Energy Conversion and Management*, 44(1), 155-162.
- Hernández, J. J., Aranda-Almansa, G., & Bula, A. (2010). Gasification of biomass wastes in an entrained flow gasifier: effect of the particle size and the residence time. *Fuel processing technology*, 91(6), 681-692.
- Herzog, A. V., Lipman, T. E., Edwards, J. L., & Kammen, D. M. (2001). Renewable energy: a viable choice. *Environment: Science and Policy for Sustainable Development*, 43(10), 8-20.
- Hoque, M., & Bhattacharya, S. (2001). Fuel characteristics of gasified coconut shell in a fluidized and a spouted bed reactor. *Energy*, 26(1), 101-110.
- Hos, J., & Groeneveld, M. (1987). Biomass gasification (pp. 237-255): Chichester, UK: John Wiley & Sons.
- Huang, J., Schmidt, K. G., & Bian, Z. (2011). Removal and conversion of tar in syngas from woody biomass gasification for power utilization using catalytic hydrocracking. *Energies*, 4(8), 1163-1177.
- IEA. (2013). World Energy Outlook 2013: IEA Publications Paris.
- Iversen, H. L., & Gøbel, B. (2004). Update on gas cleaning technologies for biomass gasification gas for different applications. *Biomass Gasification Group, Denmark*, 226.
- Jansen, J. I. C., Jönsson, K., & Hagman, M. (2002). Biological detoxification of tar-water. *Water Science and Technology*, 46(4-5), 59-65.
- Jenkins, B., Baxter, L., & Miles, T. (1998). Combustion properties of biomass. *Fuel Processing Technology*, 54(1), 17-46.
- Jordan, C. A., & Akay, G. (2013). Effect of CaO on tar production and dew point depression during gasification of fuel cane bagasse in a novel downdraft gasifier. *Fuel Processing Technology*, 106, 654-660.

- Karmakar, M. K., Chandra, P., & Chatterjee, P. K. (2015). A review on the fuel gas cleaning technologies in gasification process. *Journal of Environmental Chemical Engineering*, 3(2), 689-702.
- Kaushal, P., & Tyagi, R. (2017). Advanced simulation of biomass gasification in a fluidized bed reactor using ASPEN PLUS. *Renewable Energy*, 101, 629-636.
- Kim, Y. D., Yang, C. W., Kim, B. J., Kim, K. S., Lee, J. W., Moon, J. H., Yang, W., Tae, U. Y., & Do Lee, U. (2013). Air-blown gasification of woody biomass in a bubbling fluidized bed gasifier. *Applied Energy*, 112, 414-420.
- Kinoshita, C., Wang, Y., & Zhou, J. (1994). Tar formation under different biomass gasification conditions. *Journal of Analytical and Applied Pyrolysis*, 29(2), 169-181.
- Kirubakaran, V., Sivaramakrishnan, V., Shanmugapriya, S., Premalatha, M., & Subramanian, P. (2009). Autocatalytic Kinetics and Mechanism of Biogas Generation. *Energy Sources, Part A*, 31(19), 1700-1707.
- Klass, D. L. (1998). *Biomass for renewable energy, fuels, and chemicals*: Academic press.
- Klass, D. L. (2004). Biomass for renewable energy and fuels. *Encyclopedia of energy. Elsevier Inc, 1*, 193-211.
- Klein, A. (2002). *Gasification: an alternative process for energy recovery and disposal of municipal solid wastes*. Columbia University.
- Kook, J. W., Choi, H. M., Kim, B. H., Ra, H. W., Yoon, S. J., Mun, T. Y., Kim, J. H., Kim, Y. K., Lee, J. G., & Seo, M. W. (2016). Gasification and tar removal characteristics of rice husk in a bubbling fluidized bed reactor. *Fuel*.
- Kumar, A., Eskridge, K., Jones, D. D., & Hanna, M. A. (2009). Steam–air fluidized bed gasification of distillers grains: effects of steam to biomass ratio, equivalence ratio and gasification temperature. *Bioresource Technology*, 100(6), 2062-2068.
