

**Co-gasification of Oil Palm Fronds, Wood Chips and Sugarcane Bagasse for
Power Generation**

By

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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Approved by,

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

AINI BINTI ABD JAMIL

ABSTRACT

Malaysia is rich with agriculture products that are suitable to be developed as sustainable and clean source of energy. Lignocellulosic biomass from residues of agriculture by-product has been studied for generation of power. These studies implied the ability of Malaysia's biomass in reducing environmental pollution and in providing carbon-neutral energy generation. In the early years, co-gasification studies between biomass and other fuels such as coal were conducted to reduce the emission of the greenhouse gases produced by coal and to increase the efficiency of the gasification. No studies were found on co-gasification between lignocellulosic biomass. On top of that, certain type of lignocellulosic biomass may experience supply problems due to seasonal factors and availability of the specific type of plant. Therefore, co-gasification performances of oil palm fronds (OPF), wood chips from Acacia Mangium tree and sugarcane bagasse (SCB) were studied in this paper. The feedstock was mixed with different weight ratios for OPF and wood chips and OPF and SCB while the air flow rate was varied in the range of 300 to 400 litres per minute. By using a downdraft gasifier, the dynamic temperature profile for drying, pyrolysis, combustion and reduction zone that were recorded using seven type-K thermocouples shows a good co-gasification performance for OPF and wood chips mixture with the highest syngas temperature of 442°C for 80:20 ratio. This mixture also produced a stable bright orange flame with a bit of bluish colour at the bottom at an average height of 118 cm. The maximum temperature of the flame was recorded for 50:50 of OPF to wood mixture with an average reading of 705°C, 554°C and 266°C at the top, middle and bottom position of the flame respectively, followed by 80:20 of the same mixture with the average temperature of 672°C, 545°C and 294°C respectively. On the other hand, SCB was co-gasified rapidly causing the operation time to decrease as the ratio of SCB was increased. The dynamic temperature profile for co-gasification between OPF and SCB also shows the occurrence of frequent bridging during the operation. Since the syngas combustion did not produce stable flares, the height and temperature could not be obtained.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

The main cause for the global warming over the last 50 years has been observed to be due to the emission of greenhouse gases (GHG) such as carbon dioxide, methane, and nitrous dioxide. The Fourth Assessment Report (AR4) which was released on 17th December 2007 stated that the global increment in carbon dioxide concentration was due to the combustion of fossil fuels (IPCC, 2007). In 2006, Malaysia was ranked as the third largest carbon emissions contributor in South-East Asia after Indonesia and Thailand. Based on Figures 1.1 and 1.2, the consumption of oil and gas had increased gradually from 1990 to 2011, during which the consumption of crude oil had overcome the production rate in 2008. Based on the production level of crude oil and natural gas in 2005, it was estimated that the reserves would last for another 15 years for oil and 29 years for gas (APEC Energy Demand and Supply Outlook, 2006). Therefore, Malaysia has begun to make efforts in developing strategies for utilization of alternative energy with three main objectives: (a) to fully utilise the available renewable energy (RE) sources, (b) to fulfil the energy demand in the future and (c) to reduce carbon emission. Dato' Sri Haji Mohammad Najib bin Tun Haji Abdul Razak, Malaysia's sixth Prime Minister has agreed to commit in reducing the carbon emission to 40% (relative to that in 2005) in terms of emission intensity of gross domestic products (GDP) by the year 2020 during the Copenhagen Climate Change Summit in December 2009 (Salsabila *et al.*, 2009). The Fit-in Tariff (FiT) system is one of the effort used to push Malaysia towards mitigating climate change. Introduced in April 2011, the FiT distributes license to produce electricity from RE resources and sets the FiT rate at a favourable price per unit rate of RE. Four renewable resources that are covered by the FiT includes biogas, biomass, small hydropower and solar photovoltaic.

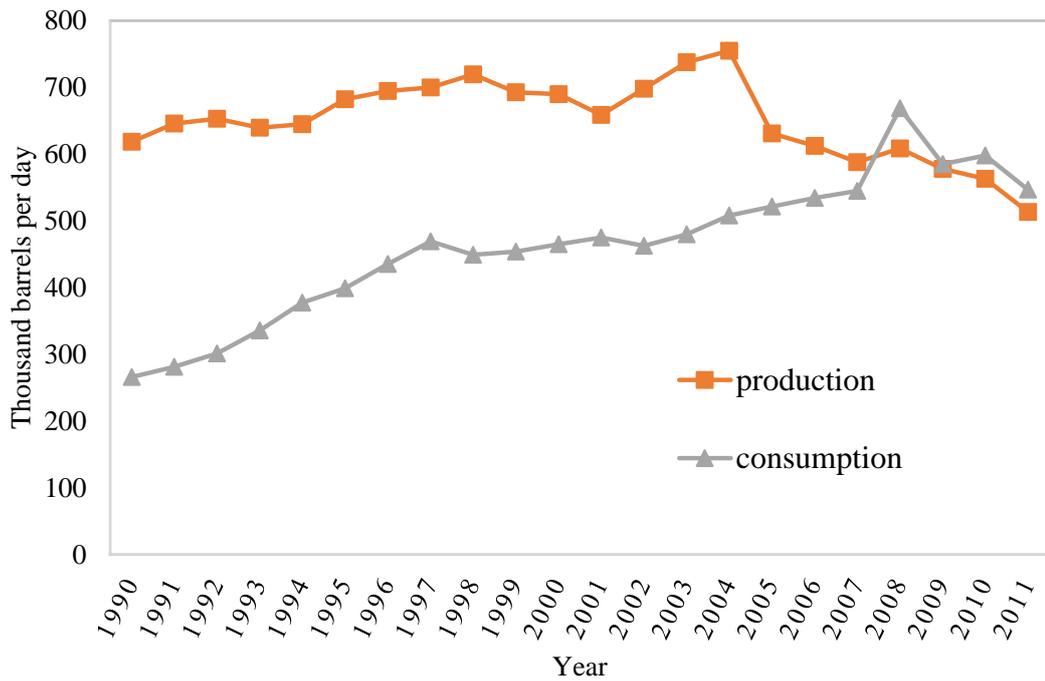


Figure 1.1 Malaysia crude oil production and consumption from year 1990 to 2011 based on data from MATRADE (2013)

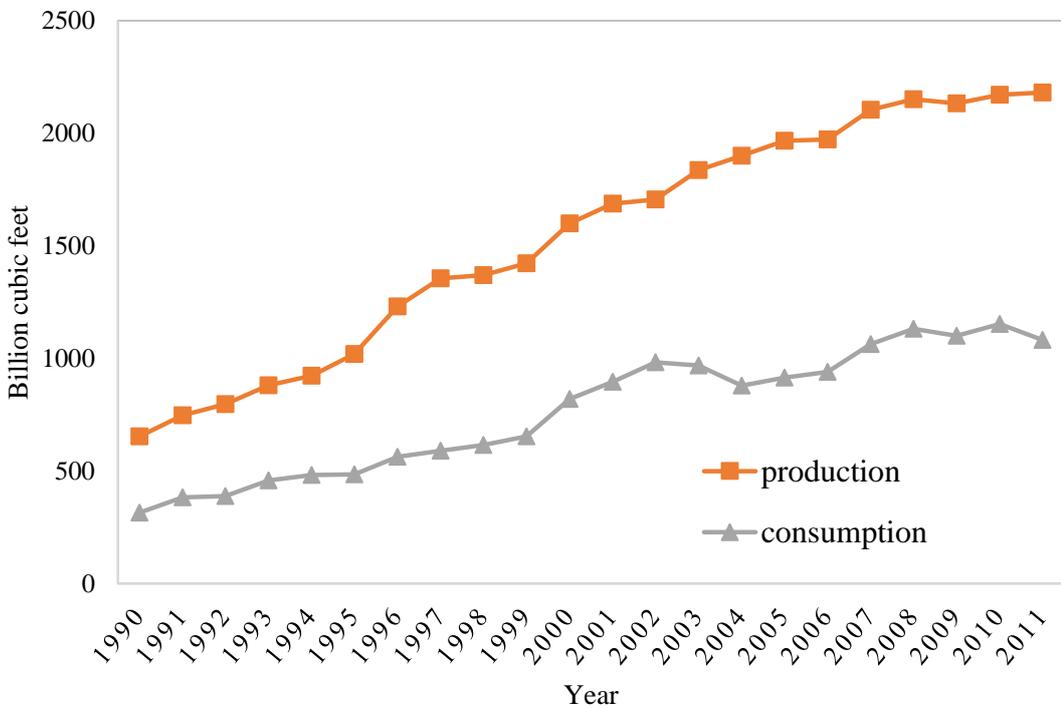


Figure 1.2 Malaysia dry natural gas production and consumption from year 1990 to 2011 based on data from MATRADE (2013)

Biomass is one of the RE sources that has the highest potential to generate power for both industrialised and developing countries (Ong *et al.*, 2010). Currently, Malaysia is one of several Asian countries that have targeted to use materials derived from living organisms as an alternative RE for fuel sources. Endowed with a total land area of 32.90 million ha (Hoi, 2005), Malaysia had committed to minimise carbon dioxide emission by adopting sustainable agriculture practices that conserve the rainforest and wildlife (Basiron, 2007). With the total land area under natural forest and agriculture area of 20.1 million ha (61%) and 4.89 million ha (14.9%) respectively, lignocellulosic biomass which is a plant related biomass composing of cellulose and hemicellulose - a complex carbohydrates and lignin (Maha, 2013) has a high potential to be harvested into clean chemical energy. The energy produced by energy conversion technologies of biomass gave huge advantage in reducing environmental pollution and providing carbon neutral sustained energy production (Bocci *et al.*, 2009; Nipattummakul *et al.*, 2011). Biofuels and synthetic natural gas (syngas) produced via physical, thermochemical or biological processes were used to generate electricity and heat (Jorapur *et al.*, 1994; Jorapur *et al.*, 1996). During World War One, due to the unavailability of oil, biomass energy was also developed to generate power for vehicles (Reed *et al.*, 1988). However, present studies and developments concentrate more on stationary biomass plants that those mounted on vehicles. Therefore, provided with continuous effort and awareness towards developing biomass energy, Malaysia can yet utilised the RE resources available to their maximum potential and make the fuel mix for 2020 secure and environmentally stable.

Gasification of biomass is a thermochemical process that uses incomplete combustion to produce clean combustible gases. The interest in gasification of biomass was developed after the OPEC oil embargo in 1973 with a number of individuals and groups building different versions of downdraft gasifiers (Reed *et al.*, 1988). Compared to direct combustion, the products of gasification differ to each other as the oxygen-to-fuel ratios differ. The mixture that were gasified were fuel-rich due to the limited oxygen atoms available to react with the feed (Phillips, 2006). Table 1.1 shows the differences in product produced by combustion and gasification. Many studies were done using different parameters to study the characteristic of the syngas produced via gasification. Researches in co-gasification between biomass and coal were one of

the popular studies conducted to obtain a cleaner product based on the renewable character and low contamination content in biomass (Li *et al.*, 2009).

Table 1.1 Comparison of the primary products generated by the main fuel constituents in combustion and gasification (Phillips, 2006)

	Combustion	Gasification
Carbon	CO ₂	CO
Hydrogen	H ₂ O	H ₂
Nitrogen	NO, NO ₂	HCN, NH ₃ or N ₂
Sulphur	SO ₂ or SO ₃	H ₂ S or COS
Water	H ₂ O	H ₂

1.2 Problem Statement

Biomasses that are derived from plants may pose limitations in term of supply. Certain types of lignocellulosic biomass are very sensitive to weather and temperature. For example, sugarcane only grow in a place with distinct dry season. Development of sugarcane plantation in Perak and Negeri Sembilan were unsuccessful due to the high moisture content in those areas. Therefore, if sugarcane was to be used for gasification, the operation maybe affected when there are changes in weather at the plantation area.

In order to obtain uniform gasification operation, similar type of biomass should be used. Different species of wood will give different chemical components which will then affect the syngas composition produced. As a result, lignocellulosic biomasses may also face limitation in quantity of the supply since it will be difficult to collect the same specific biomass in large quantity. On the other hand, co-gasification can be a practical action to overcome this problem as it will enable uninterrupted operation of a gasifier-based power plant.

Furthermore, there has been no report on study of co-gasification of biomass with a different biomass. Therefore, the study on co-gasification of lignocellulosic biomass would be required in order to explore its potential.

1.3 Objective

The objective of this project was to study the performance of co-gasification of OPF and wood chips; and of OPF and SCB by manipulating the weight ratios of the feedstock. With further extensive study, co-gasification of biomass could maximise the utilisation of different types of biomass available in Malaysia and encourage people to develop personal gasifier for small-scaled applications.

1.4 Scope of Study

This project studied the performance of co-gasification of selected lignocellulosic biomasses, with interests on two factors:

- i) Temperature profile of the downdraft gasifier bed and syngas temperature
- ii) Flame quality and temperature of the combusted syngas at flare point

Based on these factors, the results obtained were analysed to understand the co-gasification performance for each of the weight ratios used with other parameters kept constant. Production of syngas is the most important aspect in the study. However, since the gas analyser is malfunction, the study was limited to identifying the stability of the syngas production and the quality of syngas based on the flame of the syngas burnt. Therefore, the syngas composition was not analysed, although it would be highly beneficial for the study. The production of syngas was determined by the flare produced by the burning of syngas. The temperature profile along the bed should give a similar pattern of graph that determined the performance of the co-gasification of the feedstock mixtures. Quantification of energy in the resulting syngas was also not included in this study.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Biomass Energy

RE sources are available significantly in Malaysia. Biomass energy ranks third after hydropower and solar photovoltaic in the list of RE potential energy for power generation in this country as summarised in Table 2.1 (Oh *et al.*, 2010). Numerous agricultural and forest sectors produced large amount of residues which does not have any commercial values. However, present effort in developing biomass as an alternative energy has found that they were very useful for power generation (Kamaruzzaman *et al.*, 2000; Mekhilef *et al.*, 2011). With 16% contribution in the country's energy consumptions, 51% of the biomass fuel came from palm oil waste, 27% from wood waste, and the remaining were contributed by other plant cultivations, animal and urban waste (Kamaruzzaman *et al.*, 2000). Figure 2.1 depicts the scope of biomass initiative as a RE (Sumathi *et al.*, 2008).

Table 2.1 Renewable energy potential in Malaysia (Oh *et al.*, 2010)

Renewable energy	Potential (MW)
Hydropower	22,000
Solar photovoltaic	6,500
Biomass/biogas	1,300
Mini-hydro	500
Municipal solid waste (MSW)	400
Wind	Low wind speed

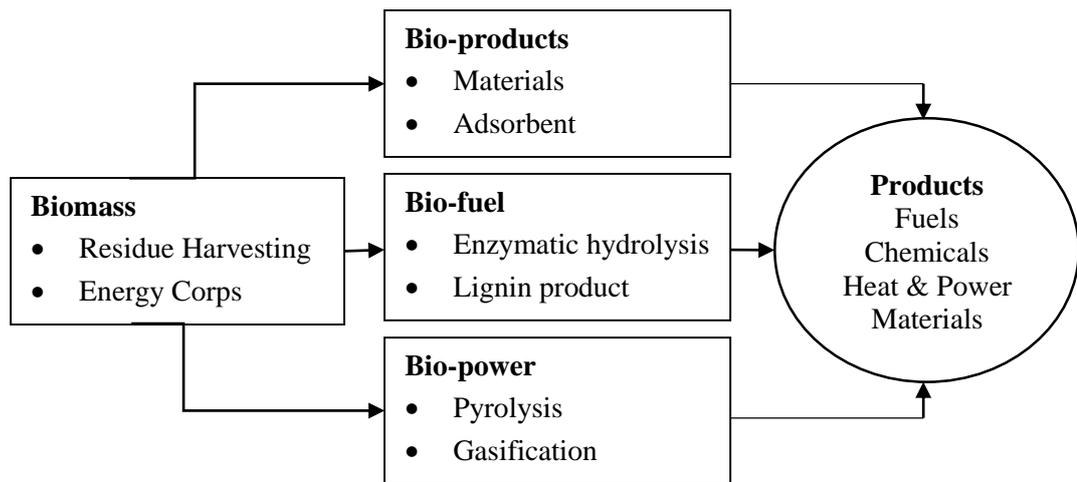


Figure 2.1 Biomass initiatives as renewable energy (Sumathi *et al.*, 2008)

As the leader of one of the foremost agricultural countries in the world, the Malaysian government has targeted to develop biomass energy from the by-products of this sector (Mekhilef *et al.*, 2011). Ranking third in Malaysia’s main export component, agriculture contributes RM33.01 billion in 2013 (9.8% of total exports) after manufactured goods and mining goods as presented in Figure 2.2. Based on study by Hassan *et al.* (2003), the different types of biomasses that were available in Malaysia are as shown in Figure 2.3 where palm oil dominated the production with 85% out of more than 70 MT (million tonnes) produced followed by municipal solid 9.5%, wood industry 3.7%, rice 0.7% and sugarcane 0.5%. These industries have been growing significantly in number and capacity over the last few years. The abundant

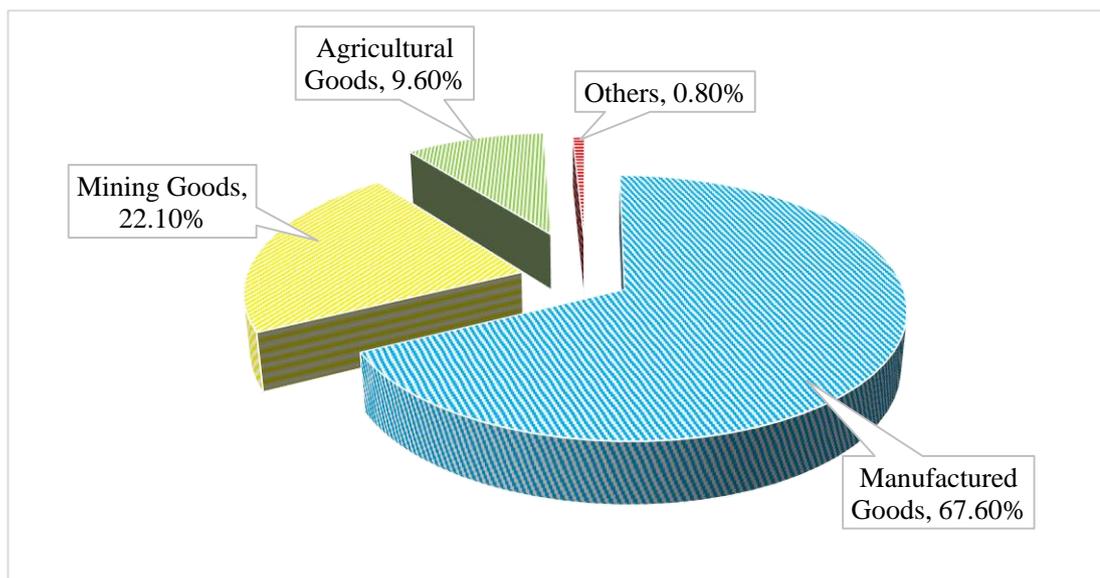


Figure 2.2 Major export components in Malaysia in 2013 with the total export of 524.72 billion based on data from MATRADE (2013)

agriculture waste produced by them can be utilised into biomass energy via gasification. Researches have also shown that the gasification of OPF, wood chips and SCB has the potential to serve as biomass energy source to produce electricity.

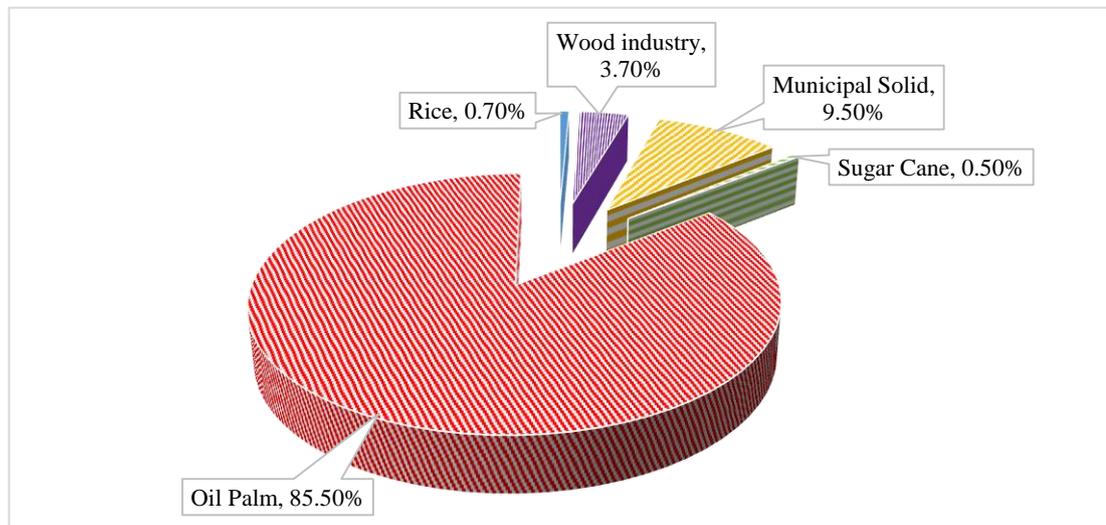


Figure 2.3 Distribution of biomass produced from different industries in Malaysia (Hassan *et al.*, 2003)

Several researches on co-gasification between biomass and fossil fuels were also done. Based on researches that were conducted, it was proven that the gasification of lignocellulosic biomass can reduce the emission of hazardous GHG (Aigner *et al.*, 2011) due to the low nitrogen and sulphur content in the biomass compared to non-renewable fossil fuels. However, there are not many studies regarding co-gasification between different biomass fuels.

