Chapter 5

Co-gasification study of lignite and wood waste

5.1. Introduction

In the view of using lignite as primary fuel, an experimental study of the gasification of lignite with various particle sizes was carried out in a pilot-scale (10 kWe) downdraft type fixed bed gasifier and presented in previous chapter. Several operational issues were faced during gasification of lignite due to high ash content in lignite. One of the major issues observed during lignite gasification was clinker formation. So, reducing the clinker formation is one of the tasks in lignite gasification. The present chapter is focused to address the problems associated with lignite gasification such as clinker formation, ash agglomeration, low heating value of producer gas, etc. by co-gasifying lignite with wood waste.

This chapter includes the gasifier performance on co-gasification of lignite and wood waste. Extensive research is carried out on gasification of either pure biomass or pure coal. However,
there are limited studies reported on the co-gasification of coal and biomass, and there is an apparent lack of fundamental understanding of the interactive effects of coal and biomass during the co-gasification. The coal and biomass are diverse in properties, and hence the mechanism of co-gasification of coal and biomass mixtures is complicated and effect of the mixture ratio on gasification process are unclear and unpredictable [Pan et al., 2000; Pinto et al., 2003; Pinto et al., 2007].

5.2. Literature review – Co-gasification overview

Generally, the types of the coal include anthracite, bituminous, sub-bituminous and lignite, whereas biomass types covers woody plant, herbaceous plants, aquatic plants and manures [Kirubakaran et al., 2009; McKendry, 2002; Higman and Burgt, 2003]. Woody and herbaceous plants type biomasses are more suitable for gasification as they content lower moisture than other species. The properties of coal and biomass are widely different in terms of moisture content, heating value, volatile matter, reactivity, ash content, bulk density, etc. The properties of biomass differ from coal and coke and same are presented in Table 5.1. [Demirbas, 2003; McKendry, 2002; Valero and Uso´n, 2006; Lapuerta et al., 2008].

Biomass properties such as size, shape and structure influences the gasification rate. The rate of gasification reaction depends upon the temperature in the reactor and biomass particle size is one of the factor which controls the reaction temperature [Kirubakaran et al., 2009]. Biomass can be used in form of pallets, however palletizing increases the cost but reduces the size of gasifier. Gasification of biomass with high porosity and larger surface area results in to a gaseous product with uniform compositions.

The individual gasification of coal and biomass offers certain advantages such as cost effectiveness of coal and CO₂ neutrality of biomass. However, gasification of coal and biomass alone suffers from drawbacks like environment pollution problem in case of coal and seasonal availability of biomass coupled with land shortage. Drawback of coal, however, up to certain level can be solved by co-gasification of coal with biomass.
Table 5.1. Key difference in biomass properties compared to coal and coke [Demirbas, 2003; McKendry, 2002; Valero and Uso´n, 2006; Lapuerta et al., 2008].

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Properties (Biomass)</th>
<th>Value</th>
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<tbody>
<tr>
<td>1</td>
<td>Moisture content</td>
<td>Higher</td>
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<td>2</td>
<td>Volatile matter</td>
<td>Higher</td>
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<td>3</td>
<td>Reactivity</td>
<td>Higher</td>
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<td>4</td>
<td>Ash</td>
<td>Lower</td>
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<tr>
<td>5</td>
<td>Alkali content</td>
<td>Higher</td>
</tr>
<tr>
<td>6</td>
<td>Bulk density</td>
<td>Lower</td>
</tr>
<tr>
<td>7</td>
<td>Oxygen and hydrogen content</td>
<td>Higher</td>
</tr>
<tr>
<td>8</td>
<td>Nitrogen content</td>
<td>Lower</td>
</tr>
<tr>
<td>9</td>
<td>Sulfur content</td>
<td>Lower</td>
</tr>
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Some of the researcher have found out that co-gasification of coal having high ash and sulfur contents with wood and biomass is a promising and potential resolving technology [Rizkiana et al., 2014; Yilm et al., 2010; Pinto et al., 2003; Fermin et al., 2009; Koukouzas et al., 2008; Pan et al., 2000; McLendon et al., 2004; Kumabe et al., 2007; Chmielniak and Sciazko, 2003]. Co-gasification of coal and wood or biomass is a clean, cost-effective and a stable process with high thermal efficiency. It has been reported that gasification of coal with high ash and sulfur content leads to certain operational problems and reduces the system life due to erosion and corrosion [Luque and Speight, 2015]. However, adverse effect of gasification of coal with high ash and sulfur content may be reduced by co-gasification with biomass or wood.