- Kurchania, A. (2012). Biomass energy *Biomass Conversion* (pp. 91-122): Springer.
- Kurella, S., Bhukya, P. K., & Meikap, B. (2017). Removal of H₂S pollutant from gasifier syngas by a multistage dual-flow sieve plate column wet scrubber. *Journal of Environmental Science and Health, Part A*, 52(6), 515-523.
- Larsson, A., Israelsson, M., Lind, F., Seemann, M., & Thunman, H. (2014). Using ilmenite to reduce the tar yield in a dual fluidized bed gasification system. *Energy & fuels*, 28(4), 2632-2644.
- Laurence, L., & Ashenafi, D. (2012). Syngas treatment unit for small scale gasification-application to IC engine gas quality requirement. *Journal of Applied Fluid Mechanics*, 5(1), 95-103.
- Le, C. D. (2012). *Gasification of biomass: An investigation of key challenges to advance acceptance of the technology*. University of Bath.

- Leung, D. Y., Yin, X., & Wu, C. (2004). A review on the development and commercialization of biomass gasification technologies in China. *Renewable and Sustainable Energy Reviews*, 8(6), 565-580.
- Li, C., & Suzuki, K. (2009). Tar property, analysis, reforming mechanism and model for biomass gasification—an overview. *Renewable and Sustainable Energy Reviews*, 13(3), 594-604.
- Lien, C. C., Wang, M. W., & Lin, W. C. (2017). *Study on the Removal of Hydrogen Sulfide from Biogas Biomaterial Using Water Scrubbing*. Paper presented at the Key Engineering Materials.
- Lim, M. T. (2007). *Characterization Of A Bubbling Fluidized Bed Biomass Gasifier*. USM.
- Lincoln, T., & Zeiger, E. (2006). Secondary Metabolites and Plant Defense. *Plant Physiology. Fourth Edition. Sinauer Associates, Inc. Capítulo, 13*, 125.
- Livingston, B., & Babcock, M. (2006). *Ash Related Issues in Biomass Combustion*. Paper presented at the Thermal Net Workshop Proceedings.
- Lucas, C. (2005). *High temperature air/steam gasification of biomass in an updraft fixed bed batch type gasifier*. KTH.
- Lv, P., Xiong, Z., Chang, J., Wu, C., Chen, Y., & Zhu, J. (2004). An experimental study on biomass air–steam gasification in a fluidized bed. *Bioresource Technology*, 95(1), 95-101.
- Ma, X., Birnie, M., Riffat, S., & Gillott, M. (2008). Experimental investigation of a side-emitting optical fibre mop fan for air cleaning. *International Journal of Low-Carbon Technologies*, 3(2), 126-136.
- Ma, Z., Ye, J., Zhao, C., & Zhang, Q. (2015). Gasification of rice husk in a downdraft gasifier: the effect of equivalence ratio on the gasification performance, properties, and utilization analysis of byproducts of char and tar. *BioResources*, 10(2), 2888-2902.
- Mahishi, M. R., & Goswami, D. (2007). Thermodynamic optimization of biomass gasifier for hydrogen production. *International Journal of Hydrogen Energy*, 32(16), 3831-3840.
- Maniatis, K. (2008). Progress in biomass gasification: an overview. *Progress in thermochemical biomass conversion*, 1.
- Mastellone, M. L., & Arena, U. (2008). Olivine as a tar removal catalyst during fluidized bed gasification of plastic waste. *AIChE Journal*, 54(6), 1656-1667.
- Mayerhofer, M., Mitsakis, P., Meng, X., de Jong, W., Spliethoff, H., & Gaderer, M. (2012). Influence of pressure, temperature and steam on tar and gas in allothermal fluidized bed gasification. *Fuel*, 99, 204-209.
- McKendry, P. (2002). Energy production from biomass (part 1): overview of biomass. *Bioresource Technology*, 83(1), 37-46.