On the contrary, there are some conditions and limitations that need to be taken into account in using a lignocellulosic biomass for gasification. Oil palm industry has been producing very large amount of biomass sources in Malaysia. It produces five types of biomass as shown in Table 2.2. Currently, pruned OPFs are used for erosion control, soil conservation and serve as a long term benefit of nutrient recycling by placing them between the rows of palm trees (Abu Hassan and Ishida, 1994; Lim *et al.*, 2000). On top of that, OPFs are also developed as roughage sources for ruminants considering that the digestibility of dry OPF is high (Abu Hassan and Ishida, 1992) and the production of low-cost and cost-effective balanced ruminant diets for integrated farming systems results in higher animal productivity (Devandra, 2009). However, there are still no detailed statistics on the usage of OPF in Malaysia. Other

than that, fibrous residues produced by the act of shredding and cutting the OPF when it is dry could cause bridging during the gasification operations. Therefore, the OPFs need to be chopped within one week after pruning to avoid the fibrous residues making the preparation of the feedstock more difficult and time consuming.

Table 2.2 Oil palm biomass collected in 2005 and their energy potential (Shuit *et al.*, 2009)

Biomass component	Quantity available (million tonnes)	Calorific Value (kJ/kg)	Potential energy generated (Mtoe)
EFB	17.00	18,838	7.65
Fibre	9.60	19,068	4.37
Shell	5.92	20,108	2.84
Fronds & trunks	21.10	-	-
Palm kernel	2.11	18,900	0.95
Total	55.73	-	15.81

Wood has undergone many researches as a potential biomass sources in the world due to its availability and renewable properties compared to fossil fuels. Malaysia is bestowed as one of the major wood processing countries in the region. Wood residues produced by forestry, logging and timber industries serves as a great potential for developing wood as source of energy due to its lack of other commercial values (Kamaruzzaman *et al.*, 2000). Although vast amount of wood is available in Malaysia, different types of wood will give out different fuel properties. Hardwood species usually give higher heating value (HV) of around 8,600 Btu/lb (20,000 J/kg) as compared to softwoods which are around 9,000 Btu/lb (21,000 J/kg) (Baker, 1983). HV is important in determining the amount of energy produced from the feedstock. Uniform energy will not be produced if the type of wood used is inconsistent. Therefore, problems will arise in the gasification process as the wood industries may not be able to supply the same amount of wood residues all the time.

Sugarcane cultivation comprises a small portion in the agriculture industry. The cultivation of sugarcane is concentrated in the states of Perlis and Kedah where there is a distinct dry season which is suitable for harvesting. Due to the sensitivity of sugarcane towards the temperature and weather, the plantings in other state such as Perak and Negeri Sembilan were unsuccessful (FAO, 1997). Therefore, the supply of SCB is very limited compared to other types of biomass.

In addition to the above limitations, a natural disaster such as extreme drought or huge flood can jeopardised the plantations and will affect the supply of biomass for gasification in that area. Therefore, it is important to determine an alternative way to avoid the overdependence on only one type of biomass. Studies on co-gasification of lignocellulosic biomass may provide the solution to this problem where it can ensure that the gasification operation will not be wholly affected by these limitations.

2.2 Gasification of Biomass

Conversion technology biomass can be categorised into three main processes – physical, thermochemical and biochemical process. Each of the processes produces different types of product, which can be used in different applications. Figure 2.4 shows the summary for the processes taken from Shuit *et al.* paper on ‘Biomass as a Sustainable Energy Sources’ (2009). Gasification of biomass offers high potential conversion of the vast amount of waste produced into useful and clean syngas. It is basically known as choked combustion where the combustion of fuel is incomplete so that the output gas still has the combustion potential. The output gas or the syngas produced can be utilised for electric power generation, heat generation and in other industrial, transportation and domestic sectors. Gasification is included under thermochemical process which produces combustible gases - hydrogen (H₂), carbon monoxide (CO) and traces of methane (CH₄); and non-combustible gases - carbon dioxide (CO₂) and nitrogen (N₂) (Rahman *et al.*, 2004).

Figure 2.5 shows the different types of fixed-bed gasifier. They consist of four discrete thermal processes which are drying, pyrolysis, combustion and reduction. All these processes are naturally found in the flame of a burning match. Gasifiers are created as a mean to disintegrate and isolate these processes to obtain and collect the gases from the incomplete burning.

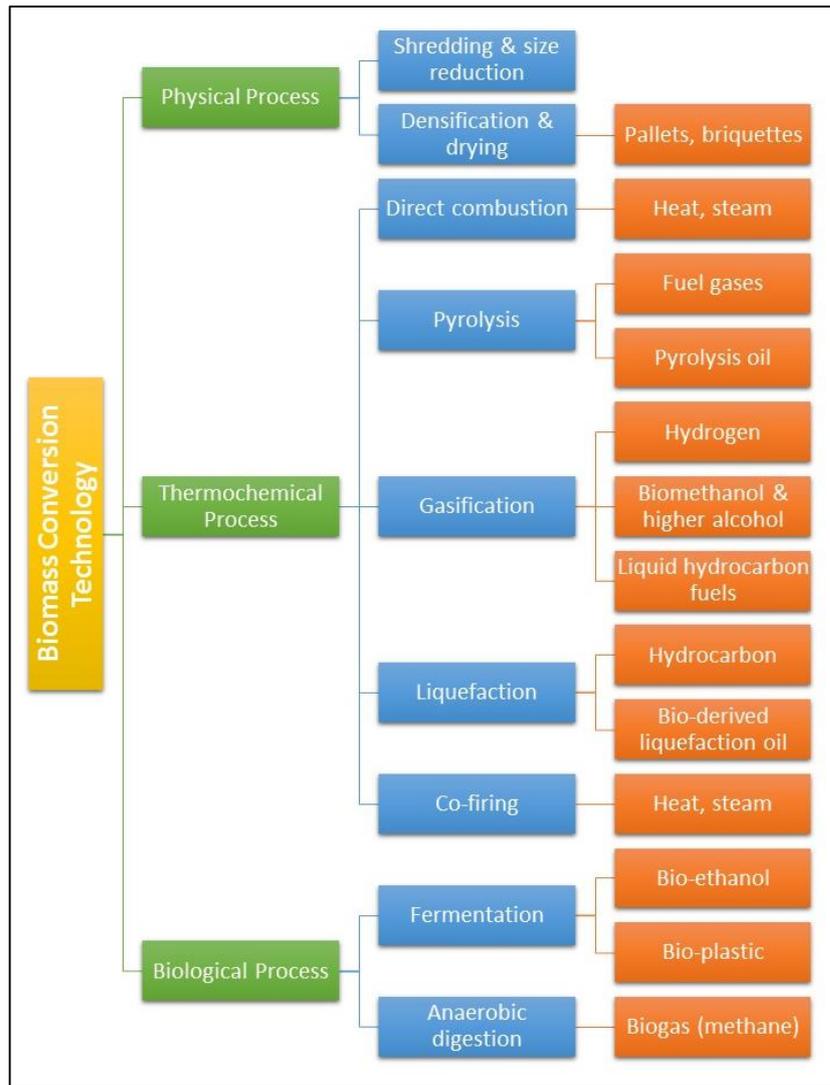


Figure 2.4 General biomass conversion technologies (Shuit *et al.*, 2009)

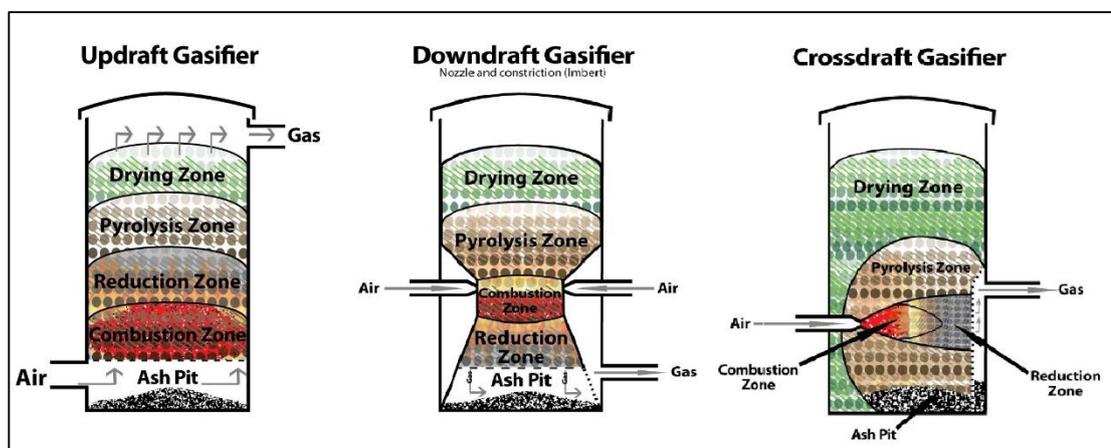


Figure 2.5 Different types of fixed-bed gasifier (Gasifier Types)

2.2.1 Drying

Drying zone is where the moisture from the feedstock is removed before it enters the pyrolysis zone. It is an endothermic reaction where the moisture changes its state from liquid to vapour at a temperature of around 100°C. The reaction is as follows:



2.2.2 Pyrolysis

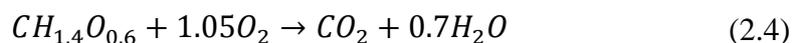
By definition, pyrolysis is to break down (lysis) a material by the application of heat (pyro) in the absence of air. The biomass undergoes fast decomposition as it enters pyrolysis zone at the temperature range of 200°C to 650°C. It then breaks down into gases comprising of CO, CO₂, H₂, H₂O and CH₄, tar vapours with an approximate atomic makeup of CH_{1.2}O_{0.5}, and charcoal (Reed *et al.*, 1988). The reactions can be shown as follows:



In this zone, the volatile components in the biomass become tar vapours while the fixed carbon-to-carbon remains as charcoal in solid state. The tar vapour in pyrolysis temperature is in the gaseous state. As it cools down, it condenses to form smoke with fine tar droplets.

2.2.3 Combustion

Combustion is an exothermic reaction between an oxidant (i.e. oxygen, O₂) and fuel with the presence of heat. A complete combustion will produce carbon dioxide (CO₂) and water (H₂O). The overall global reaction of biomass combustion can be represented as follows:



where CH_{1.4}O_{0.6} is an average formula for a typical biomass (Reed *et al.*, 1988). The product from this reaction will then be reduced in the reduction zone. In the downdraft

gasifier, the tar gases from the pyrolysis zone will be burn to generate heat for the next process which is the reduction process. The combusted fuel must have good mixing and produced high temperature of below 1500°C. This is important to ensure all the tars are completely burned and are not present in the outgoing gas produced.

2.2.4 Reduction

Reduction is the reverse process of combustion where it removes oxygen from the hydrocarbon (HC) molecule by absorbing heat (endothermic reaction). The oxygen atom is separated from the combusted HC to produce combustible gases again. Chemical reactions that occurred in the reduction zone can be represented as follows:



where the product consists of combustible gases methane (CH₄), carbon monoxide (CO) and hydrogen (H₂). In the downdraft gasifier, the reduction zone is at the bottom of the gasifier between the combustion zone and the gas outlet. At a temperature of more than 700°C, the products of combustion which are carbon dioxide (CO₂) and water vapour (H₂O) flow across a bed of red hot char which is highly reactive with oxygen. The hot char will strip the oxygen off the gasses, and redistribute it to as many single bond sites as possible. There are little amount of oxide in diatomic (O₂) form because they are more attracted to the bond site on the C than to itself. The reduction stops when there are no more oxide molecules left for bonding.

2.3 Past Studies on Co-gasification

Early co-gasification researches started with the aim to reduce the pollution and greenhouse gases (GHG) that were produced by combustion of coal (McLendon *et al.*, 2004; Maria *et al.*, 2006). Coal was mixed with wood due its renewable character and low contamination content in biomass (Li *et al.*, 2010). This in turn reduced the levels of hazardous gases such as carbon dioxide, nitrogen and sulphur emission in the

syngas produced (Alzate *et al.*, 2008; Aigner *et al.*, 2011). The high volatile matter in wood as compared to coal as shown in Table 2.3 increases the combustibility of the mixture which simultaneously increases the efficiency of the gasification process.

Table 2.3 Elemental analyses for coal and wood by Alzate *et al.* (2008)

(% w/w)	Coal	Wood
<i>Proximate Analysis</i>		
Volatile matter	38.2	76.3
Fixed carbon	38.4	13.5
Ash	14.4	0.1
<i>Ultimate Analysis</i>		
Carbon	58.67	52.15
Hydrogen	5.11	6.32
Oxygen	11.77	30.96
Nitrogen	0.68	0.35
Sulphur	0.37	0.02
Calorific Value (HHV)	17.28 MJ/kg	18.09 MJ/kg
Moisture content	9.0	10.1

In order to understand the quality and characteristic of the syngas produced by co-gasification of lignocellulosic biomasses, many researches were carried out by using different parameters, materials and type of gasifier. Experiments with varied reactor's temperature and constant steam flow rate showed that the overall syngas produced were slightly affected (Nipattummakul *et al.*, 2011). However, the chemical composition of the syngas yield varied tremendously. On the other hand, the heating value and ratio of energy yield for the syngas were strongly dependent on the reactor temperature (Nipattummakul *et al.*, 2010).

Past researches on co-gasification of coal and biomass were done to study the effect of varied blending ratios with the composition of the syngas produced. Experiments were done using coal to biomass ratio of 80 to 20 by Li (2010) and Aigner (2011); 50 to 50 and 20 to 80 by Aigner (2010); 60 to 40 by Mastellone (2010); and 5%, 10%, 20% and 30% of coal ratio by Alzate (2008). Based on these experiments, the resulting syngas was said to produce higher H₂ (Alzate *et al.*, 2008; Li *et al.*, 2010), CO (Alzate *et al.*, 2008; Aigner *et al.*, 2011) and CH₄ (Aigner *et al.*, 2011) content with the increase in biomass ratio. Although all of the studies used the same type of

gasifier and type of material, the studies did not obtained similar results. This may due to the difference in elemental composition of the material of the specific species. The conditions used to conduct the experiment were also part of the reasons for the results to contradict each other.

Dynamic temperature profile along the gasifier bed was also studied to understand the performance of the gasification. A downdraft gasifier consists of four distinct zones which undergo different reaction at different temperatures. According to Sulaiman *et al.*, (2009) average temperature values recorded for drying, pyrolysis, oxidation and reduction zone are 125°C, 324°C, 796°C and 543°C respectively which were found to be in agreement with the values reported by Borisov *et al.* (1998) and Zainal *et al.* (2002). The combustion zone should be in the range of 750°C to 900°C. Below that temperature range will turn the process into pyrolysis which will produce more tar and charcoal while above that, complete combustion will occur and more carbon dioxide will be produced in the co-gasification product. Temperature at the oxidation zone depends upon the heat released from the combustion of biomass and the air flow rate. The amount of oxygen to be oxidised will increase with an increase in air flow rate. However, it will also bring inert gases such as nitrogen that acts as heat carrier and reduces the temperature of the oxidation and pyrolysis zones (Sheth *et al.*, 2009). The optimum amount of equivalent ratio can also be determined by the maximum value of temperatures in the pyrolysis and oxidation zones.

CHAPTER 3

METHODOLOGY

3.1 Project Flow

In order to study the performance of co-gasification of lignocellulosic biomass, the project was conducted according to the process flow chart in Figure 3.1. The identification and selection of the feedstock was done by literature review based on past researches. Extensive research was also conducted to identify the availability of the feedstock in Malaysia and the limitations for each of the feedstock in order to relate with the problem statement of the project which is to avoid overdependence on only one type of feedstock that would pose supply limitation. Other than that, the feedstocks were also chosen to suit the specification of the downdraft gasifier used which could not support small sized feedstock. The chosen feedstocks were collected from their respective suppliers. They were cut up to the maximum of 3 cm length and width. They were then placed in the oven at 105°C for 24 hours until the moisture content was below 15%. This was to ensure their suitability for use in the downdraft gasifier for the experiment. Elemental analyses were conducted for each of the feedstock to identify their chemical and physical properties, calorific values and moisture contents. Results of the analyses are tabulated in Table 4.1 in Chapter 4. Six trials of co-gasification were done using different weight ratios of OPF to wood and OPF to SCB mixtures by adjusting the air flow rate in the range of 300 to 400 litres per minute. The temperature profile of the gasifier bed, flame temperature and flame quality were observed and measured.

3.2 Feedstock Characterisation & Preparation

The feedstocks for this study were chosen based on two factors which are (a) their availability in Malaysia and (b) their size. From the literature review section, there were five main biomass sources that possessed high potential to generate energy available in this country. They are rice, OPF, municipal waste, sugarcane, and wood industry. This study however, focuses on co-gasification between lignocellulosic

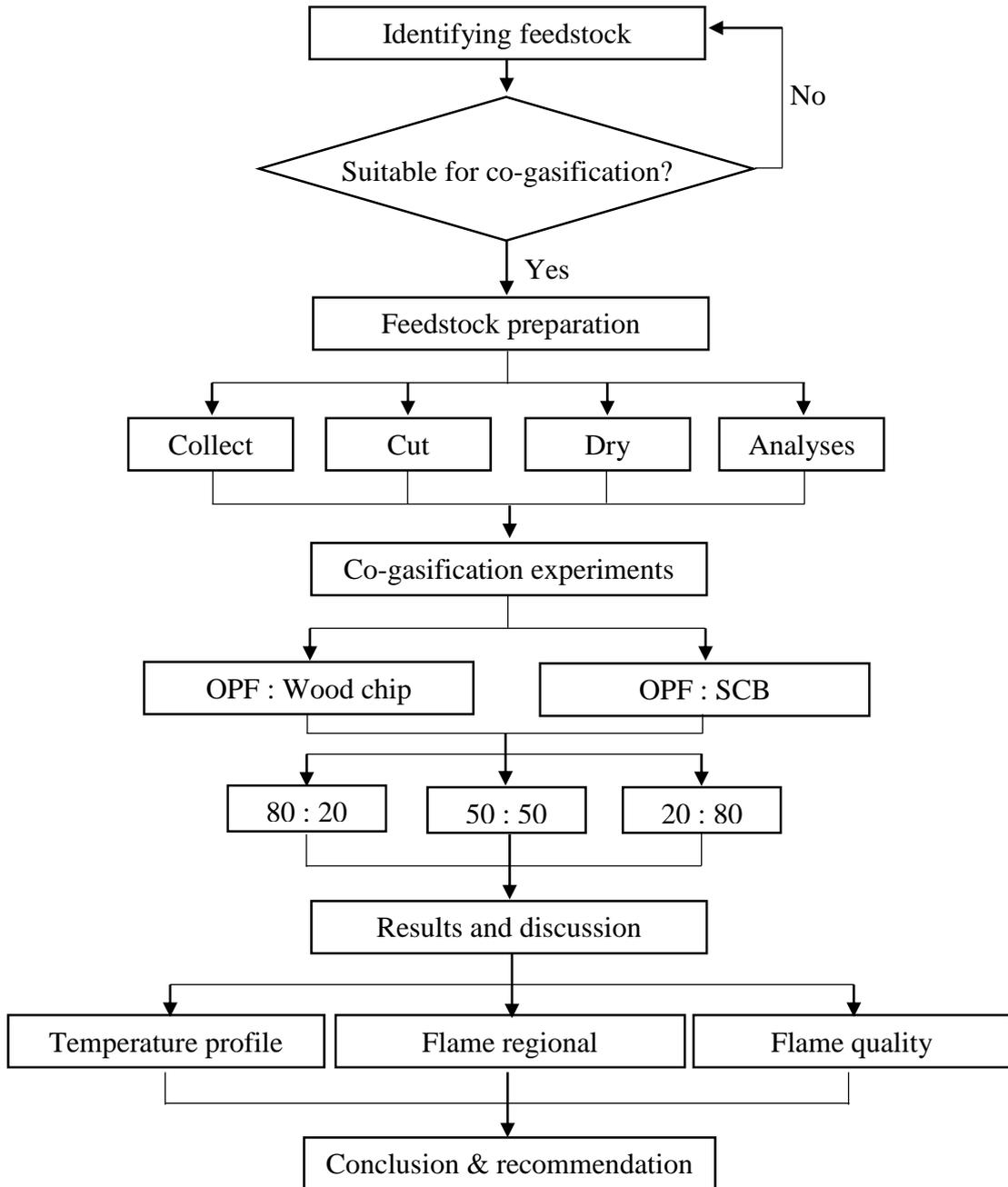


Figure 3.1 Process flow chart for the project

biomasses. Therefore, municipal waste was excluded due to the contradiction with the objective of this study. Rice on the other hand, was omitted due to its size. The downdraft gasifier used could not handle feedstock which is smaller than 2 cm. A small size feedstock will go through the grate under the combustion zone and blocked the syngas pathway. Of these five sources OPF, wood chips and SCB were chosen as they matched with all the factors stated above. The feedstocks were collected in stages where each collection session comprised around 10 to 15 kg in weight. Each feedstock was dried until the moisture content was below 15% where it was determined by

weighing the feedstock before and after the drying process and divides the value with the initial weight. A dried lignocellulosic biomass turned brownish in colour.