Co-gasification of coal and biomass have been reported for different reactor system i.e. fixed-bed, fluidized bed, entrain flow gasifiers [Hernández et al., 2010; Koukouzas et al., 2008; Kumabe et al., 2007; Andre´ et al., 2005; Gao et al., 2010; Pinto et al., 2009; Aigner et al., 2011]. Several researchers claim that synergetic effect between coal and biomass results in an improvement in gaseous compositions, gasification efficiency and char reactivity while decreasing the release of tar [Lapuerta et al., 2008; Hernández et al., 2010; Li et al., 2010; Ve´lez et al., 2009; Sjöström et al., 1999; de Jong et al., 1999; Brown et al., 2000; Pan et al., 1996]. Some of the biomass type, especially herbaceous types, contain alkaline materials which act as reasonable catalysts for the co-gasification process [Brown et al., 2000; Zhu et al., 2008].
Properties of coal and biomass are widely different and even all types of coal or biomass are different from each other as far as their properties are concerned. So, in the co-gasification study it is possible to vary the compositions and yield of gas by changing the amounts and properties of the fuel mixture. The properties of fuels could be improved by applying various types of pre-treatment methods prior to thermochemical conversion [Jenkins et al., 1996]. Figure 5.1 shows the steps involved in coal and biomass co-gasification process [Brar et al., 2012].

![Diagram of various steps of coal and biomass co-gasification process](image)

Figure 5.1. Various steps of coal and biomass co-gasification process [Brar et al., 2012].

The following section describe the effect of varying the types of biomass and their relative percentages in the fuel mixture (coal and biomass) on the products of the co-gasification process.
5.3. Literature review – Effect of biomass contents on co-gasification

Biomass type and its contents in the mixture of coal and biomass has a significant effect on different output parameters of gasifier such as gas yield, gas composition, calorific value, cold gas efficiency, carbon conversion, tar yield and release of H₂S and NH₃ [Fermoso et al., 2009; Hernández et al., 2010; Andre´ et al., 2005; Pinto et al., 2009; Aigner et al., 2011; Pinto et al., 2010; Pinto et al., 2007]. However, several researchers found the certain limitations of many biomass types [Pan et al., 2000; Andre´ et al., 2005; Li et al., 2010; Ve´lez et al., 2009; Pinto et al., 2005].

5.3.1. Gas yield

A numerous researchers reported that biomass content significantly influences the gas yield in co-gasification and found the higher gas yield with increase in biomass percentages [Fermoso, 2009; Seo et al., 2010; Pan et al., 2000; Kumabe et al., 2007; Andre´ et al., 2005; Pinto et al., 2009; Sjöström et al., 1999; Fermoso et al., 2009; Pinto et al., Aznar et al., 2006; Fermoso et al., 2010]. They reported that gas yield increases with an increase in biomass content due to various reasons. A one of the reasons to increase of gas yield with an increase of biomass content is higher conversion of fuel during co-gasification [Fermoso et al., 2009; Fermoso, 2009; Fermoso et al., 2010]. One of the co-gasification study of coal and bagasse revealed that as the bagasse content increases, the gas yield increased due to higher concentration of hydrocarbons. Seo et al. (2010) carried out co-gasification study of coal and biomass and highlighted that more decomposition of coal take place as a consequence of transfer of hydrogen radicals from biomass to coal. In addition, they found that gas yield reaches to a maximum value when the fuel mixture consists of 50% of biomass. Pan et al. (2000) investigated the co-gasification of black coal and pine chips. They reported that gas yield increases from 1.8 Nm³/kg to 3.2 Nm³/kg as pine chips content varied from 0 to 80% in fuel mixture. They also reported that co-gasification of Sabero coal with pine chips resulted in to an increase in gas
yield from 0.75 Nm$^3$/kg to 1.75 Nm$^3$/kg as blend ratio of pine chips to Sabero coal varied from 20/80 to 80/20. Pinto et al. (2005) reported that gas yield in coal gasification increases when EOW (edible oil waste) is blended with coal for co-gasification purpose. The increases in gas yield is attributed to higher volatile matter content in the EWO. Another co-gasification study of coal (coke) with biomass (grapevine pruning wastes) was conducted by Lapuerta et al. (2008). In their study, they reported that gas production was higher for co-gasification compared to coal gasification alone because of lower reactivity of coal and less volatile matter than biomass [Pinto et al., 2009].