- Miccio, F., Piriou, B., Ruoppolo, G., & Chirone, R. (2009). Biomass gasification in a catalytic fluidized reactor with beds of different materials. *Chemical Engineering Journal*, 154(1), 369-374.
- Milne, T., & Evans, R. (1998). Biomass gasification “tars”: their nature, formation and conversion. NREL, Golden, CO, USA: report no. NREL/TP-570-25357.
- Moulijn, J. A., Makkee, M., & Van Diepen, A. E. (2013). *Chemical process technology*: John Wiley & Sons.
- Mussatti, D., & Hemmer, P. (2002). Wet Scrubbers Particulate Matter: US EPA, Washington, DC.
- Myren, C., Hörnell, C., Björnbom, E., & Sjöström, K. (2002). Catalytic tar decomposition of biomass pyrolysis gas with a combination of dolomite and silica. *Biomass and bioenergy*, 23(3), 217-227.
- Nakamura, S., Kitano, S., & Yoshikawa, K. (2016). Biomass gasification process with the tar removal technologies utilizing bio-oil scrubber and char bed. *Applied Energy*, 170, 186-192.
- Narvaez, I., Orio, A., Aznar, M. P., & Corella, J. (1996). Biomass gasification with air in an atmospheric bubbling fluidized bed. Effect of six operational variables on the quality of the produced raw gas. *Industrial & Engineering Chemistry Research*, 35(7), 2110-2120.
- Paethanom, A., Nakahara, S., Kobayashi, M., Prawisudha, P., & Yoshikawa, K. (2012). Performance of tar removal by absorption and adsorption for biomass gasification. *Fuel processing technology*, 104, 144-154.
- Patra, T. K., & Sheth, P. N. (2015). Biomass gasification models for downdraft gasifier: A state-of-the-art review. *Renewable and Sustainable Energy Reviews*, 50, 583-593.
- Pedersen, K., & Larsen, E. (1999). *Karakterisering af tjære i gas fra termisk forgasning af biomasse*: Teknologisk Institut.
- Pereira, E. G., da Silva, J. N., de Oliveira, J. L., & Machado, C. S. (2012). Sustainable energy: a review of gasification technologies. *Renewable and Sustainable Energy Reviews*, 16(7), 4753-4762.
- Pfeifer, C., Rauch, R., & Hofbauer, H. (2004). In-bed catalytic tar reduction in a dual fluidized bed biomass steam gasifier. *Industrial & engineering chemistry research*, 43(7), 1634-1640.
- Phuphuakrat, T., Namioka, T., & Yoshikawa, K. (2010). Tar removal from biomass pyrolysis gas in two-step function of decomposition and adsorption. *Applied Energy*, 87(7), 2203-2211.
- Phuphuakrat, T., Nipattummakul, N., Namioka, T., Kerdsuwan, S., & Yoshikawa, K. (2010). Characterization of tar content in the syngas produced in a downdraft type fixed bed gasification system from dried sewage sludge. *Fuel*, 89(9), 2278-2284.

- Pinto, F., Franco, C., Andre, R. N., Tavares, C., Dias, M., Gulyurtlu, I., & Cabrita, I. (2003). Effect of experimental conditions on co-gasification of coal, biomass and plastics wastes with air/steam mixtures in a fluidized bed system. *Fuel*, 82(15), 1967-1976.
- Pumiglia, D., Vaccaro, S., Masi, A., McPhail, S. J., Falconieri, M., Gagliardi, S., Della Seta, L., & Carlini, M. (2017). Aggravated test of Intermediate temperature solid oxide fuel cells fed with tar-contaminated syngas. *Journal of Power Sources*, 340, 150-159.
- Quaak, P., Knoef, H., & Stassen, H. E. (1999). *Energy from biomass: a review of combustion and gasification technologies* (Vol. 23): World Bank Publications.
- Rabou, L. P., Zwart, R. W., Vreugdenhil, B. J., & Bos, L. (2009). Tar in biomass producer gas, the Energy research Centre of the Netherlands (ECN) experience: an enduring challenge. *Energy & fuels*, 23(12), 6189-6198.