3.2.1 Oil Palm Fronds (OPF)

The OPF were collected from the Felcra Nasaruddin Sdn. Bhd. in Bota Kanan, Perak, Malaysia where the freshly pruned petioles were chopped to the maximum length and width of 3 cm as shown in Figure 3.2. The feedstock were dried for 20 days or using an oven at 105°C for 24 hours.

3.2.2 Wood Chips

Wood branches were collected from UTP's (Universiti Teknologi PETRONAS) landscape maintenance during their tree trimming activities. Acacia Mangium tree was specifically chosen for the experiment to ensure the same chemical and physical properties were obtained from the feedstock. These branches were chipped at a wood factory using a chipper machine to the maximum of 3 cm in length as shown in Figure 3.3. It was then dried using the oven at 105°C for 24 hours.

3.2.3 Sugarcane Bagasse (SCB)

SCB biomasses are collected from night markets around Bandar Seri Iskandar, Perak, Malaysia from stalls that sell sugarcane drinks. The bagasse was cut to the maximum length of 3 cm as shown in Figure 3.4. It was dried using the oven at 105°C for 24 hours.



Figure 3.2 OPF



Figure 3.3 Wood chips



Figure 3.4 SCB

3.2.4 Elemental Analyses

Three analyses were done to determine the chemical and physical properties; and the calorific values of the feedstocks. The equipments used for the elemental analyses are as shown in Figures 3.5 to 3.7 and elaborated as follows:

i. Leco CHNS-932

It was used to conduct ultimate analysis which identifies the chemical properties of the feedstocks by means of individual, highly selective, infrared detection system. The properties that can be obtained are carbon (C), hydrogen (H), nitrogen (N), sulphur (S) and oxygen (O). The detection method and the precision of each component measurement are as shown in Table 3.1. The syngas produced could be affected by the C and H content in the feedstock. Higher C and H contents would produce a higher heating value of syngas and gave out higher temperature heat when combusted. Three samples weighing less than 2 mg were prepared for each feedstock in dust form.

Table 2.1 Detection method and measurement precision for each components in CHNS-932 equipment

Components	Detection Method	Precision*
Carbon	Infrared absorption	<1% RSD** or ± 0.001
Hydrogen	Infrared absorption	<1% RSD or ± 0.01
Nitrogen	Thermal conductivity	<1% RSD or ± 0.01
Sulphur	Infrared absorption	<1% RSD or ± 0.02
Oxygen	Infrared absorption	<1% RSD or ± 0.02

ii. Pyris 1 Thermogravimetric Analyser (TGA)

Thermogravimetric analysis technique monitored the mass of the substances as a function of time and temperature as the sample specimen was subjected to a controlled temperature programme in controlled atmosphere. Pyris 1 equipment uses this technique to conduct proximate analysis that could identify three physical properties which are the amount of volatile matter, fixed carbon and ash in the feedstocks. The value of volatile matter could be used to compare the quality of syngas produced by the fuel. A high value of volatile matter could increase the rate of combustion of the fuel which then causes them to burn at a higher temperature and produced a better syngas. It will also influence the

*Whichever is greater

**Relative Standard Deviation

formation of NO_x where the higher the volatile matter, the lower the NO_x. This equipment has a sample pan which is supported by a precision balance and was heated or cooled in the furnace during the experiment. Mass of the samples was monitored throughout the analysis with a sample purge gas that controls the sample environment. Specifications of the equipment are tabulated in Table 3.2. Three samples were prepared for each feedstock in dust form to increase the surface area and were analysed around one hour.

Table 3.2 Specification of Pyris 1 TGA equipment

	Specification
Balance type	Hangdown Pan
Temperature range	Standard furnace: Subambient to 1000°C
	High temperature furnace: 50°C to 1500°C
Balance precision	0.001%
Balance capacity	1300 mg

iii. Leco AC-350/500

The isoperibol calorimeter determined the calorific values (CV) of the feedstocks through the measurement of the heat release after combustion of the sample. It is a stand-alone bench top unit that uses a fully integrated circulatory system for a compact footprint. Electronic thermometer with a Windows®-based operating system has an accuracy of up to 0.0001°C and measures the sample temperature every six seconds. The CV could affect the combustion temperature of the fuel. Higher combustion temperature with better syngas production can be achieved with a high CV. Three samples in dust form were prepared for each feedstock inside a small crucible and left in a combustion vessel before placing in the equipment for 5 to 10 minutes to be analysed.



Figure 3.5 Leco CHNS-932



Figure 3.6 Pyris 1 TGA



Figure 3.7 Leco AC-350

3.3 Experimental Setup / Procedure

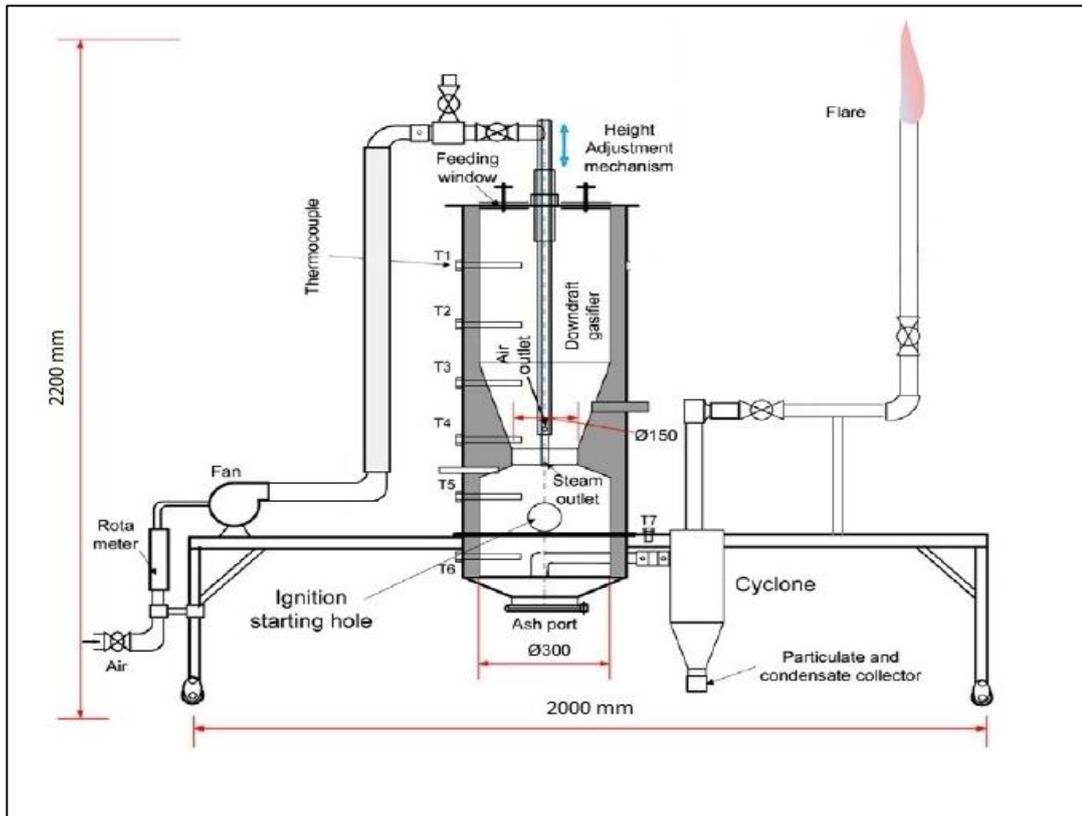


Figure 3.8 Co-gasification experimental set-up using a downdraft gasifier (Guangul *et al.*, 2012)

The downdraft gasifier used was setup as shown in Figure 3.8. It has the capacity of 10 kg of OPF feedstock with approximately 10 kg per hour of combustion rate. Previous studies have used the gasifier to conduct gasification of OPF using preheated inlet air (Guangul *et al.*, 2013) and co-gasification of OPF with wood by an undergraduate student for the internship project (Abd Rahman, 2013). The feedstock mixture was fed through the feeding window manually until the gasifier was full. Papers and cardboards were used to start the combustion, which was done at the ignition starting hole. The blower connected to the rotameter was used to control the air flow rate during the gasification process. Syngas produced by the co-gasification operation flowed to the outlet where the flare was ignited. The temperature of the flare was recorded using a handheld type-K thermocouples with an accuracy of up to 0.1°C. On top of that, seven thermocouples type-K were placed along the gasifier bed to measure the temperatures at different sections during the co-gasification process. Each of the thermocouples was connected to the temperature data logger to automatically

record the temperature at each section. The position and functions of the thermocouple are as shown in Figure 3.9 and Table 3.3 respectively.

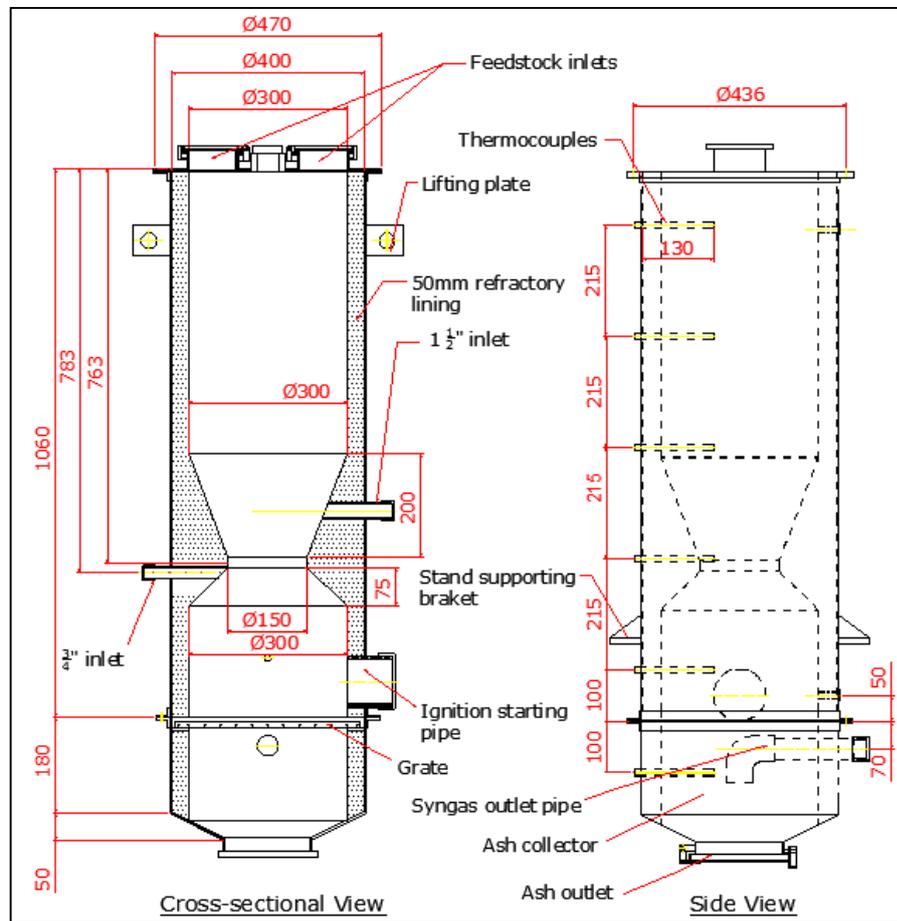


Figure 3.9 Downdraft gasifier drawing showing the position of each thermocouple (Guangul *et al.*, 2012)

Table 3.3 Functions and position of thermocouples measured from the bottom of the gasifier bed (Guangul *et al.*, 2012)

Thermocouple	Position (mm)	Functions
T1	1190	Drying
T2	975	Drying
T3	760	Drying
T4	545	Pyrolysis
T5	330	Combustion
T6	130	Reduction
T7	160	Syngas Temperature

There were two parts of the experiment consisting of three trials with different weight ratios of OPF with wood and OPF with SCB. The mixture ratios for each trial are shown in Table 3.4 in terms of percentage. Temperature profile for the gasification of OPF, wood chips and SCB were discussed based on past research using downdraft gasifier.

Table 3.4 Ratios of OPF to wood chips and OPF to SCB in percentage for co-gasification experiment

Trial	OPF : Wood	OPF : SCB
1	80:20	80:20
2	50:50	50:50
3	20:80	20:80

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Elemental Analysis

Table 4.1 shows the characteristic of OPF, wood chips and SCB comprising of the proximate analysis, ultimate analysis, calorific values and moisture content. Values for coal were taken from literature review to compare the amount of each lignocellulosic components with coal.

Table 4.1 Physical and chemical characteristics of OPF, wood chips, SCB and coal (Alzate *et al.*, 2008)

(% dry basis)	OPF	Wood Chips	SCB	Coal
<i>Proximate Analysis</i>				
Volatile matter	80.7	85.5	72.3	38.2
Fixed carbon	16.6	12.9	14.5	38.4
Ash	1.2	0.3	2.0	14.4
<i>Ultimate Analysis</i>				
Carbon	42.83	45.52	42.05	58.67
Hydrogen	5.71	5.87	4.01	5.11
Oxygen	50.75	47.55	41.92	11.77
Nitrogen	0.62	0.06	0.28	0.68
Sulphur	0.09	0.03	0.04	0.37
Calorific Value (HHV)	17.04 MJ/kg	18.09 MJ/kg	17.22 MJ/kg	17.28 MJ/kg
Moisture content (%)	13.7	11.4	11.8	9.0

Based on the results of the analyses, the amount of volatile matter for all lignocellulosic biomasses show a higher value of up to 50% more compared to coal. The amount of volatile matter indicates the ease of ignition and burning of the fuel. Wood chips shows the highest volatile matter content and trials that contained higher wood ratio should have a higher co-gasification rate for the same volume of feedstock. The low amount of fixed carbon and ashes compared to coal shows that the co-gasification between the lignocellulosic biomasses produce less charcoal and ashes at the end of the co-gasification experiment. Slightly lower amount of carbon and hydrogen present in OPF, wood and SCB show that there are small differences in the amount of combustible gases produced. On the other hand, the low nitrogen and sulphur content in the lignocellulosic biomasses produced very low amount of hazardous gases. Moisture content was a controlled variable set below 15%.

4.2 Dynamic Temperature Profile

4.2.1 OPF to Wood Chips Mixture

Co-gasification trials for OPF and wood mixture were conducted for 1 hour (60 minutes) for 80:20 and 20:80 of OPF to wood mixture and 50 minutes for 50:50 ratio. Figures 4.1, 4.2 and 4.3 show the dynamic temperature profiles for 80:20, 50:50 and 20:80 of OPF to wood ratio.

The temperature for combustion zone for 80:20 of OPF to wood ratio showed a steep increment from the beginning of the experiment until the 8th minute with a value of 795°C recorded. Some bridging problem was observed between the 9th to 13th minute where the temperature at all zones dropped slightly. This could be due to the irregular size of the OPF. This problem was overcome by stirring the feedstock inside the gasifier as soon as a drop in temperature was detected. Co-gasification operation was then continued smoothly and stable combustion temperature (T5) was obtained for about 33 minutes at the combustion zone with an average of 779°C before it reaches complete combustion point (CCP) due to the increasing in air fuel ratio. The highest temperature recorded was 1112°C at 51st minute of operation. Temperature profile for other zones showed similar pattern as the combustion zone. Average temperature recorded over total operation time for drying – T1, T2 and T3, pyrolysis – T4, combustion – T5, reduction – T6 and syngas temperature – T7 was 74.9°C, 80.8°C, 97.3, 232.5°C, 767.43°C, 506.5°C and 442.0°C respectively.

Co-gasification experiment for 50:50 of OPF to wood ratio was conducted for 50 minutes. Its temperature profile shown in Figure 4.2 implied a slow combustion process where the temperature increased slowly to 732.0°C at the 15th minute. This might be due to the bigger size of wood chips used for this experiment. Acacia Mangium wood chips has a higher density at the range of 560 to 1000 kg/m³ at 15% moisture content (Sein *et al.*, 2011), compared to OPF with density of 160 kg/m³ which causes the burning of wood to become longer. However, stable temperature was obtained for about 20 minutes from 15th to 35th minute at an average of 729.1°C before it reached the complete combustion point (CCP). The highest temperature recorded for

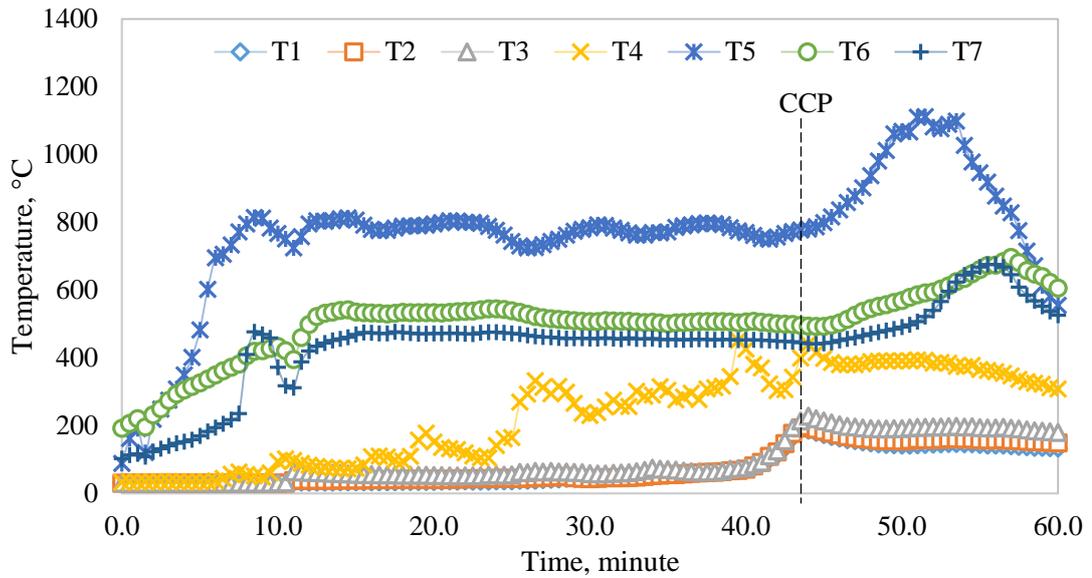


Figure 4.1 Temperature profile for 80% OPF and 20% wood

this zone was at the 44th minute with 1095.7°C. No bridging problem was detected throughout the experiment showing the feedstocks used were suitable for this downdraft gasifier. Temperatures for drying and reduction zones; and syngas produced followed the combustion temperature profiles where they obtained stable temperature around 25th minute until 45th minute before the temperature starts to increase at the end of the operation. The average temperature recorded for each zone, T1, T2, T3, T4, T5, T6 and T7 were 76.0°C, 81.4°C, 94.3°C, 289.2°C, 574.3°C, 407.1°C and 344.7°C respectively.