5.3.2. Gas compositions

$H_2$ concentration (%)

Several researchers investigated the effect of biomass content on the production of hydrogen in co-gasification study [Fermoso et al., 2009; Hernández et al., 2010; Pan et al., 2000; Kumabe et al., 2007; Pinto et al., 2002; McIlveen-Wright et al., 2006; Andre´ et al., 2005; Pinto et al., 2009; Aigner et al., 2011; Li et al., 2010; Pinto et al., 2007; Song et al., 2006; Aznar et al., 2006; Fermoso et al., 2010; Alzate et al., 2009; Fermoso et al., 2012]. Results of some studies are shown in Figure 5.2. The production of hydrogen is somewhat unpredictable during co-gasification as some researchers [Pan et al., 2000; Kumabe et al., 2007; Andre´ et al., 2005; Pinto et al., 2009; Aigner et al., 2011; Pinto et al., 2007; Pinto et al., 2005; Song et al., 2006; Aznar et al., 2006; Fermoso et al., 2010; Fermoso et al., 2012] reported that the production of hydrogen decreases with increase in biomass content in the fuel mixture and vice versa. Production of hydrogen highly depends upon the process temperature. The presence of more volatile matter in biomass leads to reduction in gasification temperature during co-gasification of coal and biomass, and hence reduction in hydrogen production [Andre´ et al., 2005; Ve´lez et al., 2009]. Pinto et al. (2009) (2007) found that the hydrogen content decreased in co-gasification of Puertollano coal with different types of biomass (pine, bagasse, refuse derived fuel) in an atmospheric fluidized bed gasifier as shown in Figure 5.2. With an increase in the pine percentage from 0 to 20%, the concentration of hydrogen decreased from 33% to 29% [Pinto et al., 2007]. Same trend was observed by Andre et al. (2005) for co-gasification of coal with bagasse and pine in a fluidized bed gasifier operated at atmospheric pressure. Pan et al. (2000) stated that the percentages of
biomass in mixture of coal-biomass influenced the hydrogen concentration by means of the dew point of the gasifying agent and solid reactivity. Kumabe et al. (2007) conducted the co-gasification study of Mulia coal and Japanese cedar in an atmospheric downdraft fixed bed gasifier, and they found that hydrogen content decreases from 47.9% to 37.5% as biomass ratio varied from 0 to 1. The experimental study of gasification of coal, wood and their mixtures was carried out by Aigner et al. (2011). They reported that the concentration of hydrogen decreased to 43% from 55% when biomass percentages changed from 0% to 100%. de Jong et al. (2003) claimed that the contents of hydrogen produced during biomass gasification were less than that of coal gasification due to rapid reaction of hydrogen with fuel-O in biomass. They also concluded that higher pressure in the reactor reduces the production of hydrogen.

![Figure 5.2. Effect of biomass content on H₂ production in co-gasification.](image)