- Rajvanshi, A. (1986). Biomass gasification. Alternative energy in agriculture, 2. Volume: CRC press, USA.
- Ramachandra, T., & Shruthi, B. (2005). Wind energy potential mapping in Karnataka, India, using GIS. *Energy Conversion and Management*, 46(9), 1561-1578.
- Rapagna, S., Jand, N., Kiennemann, A., & Foscolo, P. (2000). Steam-gasification of biomass in a fluidised-bed of olivine particles. *Biomass and Bioenergy*, 19(3), 187-197.
- Rapagna, S., & Latif, A. (1997). Steam gasification of almond shells in a fluidised bed reactor: the influence of temperature and particle size on product yield and distribution. *Biomass and Bioenergy*, 12(4), 281-288.
- Rezaiyan, J., & Cheremisinoff, N. P. (2005). *Gasification technologies: a primer for engineers and scientists*: CRC press.
- Richardson, Y., Drobek, M., Julbe, A., Blin, J., & Pinta, F. (2015). Biomass gasification to produce syngas. *Recent Advances in Thermo-chemical Conversion of Biomass*.
- Riffat, S., Shao, L., Clarke, R., & Ramshaw, C. (1995). Mop fan for livestock buildings. *Journal of agricultural engineering research*, 61(3), 191-195.
- Riffat, S., & Zhao, X. (2007). Preliminary study of the performance and operating characteristics of a mop-fan air cleaning system for buildings. *Building and environment*, 42(9), 3241-3252.
- Roy, P. C., Datta, A., & Chakraborty, N. (2009). Modelling of a downdraft biomass gasifier with finite rate kinetics in the reduction zone. *International Journal of Energy Research*, 33(9), 833-851.
- Safitri, A. (2005). Biomass gasification using bubbling fluidized-bed gasifier: investigation of the effect of different catalysts on tar reduction. *Master of Science Thesis. Technische Universiteit Eindhoven*.

- Salam, P. A., Kumar, S., & Siriwardhana, M. (2010). The status of biomass gasification. *Report. Asian Institute of Technology, Pathumthani, Thailand.*
- Schiffner, K., & Hesketh, H. (1996). Wet Scrubbers , vol. xv. *Lancaster, Pa: Technomic.*
- Ściażko, M., & Stępień, L. (2015). A Modified Gibbs Free Energy Minimisation Model for Fluid Bed Coal Gasification. *Chemical and Process Engineering, 36(1)*, 73-87.
- Sethupathy, S. B., & Natarajan, E. (2016). *Air Steam Gasification of Coconut Shell in A Fluidized Bed.* Paper presented at the Environmental Science and Sustainable Development: International Conference on Environmental Science and Sustainable Development (ICESSD 2015).
- Sheeba, K., Babu, J. S. C., & Jaisankar, S. (2009). Air gasification characteristics of coir pith in a circulating fluidized bed gasifier. *Energy for Sustainable Development, 13(3)*, 166-173.
- Shen, Y. (2015). Chars as carbonaceous adsorbents/catalysts for tar elimination during biomass pyrolysis or gasification. *Renewable and Sustainable Energy Reviews, 43*, 281-295.
- Sheth, P. N., & Babu, B. (2009). Experimental studies on producer gas generation from wood waste in a downdraft biomass gasifier. *Bioresource Technology, 100(12)*, 3127-3133.
- Sheth, P. N., & Babu, B. (2010). Production of hydrogen energy through biomass (waste wood) gasification. *International Journal of Hydrogen Energy, 35(19)*, 10803-10810.
- Siedlecki, M., De Jong, W., & Verkooijen, A. H. (2011). Fluidized bed gasification as a mature and reliable technology for the production of bio-syngas and applied in the production of liquid transportation fuels—a review. *Energies, 4(3)*, 389-434.
- Sikarwar, V. S., Zhao, M., Clough, P., Yao, J., Zhong, X., Memon, M. Z., Shah, N., Anthony, E. J., & Fennell, P. S. (2016). An overview of advances in biomass gasification. *Energy & Environmental Science, 9(10)*, 2939-2977.