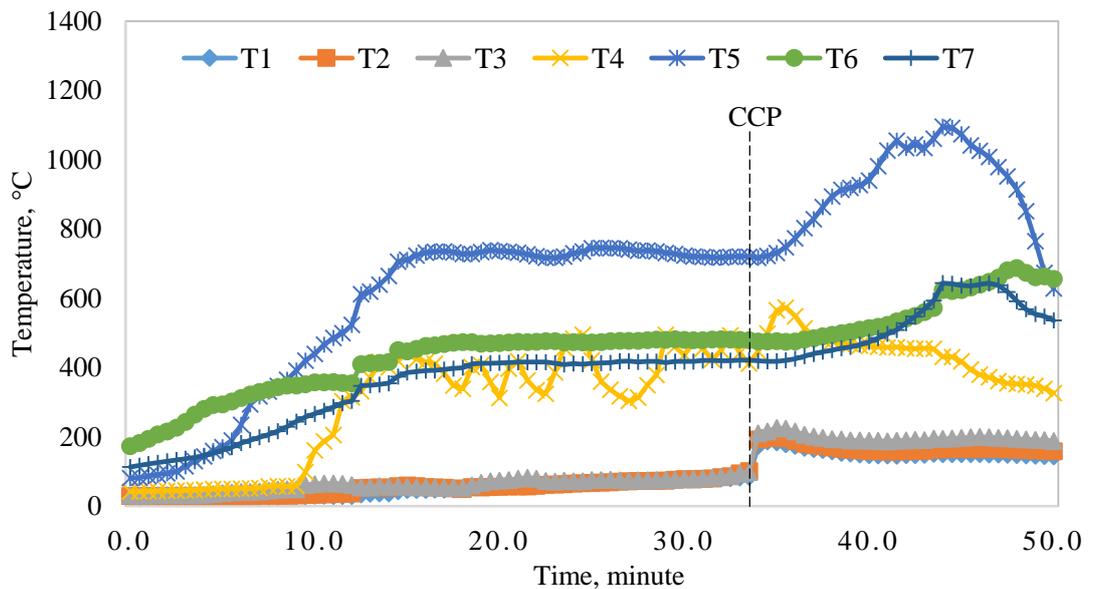


Figure 4.2 Temperature profile for 50% OPF and 50% wood

Based on Figure 4.3, 20% of OPF mixed with 80% of wood chips temperature profile showed an agreement with 80:20 and 50:50 OPF to wood ratios. The temperature in all zones increased steadily at the beginning of the experiment until the 10th minute when the temperature reached a stable reading with an average of 602.7°C for 32 minutes at the combustion zone. Then, the temperature began to increase on the

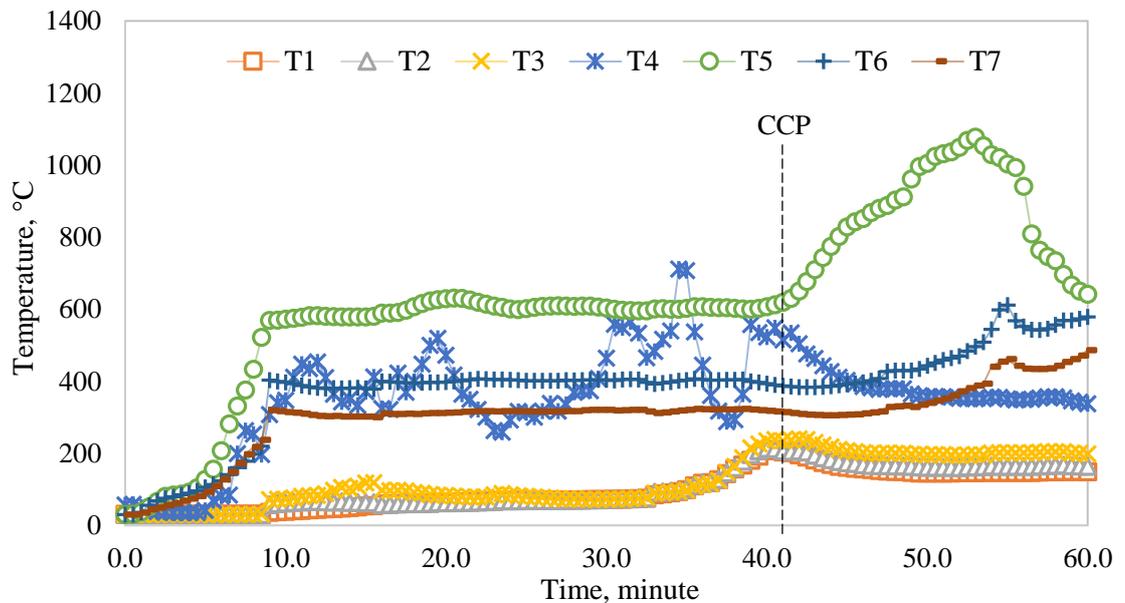


Figure 4.3 Temperature profile for 20% OPF and 80% wood

42nd minute with a maximum of 1078.0°C on the 53rd minute before it decreased until the experiment ends. Similar with 50:50 mix, there was no bridging problem proving that the size and shape of the wood chip used was suitable for the specific downdraft gasifier. The temperature profile for drying and reduction zone showed a smooth gradient. Average temperature recorded for T1 to T7 over the total 60 minutes operation time was 98.3°C, 105.5°C, 124.7°C, 357.4°C, 625.9°C, 381.0°C and 304.0°C respectively.

4.2.2 OPF to SCB Mixture

Temperature profiles for OPF and SCB mixtures are as shown in Figure 4.4, 4.5 and 4.6. Despite the potentials of SCB to generate power from gasification (Jorapur *et al.*, 1994; Jorapur *et al.*, 1995), SCB was proven to be unsuitable for this specific downdraft gasifier. Results obtained showed unstable temperatures throughout the operation verifying bridging occurrences for all ratios. SCB feedstock was too fibrous

and had a very low density which caused it to be combusted faster compared to OPF and wood.

Based on Figure 4.4 for 80:20 mix, although bridging problems occurred, the experiment lasted for 60 minutes as with all 80:20 and 20:80 of OPF and wood mix due to the high ratio of OPF in the mixture. Steep increment in temperature was observed at the beginning of the operation where it reached the maximum temperature of 914.8°C in 17 minutes. Two downhill slopes were observed in the graph at 17.5th to 31st minute and 35.5th to 44.5th minute which showed the occurrences of bridging. The temperature then becomes stable for 9 minutes at an average temperature of 916.3°C due to the decreasing amount of feedstock. The dynamic temperature profiles showed erratic behaviour with an average temperature recorded of 66.1°C, 76.8°C, 119.3°C, 246.1°C, 635.1°C, 411.6°C and 369.9°C respectively.

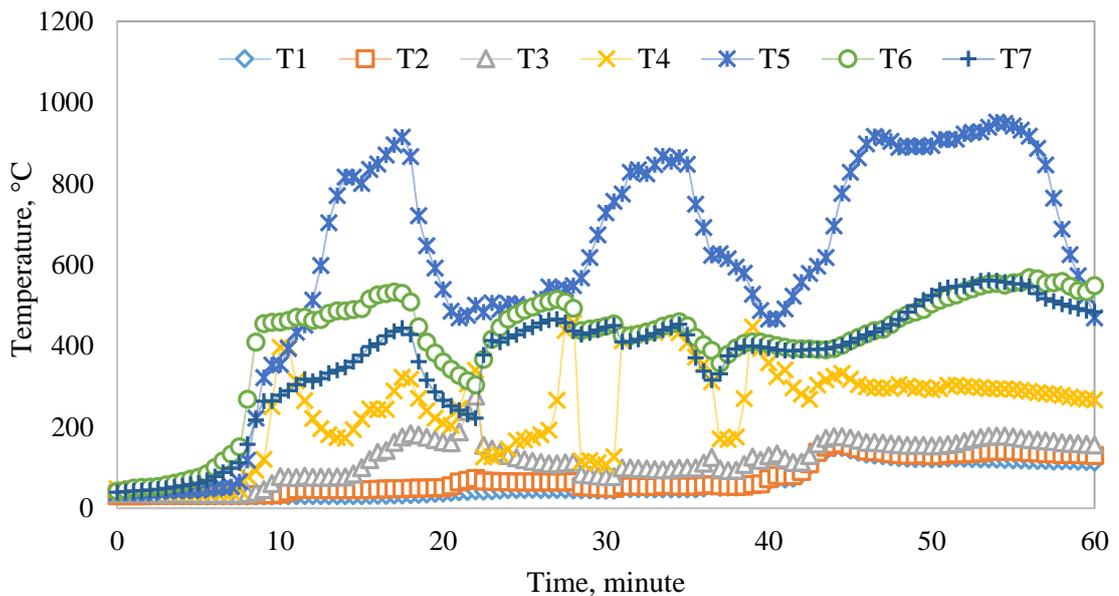


Figure 4.4 Temperature profile for 80% OPF and 20% SCB

Figure 4.5 shows the temperature profile for 50:50 OPF to SCB mix. The operation time lasted for only 30 minutes before the feedstock was completely combusted. Although the operation was conducted in a shorter time, four major peaks were observed indicating more bridging problems had occurred with the increase in SCB ratio. Combustion temperature increased rapidly from room temperature of 29.7°C at the beginning of the experiment to the maximum temperature of 883.4°C in

5 minutes. This proved that SCB was combusted rapidly before first bridging occurred during the 5th to 10th minute of the operation. Second bridging took place as soon as the first one was handled with the third right after that. The combustion zone temperature then started decreasing at 23rd minute where the feedstock was completely combusted. The temperature at other zone also showed unstable readings with the average temperatures recorded for T1 to T7 over the total operation time of 46.9°C, 56.4°C, 167.4°C, 325.2°C, 591.2°C, 385.8°C and 334.8°C respectively.

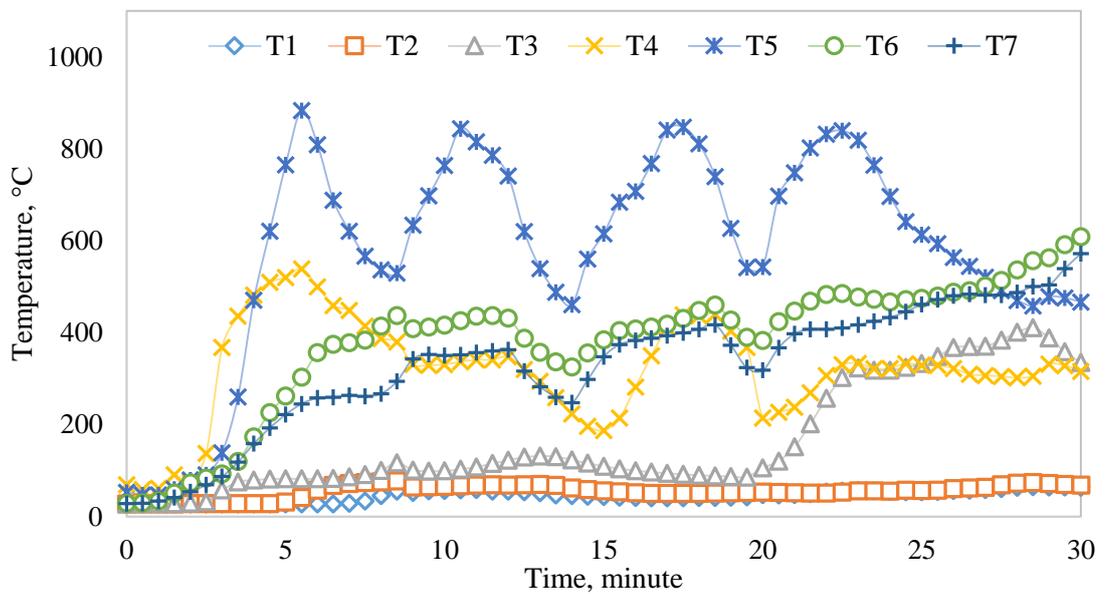


Figure 4.5 Temperature profile for 50% OPF and 50% SCB

As the ratio of SCB was increased, the duration for co-gasification experiment became shorter. The temperature profile for 20:80 of OPF to SCB ratio was only recorded for 20 minutes before the feedstock was completely combusted. Figure 4.6 was observed to have underwent the same bridging problems as the 80:20 and 50:50 mix. The experiment was conducted right after the 100% gasification of wood. Therefore, due to the high combustibility of SCB and high temperature inside the gasifier, the combustion starts immediately after the feedstock mixture was filled in. The combustion zone temperature increased to 826.1°C in the 3rd minute of operation. At that moment, a thick yellowish smoke was detected coming out of the flare tip indicating the presence of syngas. However, the syngas produced only last for about 1 minute until the bridging starts. No stable flare was obtained. Four major peaks were detected at the 5th minute, 7.5th minute, 11th minute and 16.5th minute with maximum

temperature recorded of 840.1°C, 759.7°C, 828.1°C and 903.5°C respectively. Three downhill slopes between the peaks recorded the minimum values of 508.1°C at 6th minute, 470.4°C at 9th minute and 497.3°C at 13th minute. The minimum values recorded showed that the feedstock in combustion zone is out of its range and undergone pyrolysis process which may lead to production of more tars and charcoal. The drying zone temperature - T1, T2 and T3 however, showed stable and uniform readings throughout the operation compared to the pyrolysis, reduction and syngas temperature which gave erratic readings. Average temperatures recorded for T1 to T7 over the total operation time were 54.2°C, 53.3°C, 76.2°C, 349.3°C, 635.1°C, 414.3°C and 355.0°C respectively.

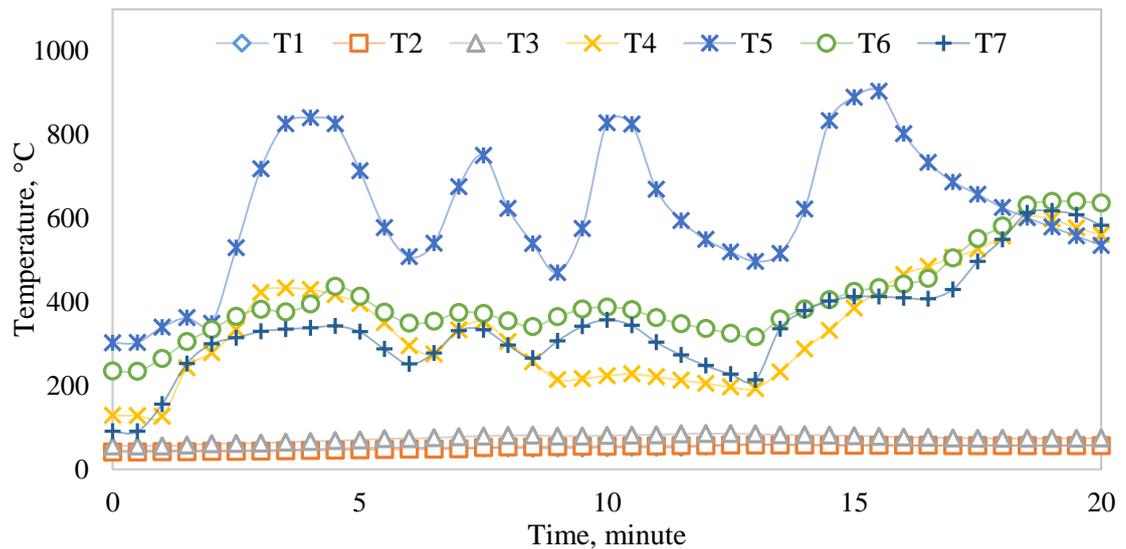


Figure 4.6 Temperature profile for 20% OPF and 80% SCB

4.2.3 Gasification of OPF and wood chips

The focus of this research was to study the dynamic temperature profile of co-gasification operation of OPF, wood and SCB. Therefore, gasification results for OPF was referred from Guangul *et al.*, (2013) research while gasification of wood chips were referred from an experiment conducted to test the gas chromatography equipment using the same downdraft gasifier and material. Gasification of SCB was never conducted using the specific gasifier. Based on results obtained for OPF and SCB mix, it can be predicted that 100% SCB will give undesired result with a shorter time. Therefore, it was concluded that gasification of 100% of SCB will not be conducted in this research.

Dynamic temperature profile for 100% OPF was taken from Guangul *et al.* (2013) research paper on enhancement of oil palm fronds gasification process using preheated inlet air. The result was obtained from the same downdraft gasifier used in this research for 30 minutes operation time (Figure 4.7). Combustion temperature increased steadily at the beginning of the experiment where it reached 754.4°C after 10 minutes. Then, stable combustion temperature was achieved up to 24th minute before the temperature increased to a maximum of 1006°C at the 28th minute. The average temperature obtained during the stable gasification was 796.5°C which showed the temperature was in the good range for gasification operation. Temperature profile at other zones, drying, pyrolysis and reduction also showed a similar smooth gradient as the combustion temperature profile. Average temperature recorded for T1 to T7 over a total operation time of 30 minutes was 55.8°C, 58.2°C, 73.3°C, 207.8°C, 673.1°C, 421.5°C and 353.5°C respectively.

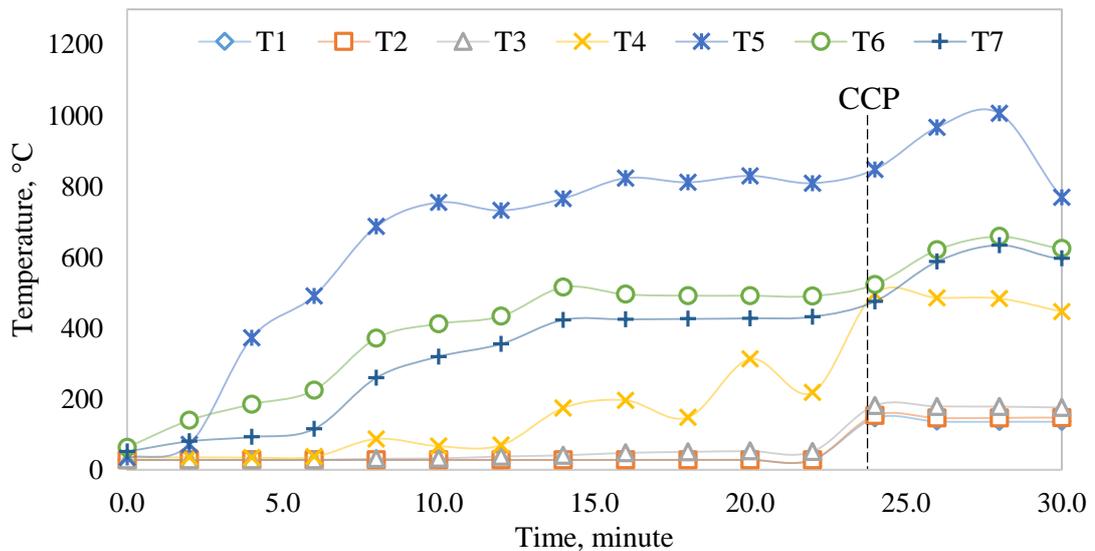


Figure 4.7 Temperature profile for 100% OPF (Guangul *et al.*, 2013)

Gasification of wood chips was conducted with 35 minute of total operation time. Based on the dynamic temperature profile shown in Figure 4.8, it showed a similar pattern with previous results of OPF to wood chips mix and gasification of OPF by Guangul *et al.* (2013). Combustion zone showed a steady temperature increment at the beginning of the operation where it reached 546.6°C in 7 minutes. Stable temperature profile was obtained for about 15 minutes with an average reading

of 675.2°C which is within a good range for gasification. The temperature then increased at the CCP on the 22nd minute to the maximum of 1067.8°C on the 29th minute before it started to decrease until the end of the operation. Other zones measured at T1, T2, T3, T4, T6 and T7 also showed a smooth gradient following the temperature profile for combustion zone. Average temperatures recorded for T1 to T7 over the total operation time were 45.5°C, 48.6°C, 57.5°C, 162.7°C, 338.1°C, 225.0°C and 219.0°C respectively.

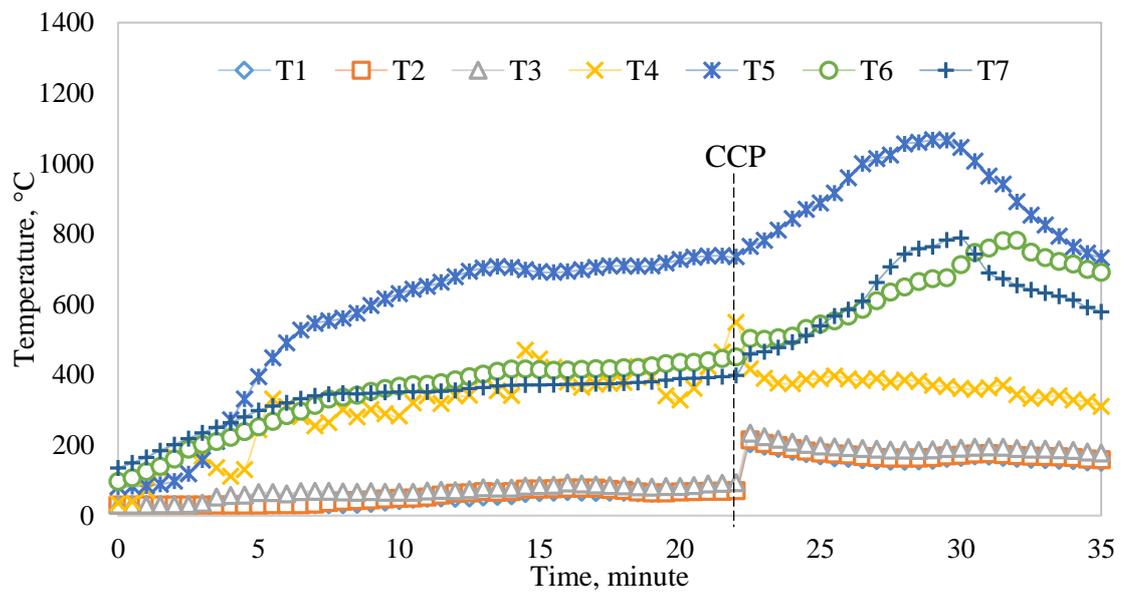


Figure 4.8 Temperature profile for 100% wood chips

4.2.4 Dynamic temperature profile comparison

The results for OPF and wood chips gasification was compared with the co-gasification results of OPF and wood chips mix; and OPF and SCB mix. Figure 4.9 showed the average temperature of T1 until T7 for all co-gasification and gasification experiments. Based on the chart, gasification of wood gives the lowest temperature profile for all zones while co-gasification of OPF with wood at 80:20 mix gave high combustion, reduction and syngas temperature of 767.4°C, 506.5°C and 395.9°C respectively. The temperature for other experiment however, showed varied temperature distribution. The mixture of 80% OPF with 20% wood produced highest temperature at T1, T2 and T4 with 66.1°C, 105.5°C and 357.4°C respectively, while the highest average temperature of 167.4°C at T3 was obtained by 20:80 ratio of OPF to SCB mixture.