On the opposing, some other studies showed an increase in hydrogen composition with an increase in biomass content in co-gasification [Fermoso et al., 2009; Hernández et al., 2010; Li et al., 2010; Fermoso et al., 2010]. Hernández et al. (2010) reported the experimental work on co-gasification of coal (coke) and de-alcoholized grape marc in an atmospheric entrained
flow gasifier. They studied the influence of biomass, temperature and fuel/air ratio and found that the hydrogen concentration increased linearly with an increase in both biomass content and fuel/air ratio as biomass is highly reactive than coal. However, they found synergistic effect between coal (coke) and biomass resulted in to non-linear production of hydrogen when the biomass content and temperature increased. Thus, higher production of hydrogen obtained for 80% biomass and 20% coal (coke) mixture compared to biomass gasification alone. Fermoso et al. (2009) (2010) conducted the co-gasification of coal PT and different types of biomass in fixed bed gasifier operated at 1.5 MPa pressure and reported that upon addition of 10% of various biomass (almond shells, olive stones, eucalyptus, olive pulp or pine sawdust) resulted in to higher production of hydrogen. They also observed the higher percentage of hydrogen for gasification at atmospheric pressure than higher pressure gasification. The higher pressure in the reactor shifted the equilibrium to the side where fewer moles of gas were presented in dry and steam reforming reactions [Fermoso et al., 2009; Fermoso et al., 2010]. The concentration of hydrogen increased to 22% from 17% when biomass ratio varied from 0 to 35% [Li et al., 2010]. It is reported that the gasification of Puertollano coal produced higher amount of hydrogen compared to Colombian coal gasification due to lower release of hydrocarbons. These results show that it was possible to achieve higher amount of hydrogen by changing types of coal and experimental condition such as temperature [Pinto et al., 2009]. Franco et al. (2003) reported higher hydrogen content for the gasification of Holm-oak and of eucalyptus than the pine gasification alone due to water gas shift reaction, which play important role in former two cases. Alzate et al. (2009) reported work on co-gasification of coal and wood pellets in atmospheric fluidized bed gasifier. They found the higher hydrogen content for biomass gasification than co-gasification. They stated that higher percentages of coal in fuel mixture reduced the production of hydrogen due to its consumption in methanation reaction. However, it is also reported that during co-gasification of brown coal with beech wood chips, the hydrogen content increased to 38% from 21% when the brown coal content was increased to 55% from 0% [Vreugdenhil et al., 2009]. Co-gasification of coal, biomass and plastic has been reported by some researchers [Pinto et al., 2002; Pinto et al., 2009; Aznar et al., 2006]. Pinto et al. (2009) observed the more hydrogen production for co-gasification of coal with mixture of 10% polythene and 10% bagasse than coal and bagasse due to fast decomposition of plastic take place as breakage of covalent bonds. Aznar et al. (2006) reported higher amount of hydrogen when using both biomass and plastic wastes for co-gasification with coal in compared to co-gasification of biomass and plastic wastes. Pinto et al. (2002) conducted a co-gasification study.
of pine and plastic waste in a fluidized bed reactor. They observed that the upon addition of plastic waste up to 20% in fuel mixture increased the hydrogen linearly and thereafter any further increment in plastic waste did not affect the production of hydrogen.

The production hydrogen in co-gasification depends upon number of factors such as type of coal and biomass, temperature, pressure, fuel to gasifying agent ratio and most importantly on the volatile matter in fuel which influences the temperature and hence concentration of hydrogen. The higher production of hydrogen can be achieved by increasing temperature or increasing fuel to gasifying agent ratio or lowering the pressure or by changing all of them simultaneously [Emami et al., 2012]. However, very high temperature in the system reduces the hydrogen concentration because of its consumption in methanation reaction that occurs at elevated temperature. Types of coal and biomass are very important as far as production of hydrogen is concerned.

**CO concentration (%)**

Several researchers investigated the effect of biomass content on production of carbon monoxide in co-gasification study and results are presented in Figure 5.3.