- Singhal, G., Renger, G., Sopory, S., & Irrgang, K. (2012). *Concepts in photobiology: photosynthesis and photomorphogenesis*: Springer Science & Business Media.
- Sjostrom, E. (2013). *Wood chemistry: fundamentals and applications*: Elsevier.
- Skoulou, V., Koufodimos, G., Samaras, Z., & Zabaniotou, A. (2008). Low temperature gasification of olive kernels in a 5-kW fluidized bed reactor for H₂-rich producer gas. *International Journal of Hydrogen Energy, 33(22)*, 6515-6524.
- Sutton, D., Kelleher, B., & Ross, J. R. (2001). Review of literature on catalysts for biomass gasification. *Fuel Processing Technology, 73(3)*, 155-173.
- Tarnpradab, T., Unyaphan, S., Takahashi, F., & Yoshikawa, K. (2016). Tar removal capacity of waste cooking oil absorption and waste char adsorption for rice husk gasification. *Biofuels, 7(4)*, 401-412.

- Thanapal, S. S., Annamalai, K., Sweeten, J. M., & Gordillo, G. (2012). Fixed bed gasification of dairy biomass with enriched air mixture. *Applied Energy*, *97*, 525-531.
- Thapa, S., Bhoi, P. R., Kumar, A., & Huhnke, R. L. (2017). Effects of Syngas Cooling and Biomass Filter Medium on Tar Removal. *Energies*, *10*(3), 349.
- Timmer, K. J. (2008). *Carbon conversion during bubbling fluidized bed gasification of biomass*: ProQuest.
- Tinaut, F. V., Melgar, A., Perez, J. F., & Horrillo, A. (2008). Effect of biomass particle size and air superficial velocity on the gasification process in a downdraft fixed bed gasifier. An experimental and modelling study. *Fuel Processing Technology*, *89*(11), 1076-1089.
- Torres, W., Pansare, S. S., & Goodwin Jr, J. G. (2007). Hot gas removal of tars, ammonia, and hydrogen sulfide from biomass gasification gas. *Catalysis Reviews*, *49*(4), 407-456.
- Trenberth, K. E., Fasullo, J. T., & Kiehl, J. (2009). Earth's global energy budget. *Bulletin of the American Meteorological Society*, *90*(3), 311-323.
- Turare, C. (1997). Biomass Gasification-Technology and Utilisation. *Artes Institute, University of Flensburg, Germany*.
- Turkenburg, W. C., Beurskens, J., Faaij, A., Fraenkel, P., Fridleifsson, I., Lysen, E., Mills, D., Moreira, J. R., Nilsson, L. J., & Schaap, A. (2000). Renewable energy technologies. *World energy assessment: Energy and the challenge of sustainability*, 219-272.
- Turn, S., Kinoshita, C., Zhang, Z., Ishimura, D., & Zhou, J. (1998). An experimental investigation of hydrogen production from biomass gasification. *International Journal of Hydrogen Energy*, *23*(8), 641-648.
- Ummadisingu, A., Sheth, P., & Babu, B. (2010). *Experimental studies on gasification of pine wood shavings in a downdraft biomass gasifier*. Paper presented at the Proceedings of the AIChE Annual Meeting.
- Valin, S., Ravel, S., Guillaudeau, J., & Thiery, S. (2010). Comprehensive study of the influence of total pressure on products yields in fluidized bed gasification of wood sawdust. *Fuel Processing Technology*, *91*(10), 1222-1228.
- van den Aarsen, F. G. (1985). *Fluidised bed wood gasifier performance and modeling*: FG van den Aarsen.
- van Heesch, E., Pemen, A., Yan, K., van Paasen, S., Ptasinski, K., Matyas, Z., Huijbrechts, P., Hultermans, B., Nicoletti, A., & Blom, P. (1999). *Experimental program of the pulsed corona tar cracker*. Paper presented at the Pulsed Power Conference, 1999. Digest of Technical Papers. 12th IEEE International.