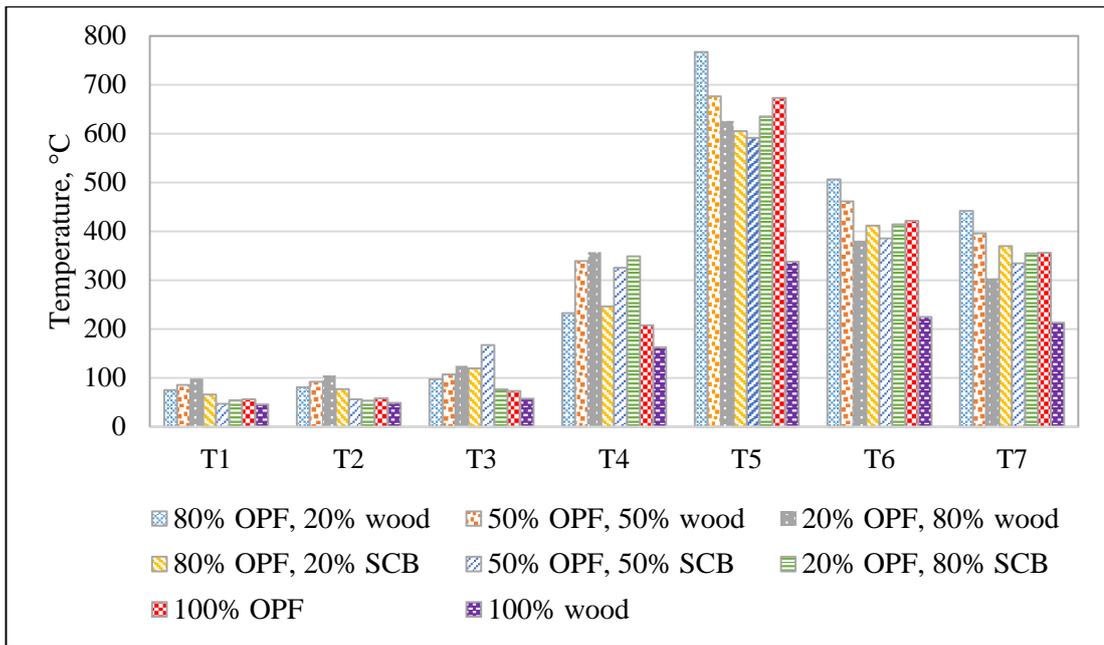


Figure 4.9 Comparison of the average temperature obtained at T1, T2, T3, T4, T5, T6 and T7 for all co-gasification and gasification experiment

Figures 4.10 and 4.11 show the temperature profile comparisons for the combustion (T5) and reduction zone (T6) respectively. Although the operation period for the experiments were different, the overall temperature profile for T5 showed the same pattern for trials of OPF and wood chip mixtures, 100% OPF and 100% wood chip. The temperature increased steadily at the beginning of the operation and achieved stable temperature around the 5th to 15th minute of the operation in the range of 550°C to 850°C. In contrary to the OPF and SCB mixture, the temperature profile showed an erratic behaviour, for which the temperature profile was cyclical due to bridging.

Similar to temperature profiles in the combustion zone, similar pattern could be observed for the gasification of OPF and wood chip mixtures, 100% OPF and 100% wood chip in the reduction zone. Steady increment in temperature was observed at the beginning of the operation before the temperature became stable at around the 5th to 15th minute. The temperature profiles for OPF and SCB mixture were not steady similar to those in the combustion zone.

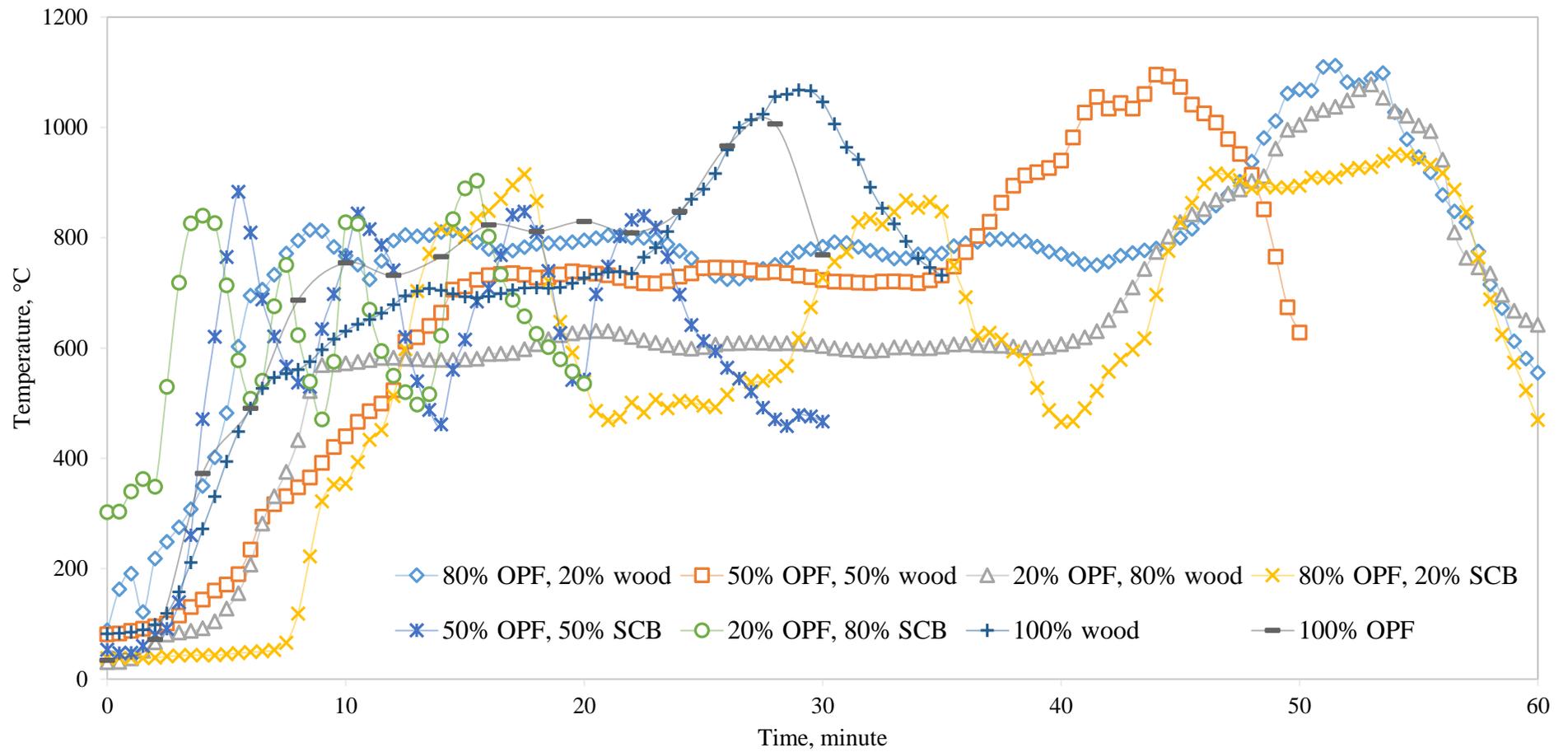


Figure 4.10 Temperature profile at the combustion zone (T5) for all co-gasification and gasification experiment

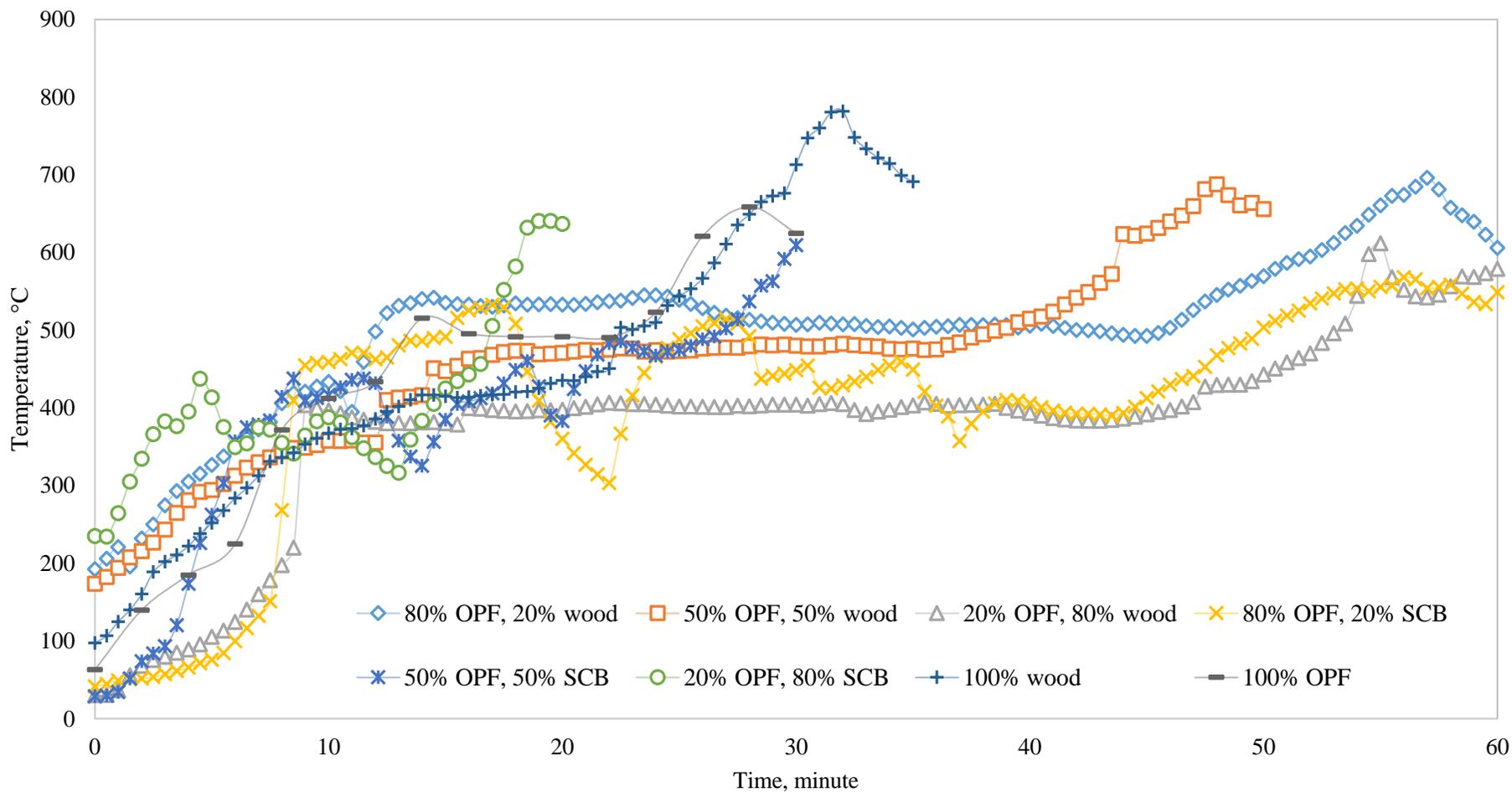


Figure 4.11 Temperature profile at the reduction zone (T6) for all co-gasification and gasification experiment

4.3 Quality and Regional Temperature of Flare

The quality of flare can be identified based on its temperature. Higher flare temperature shows a better syngas was produced. Flares were ignited as soon as the temperature at the combustion zone reached above 500°C where it entered the gasification process. Photos of flare were captured using a high definition digital camera with the temperature and height of the flare measured using a type-K handheld thermocouple and measuring tape respectively. The photos of the flare were labelled with X₁, X₂ and X₃ to show the different positions where the temperatures were recorded. These positions were measured approximately to be at the top, middle and bottom of the flare. Height of the flare was measured from the flare point tip to the highest point of the flare. These data were recorded at the 25th and 40th minute. Due to serious bridging problems for OPF and SCB mixtures, no flare was obtained in all trials. Therefore, this section only displayed the results obtained from co-gasification of OPF and wood mixture.

4.3.1 80% OPF and 20% wood chips

Smooth co-gasification operation was obtained for 80% OPF and 20% wood chips mixture. Although little bridging occurred at the beginning of the experiment, stable flare was obtained for about 20 minutes after the problem was rectified. Figures 4.12 and 4.13 show the physical characteristic of the flare obtained at the 25th and 40th minute of the experiment. Flare obtained at the 25th minute showed a smaller flare compared to the 40th minute due to the lower amount of syngas produced earlier in the operation. Three temperatures, T_{f1}, T_{f2} and T_{f3} were recorded at each position X₁, X₂ and X₃ for specified minutes and were tabulated as in Tables 4.2 and 4.3 respectively. Temperature of the flame was observed to increase as the position of temperature measured moved upwards due to the difference in regional area of the flare. Higher temperature was recorded for the flame at the 40th minutes indicating the achievement of a better co-gasification operation. Average temperatures recorded for position X₁, X₂ and X₃ were 672°C, 545°C and 294°C respectively. More distinct bluish colour flare was observed in 25th minute compared to 40th minute displaying cleaner combustion occurred at an earlier stage of co-gasification operation. Big bright orange flame produced at the 40th minute was due to the production of high carbon content in the syngas.

a) 25th minutes

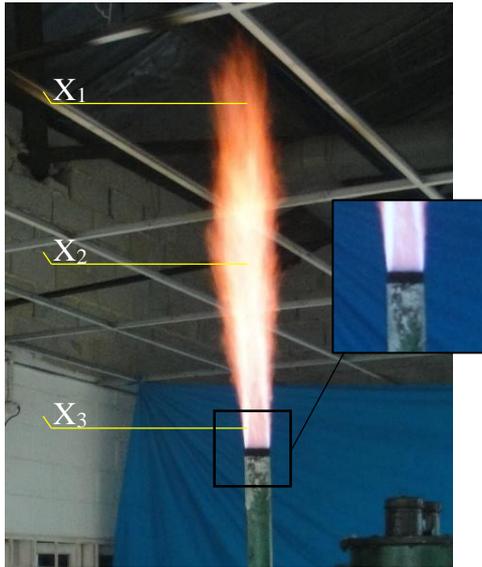


Figure 4.12 Flare at 25th minute for 80:20 of OPF:wood

- **Colour:** Bluish at the bottom and bright orange at the middle and become dark orange at the top
- **Height:** 114.7 cm
- **Temperature:**

Table 4.2 Average temperature at different position of flare for 80:20 OPF:wood at 25th minute

	T _{f1} (°C)	T _{f2} (°C)	T _{f3} (°C)	T _{avg} (°C)
X ₁	632	655	670	652
X ₂	506	514	533	518
X ₃	300	294	298	297

b) 40th minutes

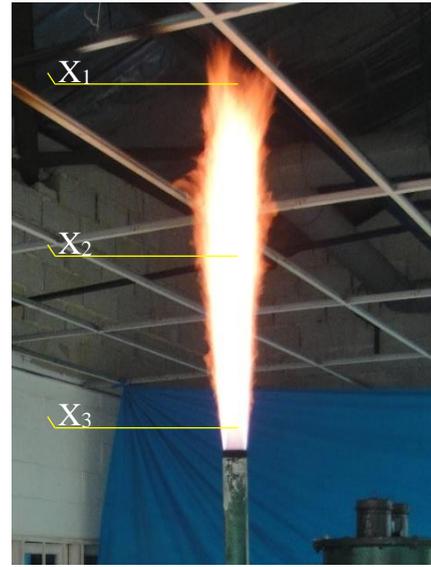


Figure 4.13 Flare at 40th minute for 80:20 of OPF:wood

- **Colour:** Bluish at the bottom and bright orange at the middle and become dark orange at the top
- **Height:** 121.5 cm
- **Temperature:**

Table 3.3 Average temperature at different position of flare for 80:20 OPF:wood at 40th minute

	T _{f1} (°C)	T _{f2} (°C)	T _{f3} (°C)	T _{avg} (°C)
X ₁	670	715	771	719
X ₂	525	575	602	567
X ₃	269	297	306	291

4.3.2 50% OPF and 50% wood chips

Based on dynamic temperature profile for 50:50 of OPF to wood chips ratio in Figure 4.2, stable co-gasification process was obtained after the 25th minute. However, as the temperature of combustion reached above 500°C at the 20th minute, the syngas was ignited and a stable flare was obtained for about 30 minutes of the total operation time. This is in contrast to 80:20 of OPF to wood ratio, where a bigger flare was

produced at 25th minute of operation as compared to the 40th minute flare as in Figures 4.14 and 4.15. This could be due to increasing in air fuel ratio which causes the syngas production to decrease until the end of experiment. However, on the 40th minute, the flare produce gives out more bluish colour compared to the initial flare recorded. The colour of flare produced on the 25th minute has a bright orange in colour with a little bluish at the bottom of the flare. Average temperatures recorded for different position

c) 25th minutes

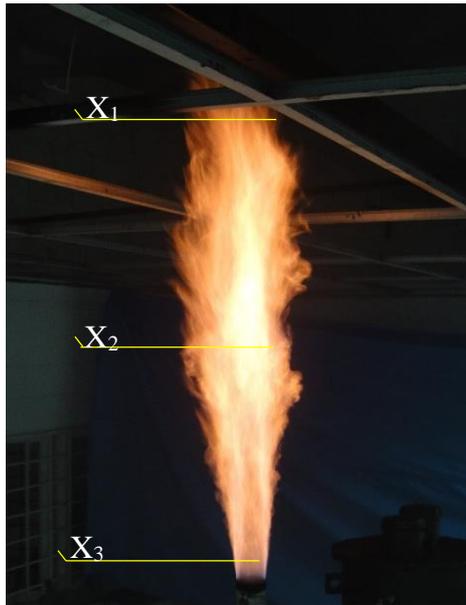


Figure 4.14 Flare at 25th minute for 50:50 of OPF:wood

- **Colour:** Bluish at the bottom and bright orange at the middle and the top
- **Height:** 127 cm
- **Temperature:**

Table 4.4 Average temperature at different position of flare for 50:50 OPF:wood at 25th minute

	T _{f1} (°C)	T _{f2} (°C)	T _{f3} (°C)	T _{avg} (°C)
X ₁	711	658	685	685
X ₂	486	543	443	491
X ₃	198	250	223	226

d) 40th minutes

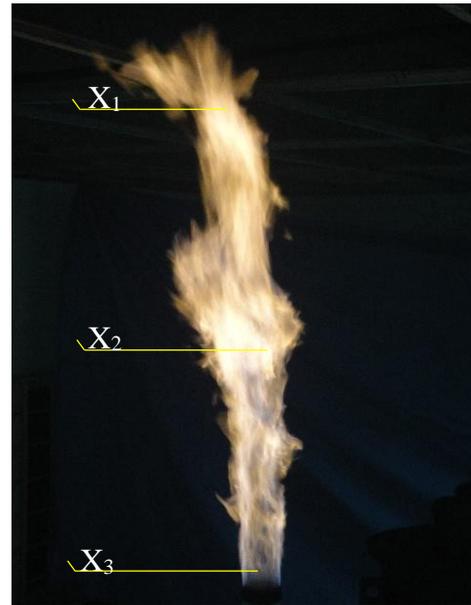


Figure 4.15 Flare at 40th minute for 50:50 of OPF:wood

- **Colour:** Bluish at the bottom up to the middle (X₂), and light orange at the middle and top
- **Height:** 116 cm
- **Temperature:**

Table 4.5 Average temperature at different position of flare for 50:50 OPF:wood at 40th minute

	T _{f1} (°C)	T _{f2} (°C)	T _{f3} (°C)	T _{avg} (°C)
X ₁	744	720	711	725
X ₂	609	624	618	617
X ₃	302	305	311	306

on the 25th minute and 40th minute were tabulated as in Tables 4.4 and 4.5. The results also showed a higher temperature was recorded at the 40th minute indicating that better co-gasification operation was obtained. The average readings for flare temperature throughout the operation were 705°C, 554°C and 266°C for X₁, X₂ and X₃ position respectively.