Many researchers found that CO concentration in co-gasification is higher than that the produced during coal gasification [Fermoso et al., 2009; Pan et al., 2000; McIlveen-Wright et al., 2006; Andre’ et al., 2005; Pinto et al., 2009; Aigner et al., 2011; Pinto et al., 2007; Pinto et al., 2005; Song et al., 2006]. The reason to increase the CO production is the improvement in Boudouard reaction due to higher reactivity of biomass and charcoal [Hernández et al., 2010; Pan et al., 2000; Fermoso et al., 2010]. The higher production of CO was also reported for biomass gasification than the co-gasification [Hernández et al., 2010; Pan et al., 2000]. Pinto et al. (2009) found that the presence of higher amount of oxygen in biomass lead to more formation of CO during co-gasification. Aigner et al. (2011) reported that by changing wood ratio from 0 to 1, the CO concentration increased from 19% to 28%. Fermoso et al. (2009) (2010) (2012) observed that the addition of different types of biomass (EB, OS, CH) up to 5% resulted in to increases in production of CO. However, they also reported that at higher pressure, the CO production decreased due to a shift in the equilibrium gas phase reactions. On contrary, Li et al. (2010) observed the reverse trend of CO production. This is because of the low fixed carbon content of biomass which resulted in an increase in the steam/fixed carbon ratio and hence CO decreased as it is consumed in the water gas shift reaction.
The effect of coal content on production of CO during co-gasification was also investigated by researchers [Alzate et al., 2009; Vreugdenhil et al., 2009]. Alzate et al. (2009) found that the production of CO decreased as coal content increased up to 20% in the fuel blend. This is due to the consumption of CO during water gas reaction. Further addition of coal in fuel mixture may result in production and consumption of CO by Boudouard and methanation reactions respectively [Vreugdenhil et al., 2009]. However, CO content can be increased by both biomass content and process temperature simultaneously during co-gasification of coal and biomass. Generally, biomass contents high amount of oxygen, which produces more CO₂ and this CO₂ gets converted in to CO via Boudouard reaction by increasing temperature.
CH₄ and other hydrocarbon concentration (%)

CH₄ and other hydrocarbon concentration is also affected by the presence of biomass in the fuel mixture. Numerous researcher have studied the effect of various biomass content and its ratio during the co-gasification with different types of coal on production of methane and other hydrocarbons [Andre´ et al., 2005; Pinto et al., 2009; Aigner et al., 2011]. Pinto et al. (2009) carried out co-gasification study of two types of coal namely Puertollano and Colombian with different type of biomass. Co-gasification of Colombian coal with 10% pine produced higher amount of methane and hydrocarbon compared to pine gasification alone [Pinto et al., 2009]. The result reported by other researchers also showed that the percentages of methane and hydrocarbons were higher for co-gasification than the coal gasification alone [Pan et al., 2000; McIlveen-Wright et al., 2006; Aigner et al., 2011; Pinto et al., 2005; Aznar et al., 2006]. In addition, the production of methane and hydrocarbon increased with increase in biomass percentage in fuel mixture. Aigner et al. (2011) observed that the CH₄ concentration increased from 6% to 10% as biomass ratio varied from 0 to 1. Pinto et al. (2009) reported that the production of methane and hydrocarbons were higher for Colombian coal than Puertollano coal due to the presence of higher amount of carbon and hydrogen in the former fuel. The same trend was observed when both coals were co-gasified with different types of biomass (pine and bagasse). However, reverse trend was observed by Song et al. (2006). They reported that the production of CH₄ decreased for co-gasification of Shenmu coal and rice haulm compared to coal gasification due to lower carbon and hydrogen contents in rice haulm. The co-gasification of coal with pine resulted in to lower percentages of methane and hydrocarbon than co-gasification of coal with bagasse [Pinto et al., 2009], whereas, same amount of these gaseous components were obtained by Andre´ et al. (2005) in a distinct study.

Other researcher [Fermoso et al., 2009; Fermoso et al., 2010; Fermoso et al., 2012] claimed that the CH₄ production remain unchanged by varying the amount of AS, EB, OS and CH in the fuel mixture during co-gasification study in order to compare their results with coal gasification alone. They explained that the CH₄ produced mainly during the pyrolysis step and remained constant due to limited methanation reaction [Lee et al., 2002]. They also stated that the gasification process that take place at higher pressure resulted in to higher amount of CH₄ production due to a shift in the equilibrium. In the co-gasification study of Japanese cedar with Mulia coal, Kumabe et al. (2007) found that the composition of CH₄ (2.6-4.6%), C₂H₆ and C₃H₄ (0.8-2.9%) were independent of the biomass ratio (0-1). Alzate et al. (2009) reported that the CH₄ content increased with addition of coal up to 20% during co-gasification and further
addition of coal resulted in to greater amount of CH₄ production due to the effect of the methanation reaction. The production of methane took place during pyrolysis process and its amount of production depends on the extent of methanation reaction. However, production of methane can be reduced by using the catalyst such as Ni/alumina or alumina or increasing the temperature at which reforming and cracking reactions take place.