- Van Loo, S., & Koppejan, J. (2008). Biomass combustion and co-firing. *Earthscan, London/Sterling*.

- Van Paasen, S., Kiel, J., Neeft, J., Knoef, H., Buffinga, G., Zielke, U., Sjoström, K., Brage, C., Hasler, P., & Simell, P. (2002). Guideline for sampling and analysis of tar and particles in biomass producer gases. *Final report documenting the Guideline, R&D work and dissemination*, 95.
- Vasudevan, P., Sharma, S., & Kumar, A. (2005). Liquid fuel from biomass: An overview. *Journal of Scientific and Industrial Research*, 64(11), 822.
- Wan Ab Karim Ghani, W., Moghadam, R. A., Salleh, M., & Alias, A. (2009). Air gasification of agricultural waste in a fluidized bed gasifier: hydrogen production performance. *Energies*, 2(2), 258-268.
- Wang, L., Weller, C. L., Jones, D. D., & Hanna, M. A. (2008). Contemporary issues in thermal gasification of biomass and its application to electricity and fuel production. *Biomass and Bioenergy*, 32(7), 573-581.
- Warnecke, R. (2000). Gasification of biomass: comparison of fixed bed and fluidized bed gasifier. *Biomass and Bioenergy*, 18(6), 489-497.
- Wei, L., Xu, S., Zhang, L., Liu, C., Zhu, H., & Liu, S. (2007). Steam gasification of biomass for hydrogen-rich gas in a free-fall reactor. *International Journal of Hydrogen Energy*, 32(1), 24-31.
- Welker, C. M., Balasubramanian, V. K., Petti, C., Rai, K. M., DeBolt, S., & Mendu, V. (2015). Engineering plant biomass lignin content and composition for biofuels and bioproducts. *Energies*, 8(8), 7654-7676.
- Wu, Z., Yang, W., Chen, L., Meng, H., Zhao, J., & Wang, S. (2017). Morphology and microstructure of co-pyrolysis char from bituminous coal blended with lignocellulosic biomass: Effects of cellulose, hemicellulose and lignin. *Applied thermal engineering*, 116, 24-32.
- Xiao, X., Le, D. D., Li, L., Meng, X., Cao, J., Morishita, K., & Takarada, T. (2010). Catalytic steam gasification of biomass in fluidized bed at low temperature: conversion from livestock manure compost to hydrogen-rich syngas. *Biomass and Bioenergy*, 34(10), 1505-1512.
- Xu, G., Murakami, T., Suda, T., Matsuzawa, Y., & Tani, H. (2006). The superior technical choice for dual fluidized bed gasification. *Industrial & engineering chemistry research*, 45(7), 2281-2286.
- Yin, C.-Y. (2011). Prediction of higher heating values of biomass from proximate and ultimate analyses. *Fuel*, 90(3), 1128-1132.
- Yu, H., Yang, X., Jiang, L., & Chen, D. (2014). Experimental study on co-gasification characteristics of biomass and plastic wastes. *BioResources*, 9(3), 5615-5626.
- Yu, Q., Brage, C., Chen, G., & Sjöström, K. (2007). The fate of fuel-nitrogen during gasification of biomass in a pressurised fluidised bed gasifier. *Fuel*, 86(4), 611-618.
- Zainal, Z., Rifau, A., Quadir, G., & Seetharamu, K. (2002). Experimental investigation of a downdraft biomass gasifier. *Biomass and Bioenergy*, 23(4), 283-289.

- Zaitan, H., Mohamed, E. F., Valdés, H., Nawdali, M., Rafqah, S., & Manero, M. H. (2016). Toluene, Methanol and Benzaldehyde Removal from Gas Streams by Adsorption onto Natural Clay and Faujasite-Y type Zeolite. *Acta Chimica Slovenica*, 63(4), 798-808.
- Zhou, J., Masutani, S. M., Ishimura, D. M., Turn, S. Q., & Kinoshita, C. M. (2000). Release of fuel-bound nitrogen during biomass gasification. *Industrial & engineering chemistry research*, 39(3), 626-634.