4.3.3 20% OPF and 80% wood chips

Co-gasification of 20:80 of OPF to wood chips ratio produced a stable flare for about 45 minutes which was 75% of the total operation time. This is in agreement with the temperature profile obtained for this mix as shown in Figure 4.3 where the co-gasification operation had obtained more than 30 minutes of stable temperature profile. The beginning of the flare ignition produced a small flare with the height of less than 80 cm. Then, it started burning more vigorously as the production of syngas increased with time. Based on Figures 4.16 and 4.17, the increasing flare's height was detected from the 25th minute to the 40th minute with the value of 105 cm to 124 cm. Colour of the flare however, did not show much difference. Bright orange with very little or no bluish colour was observed for both flares recorded. The temperature recorded for the specified minutes were tabulated in Tables 4.6 and 4.7 with a higher temperature was obtained at the 40th minute. Similar with previous mix, higher flare temperature indicated that better co-gasification operation was obtained. The average temperature at different position of X₁, X₂ and X₃ throughout the total operation time was 609.5°C, 446.5°C and 184.5°C respectively.

4.3.4 Flare regional temperature comparison

The average temperature recorded for different position of the flare of X₁, X₂ and X₃ were compared for all ratios of OPF and wood chips as shown in Figure 4.18. For 20:80 mixture, lowest average temperature was obtained for all position compared to 80:20 and 50:50 mixtures. On the other hand, the temperatures recorded for 80:20 and 50:50 mixtures showed only slight difference for all position. Higher temperature of the flare showed that the syngas produced contained higher heating value which indicates a better syngas. Therefore, 80:20 and 50:50 mixture were concluded to produce better syngas compared to 20:80 mixture.

e) 25th minute

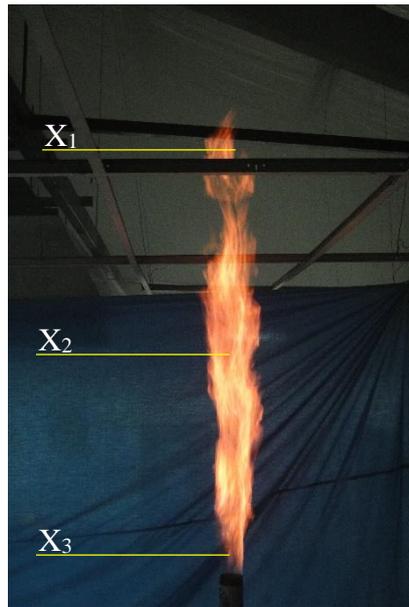


Figure 4.16 Flare at 25th minute for 20:80 of OPF:wood

- **Colour:** Colourless at the bottom and bright orange at the middle and the top
- **Height:** 105 cm
- **Temperature:**

Table 4.6 Average temperature at different position of flare for 20:80 OPF:wood at 25th minute

	T _{f1} (°C)	T _{f2} (°C)	T _{f3} (°C)	T _{avg} (°C)
X ₁	584	596	585	588
X ₂	496	453	463	471
X ₃	183	194	200	192

f) 40th minute

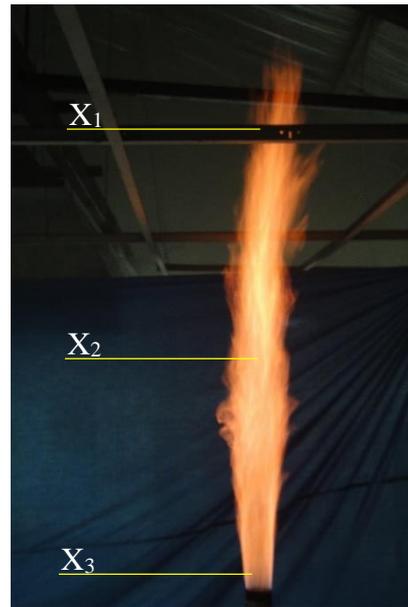


Figure 4.17 Flare at 40th minute for 20:80 of OPF:wood

- **Colour:** Little bluish at the bottom and bright orange at the middle and top
- **Height:** 124 cm
- **Temperature:**

Table 4.7 Average temperature at different position of flare for 20:80 OPF:wood at 40th minute

	T _{f1} (°C)	T _{f2} (°C)	T _{f3} (°C)	T _{avg} (°C)
X ₁	628	632	634	631
X ₂	436	418	413	422
X ₃	176	177	178	177

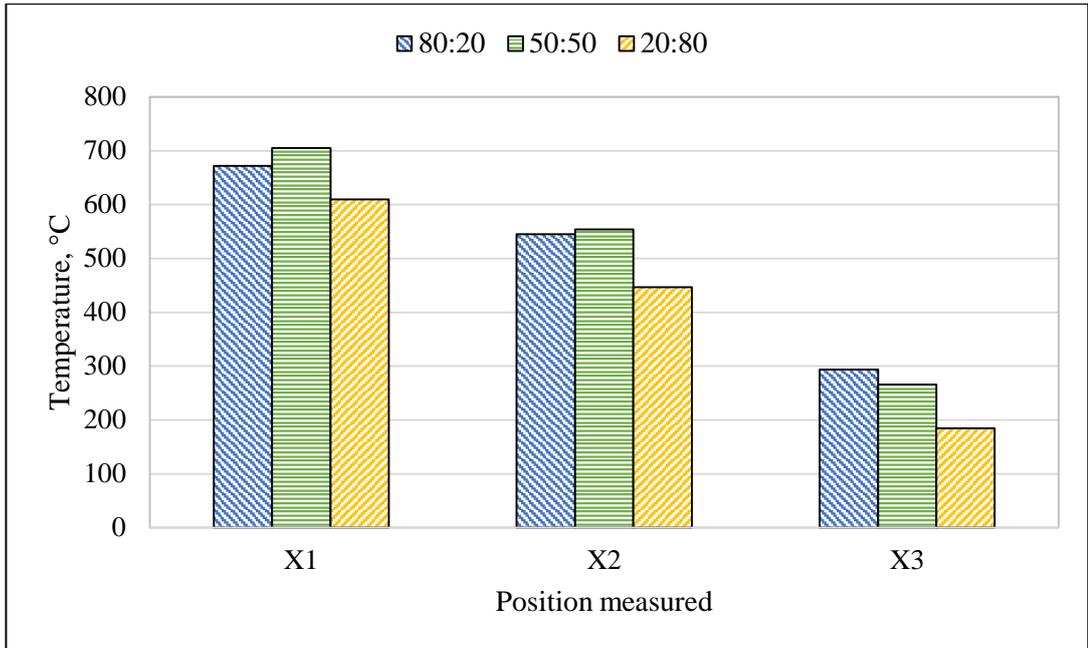


Figure 4.18 Average temperature recorded at different position X₁, X₂ and X₃ for 80:20, 50:50 and 20:80 of OPF to wood ratio

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Ultimate, proximate and calorific value analyses that were conducted for OPF, Acacia Mangium wood and SCB showed that these biomasses have high potential to produce syngas for power generation. The results showed better chemical components were present in feedstocks as compared with coal. OPF and wood mixture, 100% OPF and 100% wood chips produced good temperature profile graphs where the results were in agreement with each other and can be compared directly. Stable flare was also obtained for all three trials for more than 50% of the operation time. Highest syngas temperature was obtained for 80:20 of OPF to wood mixture followed by 50:50 of OPF to wood mixture. The temperature of flare produced also showed slight difference in values for both 80:20 and 50:50 mixture showing a similar quality of syngas was produced. On the other hand, co-gasification between OPF and SCB displayed high bridging problems. The temperature profiles were unstable throughout the operation and no stable flare was obtained for all trials with SCB. The operation time had also decreased as the ratio of SCB increased due to the fibrous characteristic of SCB causing the increased in combustion rate. Therefore, it was concluded that co-gasification of 80:20 of OPF to wood mixture produced the best syngas while SCB was observed to be unsuitable for syngas production using this specific downdraft gasifier.

5.2 Recommendation

For further studies on co-gasification with SCB using this downdraft gasifier, some measure should be taken to overcome bridging problem. The bridging problem was observed to be due to the physical characteristic of SCB itself where it is fibrous and has very low density. To reduce the fibrous characteristic and increase the density, the SCB should be pressed into briquettes with dimension less than 2 cm. Using SCB briquettes may produce a smooth flow in the gasifier which then leads to an uninterrupted co-gasification experiments.

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APPENDICES

Appendix 1 Temperature profile recorded for 80:20 of OPF to wood ratio

Time (min)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)	T6 (°C)	T7 (°C)
0.0	30.19	30.13	30.31	33.48	88.30	192.46	103.07
0.5	30.20	30.14	30.33	33.77	162.55	206.16	113.61
1.0	30.19	30.14	30.34	33.90	191.03	220.91	117.38
1.5	30.19	30.13	30.31	33.61	121.11	196.16	108.86
2.0	30.18	30.13	30.35	34.10	218.41	231.89	123.28
2.5	30.18	30.13	30.35	34.82	248.75	249.92	131.58
3.0	30.18	30.13	30.36	34.72	275.13	274.65	140.04
3.5	30.17	30.13	30.37	34.51	307.82	292.89	147.75
4.0	30.17	30.13	30.37	34.23	350.11	305.14	153.20
4.5	30.16	30.12	30.37	34.08	401.96	315.37	158.78
5.0	30.16	30.12	30.38	34.19	482.24	326.54	169.93
5.5	30.16	30.12	30.38	34.33	602.47	337.77	183.14
6.0	30.16	30.12	30.39	36.91	695.04	349.80	194.20
6.5	30.16	30.12	30.39	44.35	705.79	361.59	205.06
7.0	30.15	30.12	30.40	56.65	732.74	372.29	217.41
7.5	30.15	30.12	30.43	63.01	771.46	381.82	235.74
8.0	30.15	30.12	30.47	55.98	794.89	406.12	410.34
8.5	30.16	30.13	30.54	52.02	813.82	419.17	477.18
9.0	30.16	30.13	30.6	48.32	812.01	421.01	469.00
9.5	30.16	30.13	30.65	60.09	783.19	427.50	458.66
10.0	30.17	30.14	30.77	93.86	767.25	433.29	372.34
10.5	30.17	30.14	31.10	101.49	751.04	421.47	317.26
11.0	33.64	38.22	63.84	97.30	724.38	394.82	312.21
11.5	33.55	38.41	63.35	88.89	758.08	459.54	388.36
12.0	33.45	38.54	62.51	82.84	794.90	498.38	420.69
12.5	33.44	38.73	61.64	79.19	805.06	522.17	434.91
13.0	33.45	38.92	60.74	76.27	802.51	531.36	443.77
13.5	33.48	39.12	59.74	74.48	804.57	535.03	451.49
14.0	33.65	39.35	58.70	73.28	810.04	540.15	455.73
14.5	33.76	39.61	57.81	72.58	812.94	541.87	460.54
15.0	33.93	39.85	56.85	74.36	807.12	535.36	469.41
15.5	34.03	40.08	56.10	84.09	791.73	533.54	475.10
16.0	34.19	40.33	55.57	108.04	779.36	532.91	473.59

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 1 Continued

16.5	34.30	40.56	55.14	110.46	776.02	531.09	472.15
17.0	34.43	40.77	54.78	107.76	776.60	530.09	472.42
17.5	34.49	40.98	54.48	98.85	782.70	531.97	476.44
18.0	34.56	41.16	54.21	95.35	788.40	534.54	475.36
18.5	34.86	41.28	53.87	109.60	790.05	532.98	472.85
19.0	34.77	41.37	53.55	157.20	789.80	533.08	471.30
19.5	34.71	41.35	53.35	177.8	791.84	533.53	471.14
20.0	35.36	41.33	53.09	151.48	795.42	532.97	472.15
20.5	36.03	41.49	52.74	135.36	799.38	532.55	472.22
21.0	36.43	41.87	52.40	132.30	804.61	534.00	472.82
21.5	36.21	42.35	52.03	129.52	803.82	536.06	472.60
22.0	36.88	42.67	51.71	119.33	800.05	537.30	471.15
22.5	36.22	43.06	51.49	110.69	799.76	537.96	470.19
23.0	35.79	43.17	52.06	105.31	796.86	541.52	473.66
23.5	35.97	43.44	54.34	104.30	788.17	545.00	475.52
24.0	37.02	44.00	54.41	141.56	776.12	545.17	475.80
24.5	37.08	44.05	53.56	161.18	762.16	543.19	474.39
25.0	37.25	44.41	54.86	164.66	743.96	539.11	472.40
25.5	38.45	44.15	62.74	269.39	730.67	534.09	470.49
26.0	38.74	44.89	61.32	292.88	724.91	528.34	466.93
26.5	38.90	46.11	65.33	332.57	725.67	522.55	463.42
27.0	40.67	47.53	63.28	312.96	733.84	518.62	461.66
27.5	41.45	48.14	64.75	293.94	743.55	515.40	460.46
28.0	42.38	48.65	63.22	316.01	750.58	513.47	458.66
28.5	43.93	50.06	62.90	298.79	762.05	511.40	456.77
29.0	44.92	46.34	62.65	266.07	774.10	509.72	457.88
29.5	44.70	44.27	61.04	236.57	779.51	508.14	457.89
30.0	45.08	43.92	58.62	229.61	783.64	506.97	457.12
30.5	46.27	44.47	57.76	238.33	792.05	507.45	457.02
31.0	47.70	45.82	57.37	255.78	790.61	509.70	458.90
31.5	47.63	46.11	59.07	275.26	783.49	508.68	456.74
32.0	47.97	46.64	60.07	257.63	776.69	507.65	455.35
32.5	47.84	47.24	61.73	256.46	769.22	507.84	458.73
33.0	48.64	47.72	64.27	302.05	762.22	505.64	456.47
33.5	50.11	50.11	67.86	286.27	762.66	504.05	455.91
34.0	53.07	52.73	74.35	290.05	769.78	504.71	457.04
34.5	54.54	54.06	72.17	314.82	769.38	503.13	454.52
35.0	55.19	55.86	70.49	304.50	771.52	500.86	454.06

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 1 Continued

35.5	55.65	55.68	69.20	276.21	784.56	502.96	454.23
36.0	57.25	57.75	65.98	284.93	789.89	504.33	453.43
36.5	59.92	59.73	64.19	296.02	792.6	505.28	454.26
37.0	61.23	60.49	63.21	276.79	796.58	506.97	455.33
37.5	62.16	61.89	62.91	308.06	797.86	507.05	454.06
38.0	62.93	62.3	63.75	312.13	796.06	506.59	453.57
38.5	64.76	64.28	66.11	316.88	793.47	507.30	454.53
39.0	67.17	66.96	71.27	344.55	783.67	506.39	454.55
39.5	67.73	68.33	73.82	451.43	774.45	503.44	452.84
40.0	69.51	71.39	76.44	426.14	770.28	505.80	453.39
40.5	76.84	81.6	84.56	380.61	761.39	508.31	453.74
41.0	86.11	91.33	92.88	370.69	751.90	505.46	452.77
41.5	101.66	109.54	111.43	323.37	749.96	502.99	451.57
42.0	114.57	123.05	125.55	303.41	756.53	500.47	449.66
42.5	134.43	147.34	155.91	306.69	767.37	499.83	448.31
43.0	165.96	176.9	193.92	343.08	772.35	498.68	447.34
43.5	188.51	192.81	213.70	399.84	777.14	496.17	445.29
44.0	186.84	196.57	228.02	441.09	780.35	494.14	441.92
44.5	180.12	189.48	220.79	415.79	787.33	492.80	441.38
45.0	173.85	184.05	214.44	398.75	799.44	492.82	442.66
45.5	167.67	178.08	208.3	386.84	815.81	496.61	445.94
46.0	163.00	172.77	202.92	379.86	836.96	503.00	451.26
46.5	158.57	168.14	198.36	379.79	858.16	513.50	455.68
47.0	155.16	164.89	195.67	380.13	877.65	526.03	460.02
47.5	152.26	161.69	193.43	382.65	901.68	536.94	465.14
48.0	149.12	159.00	191.78	388.98	937.92	545.44	471.23
48.5	146.16	156.75	190.61	389.92	980.88	552.15	475.79
49.0	143.87	155.63	190.19	390.69	1011.62	557.11	480.35
49.5	142.95	155.26	191.09	390.78	1061.24	563.31	485.39
50.0	142.22	154.81	191.78	391.18	1068.57	569.48	490.79
50.5	142.34	156.15	193.13	391.53	1066.6	578.91	497.80
51.0	143.75	158.91	195.39	394.17	1109.67	586.48	507.24
51.5	144.25	158.51	195.29	393.46	1112.08	591.45	522.09
52.0	145.14	158.67	195.84	384.31	1082.00	595.03	539.54
52.5	146.42	159.55	195.94	385.95	1076.16	603.24	566.45
53.0	146.98	160.84	197.47	384.87	1089.04	612.35	596.61
53.5	146.75	160.89	197.59	375.28	1098.43	625.11	623.85
54.0	145.99	159.89	195.86	374.46	1027.37	634.47	644.22

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 1 Continued

54.5	145.72	160.30	196.74	378.15	978.53	648.56	653.16
55.0	143.93	158.76	194.66	366.10	946.01	660.79	667.73
55.5	142.41	157.55	192.83	362.51	918.39	672.85	676.08
56.0	142.32	157.84	193.26	359.31	877.39	674.20	675.31
56.5	142.51	158.75	194.75	354.62	847.85	684.59	667.70
57.0	140.36	156.97	192.26	346.72	828.13	696.14	645.93
57.5	138.96	155.72	190.11	336.49	775.13	681.16	608.73
58.0	137.85	154.1	187.34	329.54	715.19	657.60	585.11
58.5	136.22	152.56	184.74	325.29	672.23	647.86	568.39
59.0	135.73	151.55	183.66	322.22	612.22	639.8	552.40
59.5	134.78	150.43	181.64	311.98	581.00	622.89	537.49
60.0	133.61	149.00	180.07	307.84	555.21	605.9	525.80
Average Temperature	74.91	80.78	97.26	232.49	767.43	506.50	442.02

Appendix 2 Temperature profile recorded for 50:50 of OPF to wood ratio

Time (min)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)	T6 (°C)	T7 (°C)
0.0	28.90	29.48	31.91	42.35	80.92	173.90	113.21
0.5	28.91	29.51	31.97	42.82	82.49	182.46	117.52
1.0	28.88	29.54	32.04	43.33	87.13	194.24	121.92
1.5	28.87	29.57	32.13	43.95	90.89	207.83	125.87
2.0	28.89	29.60	32.23	44.55	95.23	215.85	129.96
2.5	28.93	29.64	32.35	45.30	100.68	226.83	133.73
3.0	28.97	29.68	32.53	45.94	115.09	243.61	137.45
3.5	29.01	29.70	32.83	46.70	130.40	264.82	140.98
4.0	29.03	29.74	33.51	48.65	143.90	281.23	146.21
4.5	29.03	29.78	35.20	49.72	160.06	291.92	153.38
5.0	29.03	29.84	37.79	50.11	171.13	294.46	161.94
5.5	29.05	29.93	40.02	50.41	190.08	302.07	170.54
6.0	29.10	30.06	41.32	51.06	234.91	312.93	182.35
6.5	29.13	30.20	42.12	51.62	294.36	323.05	190.63
7.0	29.17	30.37	43.06	52.85	317.07	330.24	199.10
7.5	29.20	30.56	45.54	57.43	331.09	336.29	207.43
8.0	29.28	30.80	48.36	58.37	347.77	343.96	217.04
8.5	29.35	31.11	49.21	57.19	365.44	348.58	229.87
9.0	29.64	31.53	49.12	58.13	391.84	348.76	244.48
9.5	30.05	32.13	61.53	99.05	420.74	352.29	257.65
10.0	30.44	33.18	64.00	161.88	439.92	358.01	266.60
10.5	30.31	34.26	66.11	187.41	466.18	357.65	276.11
11.0	29.96	35.19	65.48	205.38	485.36	358.30	286.71
11.5	29.81	36.12	64.44	303.04	499.62	355.55	298.09
12.0	29.71	37.30	61.12	314.45	523.26	355.40	303.88
12.5	34.49	53.28	54.89	331.75	611.62	410.28	347.86
13.0	36.16	54.10	54.31	370.71	619.33	413.47	349.18
13.5	36.95	54.31	58.48	417.72	640.04	414.29	351.55
14.0	37.60	53.81	56.12	400.69	664.39	416.36	355.04
14.5	44.04	57.93	57.23	419.87	705.82	451.01	374.56
15.0	46.87	59.88	56.71	443.82	711.53	447.41	386.26
15.5	47.48	58.29	54.74	424.35	723.80	454.24	388.82
16.0	47.60	55.72	55.60	416.96	732.02	463.12	391.54
16.5	47.85	54.72	55.12	411.30	734.39	464.26	392.06
17.0	48.27	53.54	53.89	382.73	735.79	468.33	394.94
17.5	49.25	52.17	54.05	348.30	732.74	471.85	397.70