**CO₂ concentration (%)**

Figure 5.4 shows the production of CO₂ in co-gasification process in compared to coal and biomass gasification process alone. Pinto et al. (2009) conducted the co-gasification study of various types of coal with biomass and found that the addition of pine or bagasse to coal produced more amount of CO₂ because of higher oxygen content in biomass, as confirmed by another study [Valero and Uso’n, 2006]. Co-gasification of Puertollano coal with 20% pine produced higher amount of CO₂ than pine gasification alone [Pinto et al., 2009]. Fermoso et al. (2009) (2010) (2012) carried out the co-gasification study of coal and biomass at 1.5 MPa and observed that CO₂ production was higher when biomass is added up to 10% in coal, due to the higher reactivity of biomass. They also found that the production of CO₂ was higher at increased pressure due to the presence of fewer moles of gas in the reforming reactions [Fermoso et al., 2009; Fermoso et al., 2010]. The concentration of CO₂ in case of eucalyptus (EB) was higher than for almond shells (AS), olive stones (OS), olive pulp (OP), pine sawdust (PS) and chestnut tree residues (CH). It was also reported that in EB gasification, higher amounts of CO₂ was produced than for pine gasification at different temperatures due to the main role of the water gas shift reaction [Franco et al., 2003]. Fermoso et al. (2012) studied the co-gasification of PT coal and CH and found that the concentration of CO₂ was same as biomass gasification. Other result showed that in co-gasification of coal with biomass (Japanese cedar), the concentration of CO₂ was increased to 33% from 26% when ratio of Japanese cedar varied from zero to one [Kumabe et al., 2007]. In contrary, some researchers have reported lower amount of CO₂ in co-gasification with compared to coal gasification alone [Pan et al., 2000; Pinto et al., 2002; McIlveen-Wright et al., 2006; Pinto et al., 2005; Aznar et al., 2006]. Co-gasification study of pine chips with black coal and Sabero coal revealed that upon addition of biomass, CO₂ concentration slightly reduced due to its consumption in the Boudouard reaction. It was explained that Boudouard reaction easily took place due to higher reactivity of charcoal [Pan et al., 2000]. It was also reported that using Colombian coal instead of Puertollano coal resulted in to low CO₂ formation because of lower oxygen content of Colombian coal [Pinto et al., 2009]. Some authors [Alzate et al., 2009; Vreugdenhil et al., 2009] also presented the study on
co-gasification with the variation of coal contents rather than biomass. Addition of coal up to 20% in fuel mixture increased the concentration of CO\textsubscript{2} by means of water gas shift reaction, however it gets consumed in the Boudouard reaction [Alzate et al., 2009; Vreugdenhil et al., 2009]. The higher production of CO\textsubscript{2} in co-gasification was due to higher contents of oxygen in biomass. However, the production of CO\textsubscript{2} could be reduced by increasing process temperature. The increased temperature in the reactor could lead to the depletion of CO\textsubscript{2} as its consumption in Boudouard reaction and dry reforming reactions [Emami et al., 2012].

Figure 5.4. Effect of biomass content on production of CO\textsubscript{2} during co-gasification.
5.3.3. Calorific value