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 2 Continued

18.0	49.82	49.90	52.94	339.18	727.78	473.75	399.96
18.5	57.06	55.28	60.51	401.53	728.24	473.40	410.57
19.0	56.29	54.71	67.49	407.65	733.36	469.01	412.36
19.5	57.35	55.21	71.95	358.48	739.05	469.90	412.93
20.0	57.90	56.35	74.47	312.88	736.64	470.76	413.64
20.5	58.31	57.25	75.92	397.05	734.56	472.69	414.09
21.0	58.46	57.44	79.41	418.38	732.03	474.52	416.15
21.5	58.73	57.70	82.48	363.66	727.11	473.82	416.11
22.0	60.01	58.93	79.54	334.80	721.65	475.07	415.89
22.5	63.18	62.02	72.95	324.42	717.44	476.89	415.90
23.0	64.79	63.39	71.50	386.58	717.02	476.47	412.85
23.5	65.45	64.26	73.72	456.90	721.13	472.70	409.08
24.0	67.31	65.93	72.48	483.55	729.50	474.19	411.81
24.5	68.12	66.85	72.59	494.95	735.24	472.66	409.95
25.0	68.50	67.25	75.54	421.73	744.78	473.35	412.78
25.5	69.39	68.15	76.14	359.23	745.71	473.80	413.27
26.0	70.84	69.58	76.40	336.42	745.12	476.26	414.41
26.5	72.10	70.95	74.72	317.60	745.05	477.54	418.37
27.0	73.70	72.46	74.30	304.25	740.97	477.69	418.57
27.5	74.08	73.01	74.87	313.42	736.89	477.52	416.59
28.0	74.25	73.17	74.92	349.53	737.94	479.35	417.73
28.5	74.80	73.93	75.25	379.05	735.88	481.48	417.81
29.0	75.05	74.23	76.59	494.85	731.08	480.54	414.41
29.5	76.50	76.32	76.88	460.84	728.40	481.75	417.91
30.0	78.28	78.29	78.21	436.67	723.25	480.24	417.90
30.5	78.49	78.15	79.02	473.45	720.51	479.24	417.88
31.0	79.03	79.14	80.02	455.45	720.04	479.24	420.47
31.5	79.83	80.53	81.93	423.78	718.35	481.06	420.91
32.0	80.76	83.75	85.13	449.77	717.84	482.46	420.23
32.5	81.52	87.05	87.99	492.74	720.27	480.84	420.10
33.0	83.51	95.26	94.38	442.90	720.87	479.97	422.07
33.5	84.84	101.50	99.34	411.89	719.95	479.16	421.86
34.0	174.82	192.83	210.11	447.15	717.27	475.89	419.86
34.5	187.21	196.55	216.17	499.17	722.67	475.49	418.25
35.0	184.86	199.12	226.30	565.58	731.21	476.24	418.23
35.5	179.34	196.24	223.90	573.55	747.56	474.50	420.94
36.0	174.12	188.76	215.75	548.87	773.65	475.26	425.70
36.5	168.54	180.88	206.63	513.09	803.06	480.89	433.26

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 2 Continued

37.0	164.90	176.49	201.30	493.07	828.95	484.47	439.88
37.5	162.50	173.38	197.27	483.22	863.74	490.57	445.93
38.0	158.34	169.79	193.97	477.02	894.06	494.70	450.70
38.5	153.87	165.95	192.58	469.62	912.91	499.23	455.98
39.0	152.14	163.49	190.14	468.75	918.80	503.24	459.67
39.5	149.74	161.85	189.95	464.09	926.66	510.18	466.07
40.0	147.40	159.44	189.01	463.07	939.89	514.74	474.37
40.5	146.94	159.23	188.99	459.62	981.89	517.65	485.48
41.0	146.47	157.87	187.52	458.37	1026.87	523.88	497.67
41.5	146.21	158.39	189.20	459.18	1054.97	533.30	508.58
42.0	147.45	159.11	190.02	455.99	1033.88	541.98	528.44
42.5	147.75	159.86	191.57	454.91	1044.04	549.33	547.90
43.0	148.52	160.24	190.91	455.48	1034.28	560.81	569.62
43.5	151.03	163.96	195.30	454.26	1060.52	572.41	593.58
44.0	150.39	163.87	194.47	431.36	1095.66	623.62	643.98
44.5	150.26	165.14	196.07	430.95	1092.00	621.50	642.16
45.0	150.51	165.46	197.36	418.27	1073.57	624.42	637.15
45.5	150.73	165.67	199.04	394.45	1041.44	631.50	635.20
46.0	150.46	165.76	199.84	379.49	1025.36	640.11	640.50
46.5	149.57	165.80	199.38	372.14	1008.54	647.55	643.48
47.0	149.65	165.09	197.68	361.53	978.87	659.88	637.77
47.5	148.63	164.71	196.42	354.67	951.97	681.48	618.81
48.0	147.73	163.08	194.65	352.91	913.87	687.78	592.20
48.5	146.77	162.16	193.08	351.63	851.39	673.78	568.42
49.0	145.84	161.29	191.74	347.92	765.37	660.65	554.66
49.5	144.85	160.24	190.61	339.72	673.70	663.72	547.69
50.0	143.86	158.76	188.45	326.83	628.22	656.07	536.19
Average Temperature	85.49	91.85	106.92	339.09	676.48	461.09	395.95

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 3 Temperature profile recorded for 20:80 of OPF to wood ratio

Time (min)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)	T6 (°C)	T7 (°C)
0.0	31.36	30.20	29.94	56.43	30.60	30.40	30.10
0.5	31.36	30.19	29.94	58.13	30.97	30.61	30.42
1.0	31.36	30.20	29.93	50.65	37.45	36.81	35.63
1.5	31.35	30.20	29.92	42.07	51.08	56.07	44.16
2.0	31.35	30.21	29.93	38.32	66.66	68.08	49.54
2.5	31.36	30.21	29.94	36.64	80.64	75.73	55.56
3.0	31.35	30.21	29.94	35.78	84.48	80.02	61.45
3.5	31.35	30.22	29.95	35.25	87.01	85.13	67.87
4.0	31.35	30.22	29.97	35.28	91.91	89.18	74.41
4.5	31.34	30.22	29.99	35.57	104.29	95.84	81.19
5.0	31.34	30.23	30.03	41.99	127.80	105.45	93.38
5.5	31.33	30.23	30.07	68.91	155.63	113.56	109.06
6.0	31.33	30.24	30.13	81.15	207.27	124.53	127.80
6.5	31.32	30.24	30.24	84.10	281.66	140.59	148.42
7.0	31.32	30.24	30.41	199.40	331.10	160.32	171.62
7.5	31.31	30.24	30.50	263.40	375.40	178.28	197.79
8.0	31.30	30.24	30.69	253.16	433.06	197.79	218.47
8.5	31.30	30.24	31.06	196.75	522.19	220.10	237.22
9.0	36.81	57.46	72.02	307.92	569.22	403.55	320.23
9.5	38.03	60.15	72.42	340.47	570.03	399.83	317.28
10.0	39.35	62.08	73.12	347.62	572.26	397.16	315.04
10.5	40.73	63.69	75.87	411.15	574.90	393.27	313.09
11.0	41.99	64.92	80.99	447.53	578.00	388.11	310.58
11.5	43.26	66.10	82.84	435.65	581.97	384.77	306.51
12.0	44.70	66.78	83.58	454.21	582.56	382.27	304.40
12.5	46.06	65.67	87.48	410.82	580.53	380.38	303.39
13.0	46.91	64.97	97.93	364.44	579.87	380.71	303.81
13.5	48.06	65.42	105.12	342.92	578.88	380.23	302.10
14.0	49.77	64.17	102.44	350.79	578.71	381.44	302.35
14.5	51.56	63.67	109.14	333.67	578.83	381.61	302.35
15.0	53.67	63.21	118.34	371.52	579.03	380.37	302.05
15.5	54.86	63.06	118.64	411.84	580.59	378.54	300.64
16.0	59.03	57.84	97.38	324.47	589.37	399.87	310.78
16.5	59.71	58.50	96.30	321.51	589.69	398.98	309.37
17.0	60.26	59.16	97.65	422.93	590.96	397.49	309.18

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 3 Continued

17.5	61.05	59.94	95.40	369.19	597.85	396.45	309.85
18.0	61.61	60.39	91.69	400.14	606.83	395.77	309.75
18.5	61.81	60.69	89.26	447.62	616.28	396.02	311.36
19.0	62.49	61.49	86.14	499.63	623.54	396.95	311.76
19.5	63.68	62.61	84.46	519.18	626.85	396.90	312.08
20.0	64.07	62.84	83.25	472.85	629.56	397.81	313.21
20.5	63.98	62.73	81.22	417.40	631.14	399.70	313.71
21.0	65.05	63.55	80.04	364.68	630.34	401.66	315.19
21.5	65.61	64.20	79.25	349.76	625.58	404.54	316.64
22.0	66.17	64.67	78.29	321.69	619.79	406.75	317.64
22.5	67.03	65.49	78.77	300.22	614.06	406.01	317.15
23.0	67.47	66.41	84.77	263.66	609.20	404.82	316.59
23.5	68.86	68.00	88.47	259.19	604.97	405.08	317.72
24.0	69.43	68.17	84.88	292.27	600.74	404.23	317.48
24.5	69.51	68.39	82.12	316.72	599.02	402.92	317.23
25.0	70.31	69.00	80.31	312.57	601.53	401.90	316.72
25.5	70.31	69.29	79.17	300.75	605.81	401.79	316.54
26.0	70.25	69.24	77.60	317.75	608.31	401.42	316.08
26.5	70.11	69.25	75.87	338.28	608.99	401.18	316.52
27.0	70.43	69.55	74.63	317.51	609.67	401.29	316.87
27.5	70.39	69.63	74.04	335.92	609.30	402.89	317.66
28.0	70.56	69.69	73.58	370.02	608.44	402.11	317.71
28.5	71.03	70.26	72.78	374.15	609.04	403.31	319.56
29.0	71.58	70.77	72.45	374.28	608.67	404.17	320.68
29.5	71.42	70.89	72.15	407.85	606.69	404.45	320.94
30.0	71.65	71.85	72.70	464.44	603.47	404.16	320.92
30.5	72.89	73.41	73.26	558.51	599.99	402.79	318.90
31.0	72.87	73.37	73.48	548.63	597.48	404.85	320.11
31.5	73.74	74.18	74.48	565.67	596.16	406.23	320.91
32.0	74.09	74.96	75.52	533.21	595.23	404.85	321.00
32.5	75.12	76.52	77.14	465.72	595.85	397.32	316.03
33.0	85.49	92.34	89.99	482.88	601.24	392.23	311.75
33.5	87.82	93.53	90.87	516.37	601.67	395.38	313.84
34.0	90.25	94.56	91.84	539.39	599.98	397.71	316.34
34.5	93.74	96.90	93.77	711.83	599.82	401.30	318.89
35.0	99.12	102.09	97.97	707.75	602.52	403.24	320.74
35.5	110.37	111.94	107.97	537.48	606.75	407.03	323.79
36.0	116.92	117.67	113.50	444.74	607.33	405.22	323.04

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 3 Continued

36.5	118.94	119.47	115.64	360.55	605.57	402.87	321.84
37.0	126.40	127.30	124.84	317.25	604.77	403.63	322.29
37.5	143.45	146.12	147.28	287.72	604.32	403.85	322.18
38.0	156.62	160.40	163.68	293.16	602.73	404.14	322.46
38.5	167.26	178.11	187.68	364.49	600.92	405.23	323.23
39.0	181.19	196.87	215.66	557.24	600.09	400.03	321.33
39.5	192.75	207.65	226.39	535.26	602.45	396.73	319.89
40.0	207.35	213.82	234.48	523.36	607.15	393.62	318.17
40.5	210.13	212.92	238.19	548.37	612.62	389.95	316.42
41.0	204.26	206.21	234.62	515.03	619.38	387.00	314.37
41.5	202.42	205.81	236.46	534.62	630.51	385.36	311.89
42.0	196.13	206.51	239.92	504.35	650.84	383.89	309.75
42.5	190.01	203.59	238.28	475.70	677.61	383.39	307.83
43.0	181.66	195.00	230.45	463.18	709.80	383.65	306.70
43.5	174.57	188.14	223.60	442.83	743.52	384.61	305.99
44.0	168.90	182.78	217.87	427.53	774.27	386.34	306.04
44.5	164.31	177.38	211.31	411.18	802.28	388.83	306.64
45.0	161.16	173.89	207.24	402.82	828.40	391.82	307.54
45.5	159.12	171.63	204.60	392.28	842.54	394.80	308.79
46.0	156.88	168.39	201.94	385.66	852.02	397.23	311.25
46.5	154.73	166.23	199.93	381.61	868.79	401.91	314.00
47.0	152.84	165.78	199.74	377.45	880.52	407.58	316.80
47.5	150.63	165.57	200.93	380.23	887.69	427.35	328.71
48.0	150.19	164.71	200.63	379.47	902.82	429.58	330.35
48.5	149.41	164.74	200.72	379.07	911.77	429.94	332.73
49.0	147.36	163.84	198.01	365.32	961.73	429.96	329.01
49.5	145.79	162.48	197.31	359.81	995.83	434.32	334.88
50.0	144.98	161.18	196.08	357.43	1004.85	443.15	340.77
50.5	144.95	161.45	196.38	358.32	1024.98	450.79	346.44
51.0	145.55	161.66	197.08	357.50	1031.59	458.76	353.11
51.5	145.71	161.14	195.41	355.94	1037.25	464.39	361.05
52.0	146.16	160.86	194.54	352.88	1049.00	470.12	371.98
52.5	146.55	162.01	195.85	351.79	1069.15	483.55	381.34
53.0	146.65	162.66	196.92	352.34	1078.01	496.05	388.64
53.5	147.37	163.03	196.11	352.05	1053.59	508.67	393.29
54.0	147.29	164.77	201.10	356.69	1029.25	544.34	440.74
54.5	146.81	163.77	201.69	355.22	1020.98	598.11	454.84
55.0	147.22	163.90	201.95	350.81	1003.36	611.77	461.71

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 3 Continued

55.5	147.16	164.16	201.45	348.04	993.30	568.28	443.61
56.0	147.15	164.26	201.58	348.83	941.46	551.85	434.85
56.5	147.34	164.17	202.42	349.94	809.58	543.70	434.70
57.0	147.99	164.83	203.06	353.96	763.74	542.11	434.53
57.5	148.64	165.74	204.54	357.36	746.09	545.60	436.08
58.0	148.70	166.88	205.21	357.43	735.09	556.37	443.38
58.5	149.90	167.50	204.62	353.41	696.26	569.12	454.01
59.0	150.15	165.84	201.66	345.70	667.51	568.73	461.99
59.5	149.69	164.91	200.64	341.75	650.50	573.58	471.71
60.0	148.89	164.01	198.74	337.71	642.03	579.10	486.44
Average Temperature	98.30	105.46	124.68	357.44	625.86	380.96	303.97

Appendix 4 Temperature profile recorded for 80:20 of OPF to SCB ratio

Time (min)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)	T6 (°C)	T7 (°C)
0	29.51	30.70	36.25	48.02	37.89	41.92	38.97
0.5	29.55	30.86	36.18	45.60	37.76	44.93	40.70
1.0	29.56	30.95	36.08	43.97	37.56	49.27	42.56
1.5	29.56	31.03	35.97	42.75	37.71	50.98	43.58
2.0	29.58	31.11	35.87	41.78	38.87	51.77	44.66
2.5	29.59	31.19	35.74	40.98	40.88	53.86	46.58
3.0	29.60	31.27	35.60	40.33	42.42	57.20	49.11
3.5	29.61	31.35	35.42	39.79	43.48	61.65	52.23
4.0	29.63	31.44	35.24	39.40	43.14	65.88	55.15
4.5	29.65	31.53	35.08	39.13	43.22	71.54	58.16
5.0	29.67	31.64	34.96	39.54	44.89	76.21	61.72
5.5	29.70	31.76	34.87	40.46	46.92	84.73	68.57
6.0	29.73	31.89	34.85	40.55	48.63	100.05	78.01
6.5	29.77	32.03	34.87	40.40	50.15	116.63	87.84
7.0	29.81	32.17	34.90	40.04	52.84	132.68	98.03
7.5	29.86	32.31	34.94	45.54	65.60	151.14	111.37
8.0	29.92	32.47	35.84	78.75	118.39	268.38	157.17
8.5	29.98	32.64	39.31	93.06	222.03	409.35	217.38
9.0	30.07	32.88	45.31	120.71	321.92	454.83	263.80
9.5	30.18	33.29	60.36	250.45	352.57	457.86	264.24
10.0	30.35	34.51	77.94	396.80	354.40	459.04	278.25
10.5	30.59	39.80	76.57	396.88	393.44	463.04	289.35
11.0	30.76	45.21	75.64	313.07	433.47	470.87	304.28
11.5	30.76	46.28	78.37	265.27	451.24	470.96	317.86
12.0	30.72	46.16	76.37	221.40	512.91	462.40	312.58
12.5	30.70	45.79	76.15	195.67	597.90	465.08	319.72
13.0	30.68	45.49	76.41	181.26	703.31	480.41	333.08
13.5	30.70	45.44	76.89	173.91	770.66	486.39	340.04
14.0	30.74	45.52	77.41	172.67	816.21	486.38	347.27
14.5	30.81	45.47	84.33	193.88	816.22	489.79	361.49
15.0	30.91	45.54	99.58	219.78	800.67	491.79	377.32
15.5	31.08	45.85	119.58	244.42	835.22	515.89	397.89
16.0	31.31	46.45	137.59	242.63	848.50	525.70	405.43
16.5	31.66	47.35	142.08	244.16	870.19	528.82	424.65
17.0	32.03	47.67	161.82	288.98	895.47	532.77	435.80
17.5	32.50	48.28	175.56	322.98	914.81	529.50	443.57

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 4 Continued

18.0	33.13	48.84	183.48	317.65	866.28	508.29	428.21
18.5	34.06	49.26	180.39	270.40	720.88	446.93	361.32
19.0	34.90	49.87	174.68	240.40	647.29	409.37	315.44
19.5	35.82	50.44	169.09	222.27	591.61	382.25	286.47
20.0	36.91	50.53	163.88	209.16	539.04	360.18	266.32
20.5	38.23	55.38	161.11	203.79	485.99	342.07	252.15
21.0	40.02	64.19	187.94	245.63	469.07	327.15	241.36
21.5	40.77	68.12	238.62	306.23	475.00	314.39	231.18
22.0	42.44	73.09	276.57	340.33	500.83	303.43	222.07
22.5	42.03	66.76	155.24	125.63	483.20	367.01	378.03
23.0	42.52	66.12	145.57	126.83	506.26	416.16	413.41
23.5	43.95	65.62	136.92	132.32	490.68	445.15	409.06
24.0	45.27	65.05	129.82	145.54	504.16	465.94	419.12
24.5	45.42	64.63	124.34	166.15	502.03	477.43	427.01
25.0	45.77	64.45	119.51	168.18	495.66	488.35	438.58
25.5	46.02	64.37	115.47	174.01	492.46	496.21	446.23
26.0	45.63	64.31	112.18	181.27	515.16	504.99	456.39
26.5	45.71	64.35	109.36	191.73	545.05	509.48	463.31
27.0	45.53	64.41	109.00	266.01	538.30	514.37	465.98
27.5	45.59	64.83	111.53	438.54	540.75	508.79	457.06
28.0	44.56	65.58	113.36	457.34	548.97	492.35	436.84
28.5	45.06	53.19	83.62	115.59	567.73	437.55	427.76
29.0	44.54	52.01	81.59	117.38	617.78	441.38	431.74
29.5	43.96	50.65	79.55	111.93	673.56	444.14	439.21
30.0	43.90	49.49	77.72	106.62	727.75	448.74	446.07
30.5	43.81	49.11	77.59	126.40	756.55	454.45	450.48
31.0	48.87	55.96	99.45	412.53	774.35	426.12	410.16
31.5	48.18	53.91	99.01	429.01	828.11	425.25	411.17
32.0	47.59	54.00	97.67	430.73	834.17	429.11	416.57
32.5	47.17	53.59	96.89	431.32	824.17	434.06	423.68
33.0	46.94	53.50	95.25	434.03	846.96	439.84	430.25
33.5	47.47	55.49	94.21	442.12	868.06	448.85	438.96
34.0	47.56	55.76	96.25	448.06	854.37	454.38	445.38
34.5	47.44	54.38	98.19	432.73	865.11	459.26	453.48
35.0	47.27	53.88	98.93	408.06	847.57	449.19	427.05
35.5	47.47	54.35	99.20	372.26	749.66	421.02	370.92
36.0	49.69	56.44	110.64	355.16	692.06	402.91	337.56
36.5	54.15	57.50	125.20	311.55	623.04	389.08	315.27

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 4 Continued

37.0	51.08	54.97	97.12	170.97	627.58	357.38	331.51
37.5	51.87	54.55	93.06	168.95	615.00	379.59	375.03
38.0	52.02	53.69	93.33	175.15	594.15	395.16	392.73
38.5	53.99	54.62	107.46	269.64	579.21	405.81	398.99
39.0	58.66	58.50	125.74	447.35	527.71	410.19	399.59
39.5	60.12	60.13	117.69	393.16	487.39	409.31	397.81
40.0	66.67	72.01	128.81	358.34	465.79	405.66	394.91
40.5	72.01	80.86	133.86	324.10	467.03	400.86	390.76
41.0	71.74	79.44	121.48	340.76	490.93	396.81	388.49
41.5	73.80	80.35	112.33	296.92	522.61	393.86	387.33
42.0	84.25	90.69	113.32	280.98	557.00	392.53	389.24
42.5	104.03	109.65	129.65	268.53	578.84	392.56	391.21
43.0	133.60	137.66	158.22	304.13	596.89	391.50	391.39
43.5	141.43	150.30	172.31	316.60	617.49	390.21	392.43
44.0	148.42	156.37	176.16	325.36	696.16	393.72	396.45
44.5	149.74	157.86	176.35	331.78	776.28	401.38	401.53
45.0	143.55	152.73	172.76	317.87	828.21	412.53	409.43
45.5	137.44	146.42	167.31	304.82	863.08	421.43	418.52
46.0	132.68	140.69	162.48	299.31	898.33	429.90	427.07
46.5	130.72	139.22	162.06	297.01	916.25	437.25	434.67
47.0	128.66	137.48	160.27	295.53	912.94	441.05	442.93
47.5	126.38	134.74	158.31	295.38	904.40	452.89	452.19
48.0	124.40	132.27	156.36	304.59	889.62	467.83	464.87
48.5	122.92	130.87	154.88	300.52	893.58	477.18	483.53
49.0	122.19	130.36	154.64	295.26	890.72	482.94	499.30
49.5	122.39	131.04	155.12	297.46	890.95	489.35	512.94
50.0	121.48	129.59	153.46	292.17	894.40	503.74	524.29
50.5	121.83	129.93	153.86	294.37	908.98	512.17	537.25
51.0	123.38	132.41	156.49	302.80	908.14	519.12	543.97
51.5	123.67	134.13	158.84	303.38	909.79	525.40	546.82
52.0	122.60	133.93	164.09	299.96	922.68	534.69	548.07
52.5	121.95	134.53	169.95	298.89	926.29	540.94	552.68
53.0	121.53	136.43	173.94	297.49	927.88	547.55	560.32
53.5	121.35	139.69	177.00	294.50	938.76	552.66	561.91
54.0	120.49	140.23	178.03	294.57	951.49	553.71	560.74
54.5	119.86	140.35	177.66	294.31	948.48	550.15	557.09
55.0	119.18	139.82	175.25	292.82	942.38	555.70	553.39
55.5	118.72	138.10	172.47	290.48	932.30	557.43	552.33

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 4 Continued

56.0	118.37	137.30	169.44	287.91	916.77	568.32	546.20
56.5	117.53	136.10	167.36	284.56	887.11	565.29	529.24
57.0	117.34	134.72	166.34	282.22	846.08	554.17	516.51
57.5	115.70	133.96	164.77	280.61	763.91	555.78	509.81
58.0	116.11	132.10	161.18	277.43	688.15	558.48	502.77
58.5	116.70	132.26	159.65	273.79	624.54	546.94	497.36
59.0	115.81	132.09	158.84	270.91	573.27	536.30	492.06
59.5	114.99	131.53	157.76	268.77	523.01	533.44	487.22
60.0	113.47	130.18	155.41	266.64	469.42	548.92	483.77
Average Temperature	66.11	76.80	119.35	246.07	605.36	411.63	369.90

Appendix 5 Temperature profile recorded for 50:50 of OPF to SCB ratio

Time (min)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)	T6 (°C)	T7 (°C)
0.0	27.97	28.31	28.31	69.81	53.31	29.10	28.75
0.5	27.96	28.30	28.33	59.16	47.08	29.94	29.68
1.0	27.97	28.31	28.43	61.78	47.33	34.49	34.12
1.5	27.97	28.31	28.59	90.88	60.02	51.69	41.56
2.0	27.98	28.32	29.85	75.30	79.81	73.92	54.02
2.5	28.00	28.33	33.17	137.37	90.93	84.13	69.30
3.0	28.01	28.35	58.19	367.83	139.13	93.41	87.59
3.5	28.02	28.38	76.02	436.15	260.57	120.50	119.10
4.0	28.04	28.47	79.90	481.83	471.24	173.93	159.00
4.5	28.05	29.00	81.95	509.76	620.59	226.28	193.30
5.0	28.06	31.90	82.93	520.25	765.11	262.41	222.35
5.5	28.08	41.92	82.51	538.69	883.38	303.27	245.59
6.0	28.12	57.56	82.86	499.77	809.10	357.21	258.57
6.5	28.24	68.45	83.19	459.16	687.97	375.25	259.55
7.0	29.06	72.57	87.23	448.64	621.02	378.48	263.96
7.5	34.26	74.51	92.16	414.68	566.61	383.99	261.79
8.0	45.78	76.16	100.70	387.80	537.23	414.38	267.66
8.5	55.62	77.74	117.42	379.64	529.67	437.84	294.73
9.0	53.25	64.91	101.78	331.34	634.31	409.11	343.15
9.5	56.35	65.75	99.25	329.54	697.90	412.81	352.93
10.0	57.19	66.42	100.11	331.00	763.98	416.63	350.52
10.5	58.72	67.82	103.36	336.76	843.90	426.77	352.23
11.0	59.24	69.01	108.67	341.41	815.62	436.05	356.95
11.5	55.78	69.56	115.84	341.08	786.44	437.81	360.29
12.0	55.83	68.93	123.11	347.79	741.27	431.98	363.33
12.5	54.65	69.54	129.81	320.01	619.94	388.65	317.00
13.0	52.42	70.33	132.29	294.84	539.83	357.90	282.84
13.5	47.58	68.44	130.90	259.13	488.01	337.23	260.11
14.0	46.04	62.79	123.68	223.92	461.32	325.76	248.39
14.5	44.86	59.19	116.50	196.64	560.64	356.63	298.45
15.0	43.66	56.36	110.11	187.43	615.35	385.02	348.36
15.5	42.52	54.05	104.64	215.00	684.36	405.06	374.57
16.0	41.72	52.25	100.46	281.84	708.01	408.34	383.16
16.5	41.14	51.06	97.29	350.05	768.26	412.74	387.99
17.0	41.01	50.66	94.79	411.89	841.20	418.76	393.52
17.5	41.31	50.76	92.40	439.24	847.07	431.61	399.84

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 5 Continued

18.0	41.59	51.14	90.40	436.83	810.87	449.05	408.00
18.5	41.82	51.61	88.81	440.24	739.62	460.51	417.59
19.0	42.38	52.30	87.61	403.53	627.12	427.93	373.18
19.5	43.44	53.23	86.59	367.96	541.97	390.31	324.13
20.0	47.99	53.66	106.50	215.02	543.13	383.13	318.79
20.5	47.45	53.15	121.29	227.30	697.14	424.29	367.81
21.0	48.03	52.38	152.38	238.38	747.67	447.31	397.90
21.5	50.15	51.64	202.47	269.46	802.34	468.89	408.01
22.0	53.34	51.91	257.65	307.41	832.18	483.41	407.83
22.5	55.90	53.61	303.03	330.91	839.48	485.73	410.80
23.0	57.23	56.37	324.04	333.49	818.65	477.68	417.29
23.5	56.31	56.74	318.73	321.89	764.58	472.94	425.38
24.0	55.09	55.97	318.91	322.44	696.88	467.25	433.26
24.5	54.48	57.73	325.11	332.98	641.60	472.53	446.08
25.0	54.61	57.07	333.25	329.23	612.95	475.15	461.84
25.5	55.27	58.17	348.58	329.40	594.02	479.72	472.44
26.0	56.85	61.08	368.10	322.41	564.04	488.37	480.74
26.5	58.17	62.87	370.26	310.02	544.58	491.98	484.06
27.0	59.12	64.17	370.94	307.17	521.24	502.43	482.02
27.5	61.45	69.41	384.20	305.22	491.92	513.82	481.70
28.0	63.78	73.11	401.18	302.20	470.37	537.02	487.60
28.5	65.12	74.41	411.51	305.89	458.53	557.32	500.63
29.0	64.98	72.37	388.98	332.02	478.28	562.95	504.11
29.5	64.57	70.65	358.99	328.64	475.76	591.92	539.84
30.0	63.89	69.14	335.33	316.27	466.77	609.40	572.48
Average Temperature	46.89	56.44	167.36	325.23	591.15	385.84	334.80

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 6 Temperature profile recorded for 20:80 of OPF to SCB ratio

Time (min)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)	T6 (°C)	T7 (°C)
0	44.23	41.19	56.00	128.67	302.49	235.20	90.81
0.5	44.51	41.35	55.93	128.64	303.43	234.54	90.52
1.0	44.91	41.79	55.83	126.96	339.88	264.56	155.56
1.5	44.89	42.26	57.85	242.85	362.63	305.16	252.86
2.0	44.88	42.60	61.19	278.79	348.68	334.56	299.65
2.5	45.08	43.01	61.89	334.57	529.81	366.00	314.51
3.0	45.59	43.54	62.85	422.60	718.68	382.75	329.82
3.5	46.60	44.22	64.81	433.37	826.13	376.51	335.37
4.0	48.02	45.09	66.75	430.01	840.13	395.42	338.29
4.5	49.71	45.99	68.58	417.34	826.36	437.53	342.68
5.0	51.13	46.82	70.25	396.10	713.77	413.82	328.73
5.5	52.10	47.55	73.39	350.57	577.60	375.69	287.44
6.0	52.31	48.00	73.48	295.70	508.08	349.38	251.60
6.5	51.70	48.22	75.31	275.75	540.55	354.31	277.57
7.0	51.36	49.24	78.15	333.41	675.87	374.89	331.21
7.5	51.19	51.58	79.65	353.46	750.74	372.20	333.96
8.0	51.08	53.74	80.75	305.03	623.51	355.10	297.33
8.5	50.61	53.56	81.36	257.32	539.46	341.07	265.62
9.0	50.84	54.21	79.74	214.48	470.43	364.53	306.92
9.5	51.35	54.65	79.74	216.62	575.33	382.92	341.72
10.0	52.21	55.08	80.80	224.07	828.11	388.16	357.22
10.5	52.87	55.49	82.02	228.03	825.30	381.46	343.95
11.0	52.90	55.83	82.81	221.28	669.59	362.33	303.79
11.5	52.98	56.19	84.61	213.19	594.44	348.22	273.16
12.0	55.65	56.79	85.53	205.57	549.68	336.65	248.20
12.5	58.95	57.84	85.31	196.85	520.07	325.24	227.73
13.0	59.83	58.39	84.50	193.38	497.30	316.59	213.41
13.5	59.03	58.03	82.45	233.13	516.00	359.29	335.89
14.0	58.52	57.73	82.11	287.76	622.20	383.36	379.05
14.5	57.85	57.34	81.42	331.80	833.67	405.24	402.11
15.0	57.66	57.12	80.28	385.29	889.43	425.22	413.07
15.5	57.73	57.07	78.73	426.94	903.54	434.30	412.72
16.0	57.75	56.99	77.26	465.79	802.23	442.96	410.27
16.5	57.47	56.92	76.03	485.43	733.30	456.76	407.66
17.0	57.38	56.74	75.06	506.54	687.23	505.34	430.10

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 6 Continued

17.5	57.44	56.79	74.34	526.62	657.48	551.79	497.07
18.0	57.40	56.83	73.87	557.43	625.83	582.01	549.81
18.5	57.29	56.73	73.80	602.24	601.60	632.03	612.98
19.0	57.36	56.62	73.87	598.41	579.54	640.82	617.50
19.5	57.60	56.71	74.03	577.18	557.66	640.64	608.58
20.0	58.14	56.80	74.72	561.42	535.46	636.69	583.39
Average Temperature	54.15	53.32	76.18	349.26	635.08	414.28	355.00

Appendix 7 Temperature profile recorded for 100% OPF

Time (min)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)	T6 (°C)	T7 (°C)
0.0	28.00	28.00	27.90	34.20	34.10	63.20	51.50
2.0	28.00	28.00	28.00	35.30	71.80	139.90	80.50
4.0	28.10	28.10	28.10	34.60	372.60	185.00	92.70
6.0	28.10	28.10	28.10	36.80	490.70	225.00	115.20
8.0	28.10	28.10	31.60	87.10	686.80	371.80	260.10
10.0	28.10	28.10	32.50	66.60	754.40	412.30	319.70
12.0	28.10	28.10	38.00	69.50	731.80	433.70	355.30
14.0	28.10	28.10	41.20	174.40	765.70	515.40	423.20
16.0	28.20	28.10	48.10	196.10	823.10	495.50	424.80
18.0	28.20	28.20	50.90	147.80	811.20	491.70	426.10
20.0	28.30	28.30	53.10	312.60	829.50	491.80	427.70
22.0	28.40	28.20	51.70	217.90	808.90	490.60	432.00
24.0	146.50	153.30	181.50	496.90	847.60	523.20	475.40
26.0	136.80	146.30	178.80	485.50	966.50	620.90	587.90
28.0	136.00	146.20	178.30	483.30	1006.00	658.60	634.20
30.0	135.90	147.50	175.70	446.40	768.90	624.80	596.90
Average Temperature	55.81	58.17	73.34	207.81	673.10	421.46	356.45

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 8 Temperature profile recorded for 100% wood

Time (min)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)	T6 (°C)	T7 (°C)
0	30.98	30.60	30.66	36.11	82.10	97.70	135.04
0.5	30.97	30.61	30.68	39.64	83.02	107.08	149.51
1.0	30.97	30.61	30.69	72.34	84.88	125.11	165.37
1.5	30.96	30.62	30.79	129.68	89.12	140.28	184.84
2.0	30.96	30.63	31.29	168.15	98.41	160.59	201.64
2.5	30.96	30.64	32.35	184.70	119.16	189.10	218.82
3.0	30.97	30.64	36.07	169.10	157.89	202.09	234.94
3.5	30.97	30.64	52.64	135.97	211.12	211.00	250.28
4.0	30.97	30.65	57.45	112.13	272.12	222.32	264.40
4.5	30.97	30.66	58.62	130.72	331.03	238.36	280.57
5.0	30.97	30.70	65.27	244.69	394.39	252.01	298.37
5.5	30.97	30.84	65.72	331.74	448.48	268.25	311.04
6.0	30.97	31.10	62.39	309.63	490.67	284.09	320.22
6.5	30.96	31.48	67.97	281.12	527.00	297.14	331.78
7.0	30.97	32.91	69.35	255.16	546.62	312.95	340.53
7.5	30.97	37.32	69.59	263.86	553.59	331.18	344.84
8.0	31.13	40.72	67.67	300.93	561.00	336.33	347.18
8.5	32.50	42.92	66.83	280.10	575.17	342.42	345.71
9.0	35.07	44.92	68.41	301.38	596.88	353.21	347.71
9.5	38.48	47.78	66.40	289.38	615.98	360.84	350.35
10.0	42.57	49.19	66.23	283.07	630.58	367.64	350.86
10.5	46.86	50.24	66.70	320.40	643.12	372.44	351.99
11.0	49.45	53.12	69.96	340.18	651.61	373.35	351.41
11.5	49.75	58.55	71.75	318.86	663.10	377.27	353.50
12.0	48.93	63.80	70.69	340.05	678.54	385.85	356.23
12.5	50.11	64.95	73.86	342.60	694.44	395.17	361.03
13.0	52.75	68.76	79.26	397.86	703.10	401.85	364.21
13.5	55.17	66.27	78.58	354.58	707.79	410.55	368.29
14.0	56.77	68.08	78.67	341.71	704.67	416.61	370.52
14.5	62.63	75.79	83.40	469.74	698.20	416.88	371.48
15.0	65.39	76.00	85.82	444.28	692.78	415.07	371.40
15.5	66.29	76.64	86.81	420.67	691.18	413.21	371.76
16.0	68.08	78.26	92.87	379.65	693.58	413.85	373.08
16.5	66.23	78.51	90.05	364.81	698.69	415.71	373.83
17.0	65.65	77.88	87.70	373.34	705.13	417.02	374.79
17.5	66.51	74.59	85.90	375.81	709.09	417.49	375.05

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 8 Continued

18.0	66.91	71.91	85.01	378.01	709.54	420.59	376.51
18.5	64.66	67.14	82.04	423.40	708.24	421.31	378.03
19.0	63.65	64.59	81.11	392.76	709.72	425.56	380.67
19.5	65.25	64.61	82.92	340.77	717.27	431.73	385.14
20.0	67.17	67.16	83.13	328.89	727.19	435.61	389.29
20.5	68.58	68.34	85.73	361.79	733.63	435.17	390.08
21.0	69.74	69.01	90.12	423.85	737.68	440.20	391.80
21.5	70.13	69.32	91.67	464.49	738.35	446.79	394.75
22.0	70.72	71.25	93.98	548.77	735.38	450.75	398.74
22.5	204.32	215.36	234.30	416.87	764.46	503.36	459.35
23.0	196.93	205.38	224.13	389.92	781.71	500.93	465.34
23.5	190.31	198.59	216.88	376.93	811.04	505.59	477.00
24.0	182.48	190.44	208.94	374.57	844.00	509.91	492.49
24.5	175.92	183.70	202.98	386.56	869.57	531.85	511.61
25.0	169.59	178.43	197.88	389.46	888.11	544.04	538.96
25.5	164.68	174.97	194.88	396.55	916.56	553.39	567.03
26.0	162.32	172.47	193.34	388.10	959.25	566.75	585.06
26.5	158.88	168.46	190.31	384.07	999.62	586.46	609.86
27.0	156.43	165.55	188.63	389.62	1013.74	610.71	661.94
27.5	154.50	163.25	186.18	379.00	1023.84	635.49	706.70
28.0	154.31	163.22	185.84	384.86	1055.66	649.26	742.90
28.5	155.22	163.33	185.61	381.16	1060.00	665.40	758.08
29.0	157.63	165.10	186.93	370.19	1067.81	672.74	764.15
29.5	162.58	169.44	190.54	366.21	1066.18	676.28	782.82
30.0	165.58	171.27	191.46	361.55	1046.08	713.26	788.71
30.5	169.99	175.69	194.68	358.26	1006.43	747.52	742.74
31.0	168.72	175.89	195.01	363.30	964.07	760.22	689.07
31.5	165.55	173.59	194.43	369.89	941.79	780.66	672.80
32.0	162.28	171.08	190.52	343.67	891.34	781.90	653.85
32.5	159.96	168.77	188.66	333.39	853.42	747.97	641.73
33.0	159.37	168.28	188.57	335.49	825.21	733.42	632.70
33.5	157.15	166.96	187.38	340.18	793.31	721.93	623.69
34.0	155.93	165.57	185.51	328.87	762.73	714.48	612.78
34.5	152.80	160.95	180.62	322.86	746.05	699.29	591.11
35.0	151.47	158.81	178.07	310.19	731.69	691.24	579.11
Average Temperature	45.55	48.63	57.51	162.74	338.06	225.03	219.01

Notes:



Highest Temperature



Stable temperature for combustion zone



Complete combustion point (CCP)



Bridging occurrence

Appendix 9 Comparison for the average temperature obtained at T1, T2, T3, T4, T5, T6 and T7 for all experiment

Trials	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)	T6 (°C)	T7 (°C)
80% OPF, 20% wood	74.91	80.78	97.26	232.49	767.43	506.5	442.02
50% OPF, 50% wood	85.49	91.85	106.92	339.09	676.48	461.09	395.95
20% OPF, 80% wood	98.30	105.46	124.68	357.44	625.86	380.96	303.97
80% OPF, 20% SCB	66.11	76.80	119.35	246.07	605.36	411.63	369.90
50% OPF, 50% SCB	46.89	56.44	167.36	325.23	591.15	385.84	334.80
20% OPF, 80% SCB	54.15	53.32	76.18	349.26	635.08	414.28	355.00
100% OPF	55.81	58.17	73.34	207.81	673.10	421.46	356.45
100% wood	45.55	48.63	57.51	162.74	338.06	225.03	213.01