Calorific value which can be referred as heating value of fuel, is defined as the amount of heat released by burning of fuel. It is measured in units of energy per mass or volume [McKendry, 2002]. The heating value solid fuel, liquid fuel and gas is expressed in terms of MJ/kg, MJ/l and MJ/m$^3$ respectively. Normally two forms of heating value is used, they are HHV (higher heating value) and LHV (lower heating value). The HHV is the total energy released by the fuel while LHV is calculated by subtracting the heat of vaporization of water from the fuel’s HHV. The heating value of gaseous product mainly depends on concentration of combustible components such as CO, H$_2$ and CH$_4$ [McKendry, 2002; Natarajan et al., 1997]. The calorific value of syngas or producer gas is improved with increase in biomass content in fuel mixture as the production of higher hydrocarbons contents [Valero and Uso´n, 2006; Fermoso et al., 2009; Hernández et al., 2010; Seo et al., 2010; Pan et al., 2000; Andre´ et al., 2005; Mastellone et al., 2010; Pinto et al., 2005; Aznar et al., 2006; Fermoso et al., 2010; Alzate et al., 2009]. The gas obtained during co-gasification of AS & EB with coal have maximum HHV when biomass content was 5% [Fermoso et al., 2009]. They have also stated that heating value of gas influences by the system pressure. The heating value (LHV) of gas produced during co-gasification is higher than the coal gasification and lower than the biomass gasification at all temperatures [Hernández et al., 2010]. Seo et al. (2010) have reported the maximum heating value of gas about 14.39 MJ/m$^3$ with 0.5 biomass ratio as a result of maximum gas production. The co-gasification of black coal and Sabero coal with biomass showed a significant improvement in CH$_4$, C$_2$H$_2$ and CO production, hence LHV increases and reaches to maximum values of 4.5 and 4.7 MJ/m$^3$ for 80% of biomass blended in black coal and Sabero coal respectively [Pan et al., 2000]. Also in another set of experiments conducted by Pan et al. (1999), a higher LHV for biomass is obtained than for coal gasification alone. Mastellone et al. (2010) have reported a higher LHV in co-gasification with higher amount of wood content in the fuel mixture. They have also stated that the wood gasification exhibits higher percentages of CO and H$_2$ than the co-gasification. However, lower LHV is also reported by Valero et al. (2006) for co-gasification study and explained that higher oxygen content in biomass increases the CO$_2$ and H$_2$O formation and also decreases the CO formation which consequently reduces the calorific value of gas. In other research work, addition of coal up to 20% in fuel mixture reduces the formation of H$_2$ and CO as well as the HHV. However, higher quantity of coal in fuel mixture produces higher amount of methane and hence HHV increases slightly [Alzate et
al., 2009]. However, it is also reported that the higher amount of coal in fuel mixture results in to gaseous product with lower LHV [Aznar et al., 2006]. Also, the co-gasification work in which the content of plastic is studied, it is observed that when the plastic content is increased, LHV increases because of the presence of more hydrocarbons [Aznar et al., 2006].

5.3.4. Cold gas efficiency

Cold gas efficiency is the ratio of total energy of gaseous products to total energy in coal, biomass or a mixture of them [Higman and Burgt, 2003; Fermoso et al., 2009; 'Hernández et al., 2010; Lee et al., 2002]. Many researcher have observed the enhanced calorific value with the increase in biomass content in various co-gasification processes [Lapuerta et al., 2008; Fermoso et al., 2009; 'Hernández et al., 2010; Seo et al., 2010; Pan et al., 2000; Kumabe et al., 2007; Aigner et al., 2011; Fermoso, 2009; Fermoso et al., 2010]. Fermoso et al. (2009) (2010) and Fermoso (2009) have described that higher amount of biomass in mixture resulted in to high gas yield and subsequently a high HHV and hence increase in cold efficiency. Same trend has been observed by 'Hernández et al. (2010) during co-gasification at different temperature and fuel/air ratio. Kumabe et al. (2007) have investigated the co-gasification of coal and woody biomass and observed the rise in cold gas efficiency from 65% to 85%. Also Aigner et al. (2011) have reported that in co-gasification of coal with wood, cold gas efficiency increased from 48% to 62%. They have explained that the increase in cold gas efficiency was due to higher carbon conversion and mass flow rate of the gas as wood ratio increases. Pan et al. (2000) have investigated the co-gasification of pine chips with Sabero coal and with black coal and found better efficiencies for blending ratio between 40/60 to 60/40 (pine chips/Sabero coal) and 25/75 to 40/60 (pine chips/black coal). Seo et al. (2010) have reported that the value of cold gas efficiency reached a maximum (45%) when biomass added up to 50% in the fuel mixture during co-gasification of Indonesian Tinto coal and Quercus acutissima sawdust. They have also reported the cold gas efficiency for coal and biomass gasification were of 15% and 41% respectively which are low compared to co-gasification. However, no much variation in cold gas efficiency was observed due to lower temperature profile during co-gasification as higher volatile matter contents in the biomass [Valero and Uso´n, 2006].
5.4. Experimental

5.4.1. Wood waste characterization

The objective of this study is to investigate the co-gasification of wood waste with lignite. More specifically, the influence of the mixture ratio on the clinker formation, cold gas efficiency, heating value and composition of producer gas, specific gas yield, feedstock consumption rate and temperature profile in various zone are considered.

The reasons to choose the wood waste as additive of supplemental fuel are (1) The addition of wood waste to lignite in appropriate proportion can adjust the ash content of the mixtures (2) Mixing wood waste with lignite could offset the adverse effects of ash and sulfur present in lignite, making lignite gasification more feasible (3) Favorable properties for gasification i.e. higher heating value, higher volatile matter, low moisture content, almost zero sulfur (4) It is extensively accepted, more reliable and comprehensively reviewed [Rowell, 1984; Smith, 1986; Sofer and Zabor, 1981] and (5) It is easily available as agricultural or forest residue and can be easily collected at fairly low cost in the remote regions.

Wood waste is collected from the furniture factory for experimental work. The wood specie, Tectona grandis, generally known as teak wood is used to make furniture in the furniture factory. The furniture waste is generally used for direct combustion for thermal applications which results in increased emissions (NOx, SOx and CO2). Use of such waste in co gasification reduces the emissions. The wood waste is sized on the chipping machine in to cubical size (50×50×5 mm). The cubical size of the wood waste is selected in such a way that when lignite particles are blended with wood waste, they wouldn’t segregate and mixture remain uniform in the gasifier during operation due to insignificant difference in the densities. Table 5.2 shows the characteristics of wood.

Before gasification, the samples were prepared with different mixing ratios of lignite and wood. The particle size of lignite and wood is 22-25 mm and 50×50×5 mm respectively. It was decided to terminate the further increase of wood in the fuel-mixture when clinker formation in downdraft gasifier vanishes and same was achieved with 30% wood content. The lignite was
blended with 0%, 10%, 20% and 30% wood waste by weight and stored in a plastic container therefore, it was assumed that the composition and properties of feedstocks did not changed during storage period.

Table 5.2. Characteristic of wood waste.

<table>
<thead>
<tr>
<th>Proximate&lt;sup&gt;a&lt;/sup&gt;</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Volatile matter</td>
<td>75.52</td>
</tr>
<tr>
<td>Ash</td>
<td>0.79</td>
</tr>
<tr>
<td>Moisture</td>
<td>4.02</td>
</tr>
<tr>
<td>Fixed carbon&lt;sup&gt;b&lt;/sup&gt;</td>
<td>19.67</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ultimate</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>45.8</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>6.3</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.4</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.02</td>
</tr>
<tr>
<td>Oxygen&lt;sup&gt;b&lt;/sup&gt;</td>
<td>47.48</td>
</tr>
<tr>
<td>HHV&lt;sup&gt;c&lt;/sup&gt; (MJ kg&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>19.89</td>
</tr>
<tr>
<td>Bulk density (kg m&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>413</td>
</tr>
<tr>
<td>Particle size (mm)</td>
<td>50×50×5</td>
</tr>
</tbody>
</table>

<sup>a</sup> Test method IS 1350 (Part I)-1984  
<sup>b</sup> by difference  
<sup>c</sup> Test method IS 1350 (Part II)-1970

5.4.2. Experimental procedure

Co-gasification of lignite and wood waste have been carried out for evaluation of performance of gasifier. The details regarding experimental set-up and the procedure have been reported earlier in section 3.6 and 3.7. All the experiments have been carried out at atmospheric pressure and using air as gasifying medium.


5.5. Results and discussions

5.5.1. Gasification mechanism

The gasification of mixture of lignite and wood occurs through several steps. When feedstock was loaded in the gasifier, the moisture in the feedstock evaporated and feedstock gets dried (Eq. 5.1). In the next step, the feedstock was pyrolyzed at temperature higher than 200 °C and process products were solid, liquid and gas (Eq. 5.2). Pyrolysis process can be understand better by studying thermal decomposition of material by TGA (Thermogravimetric analysis). Figure 5.5 shows the TGA of lignite and wood. From Figure 5.5, it is evident that main pyrolysis process for both lignite and wood occurs in the range of 200 °C to 400 °C. Afterward, secondary reactions such as water gas shift, methanation, tar cracking and reforming of tar, char gasification with steam took place at higher temperature. The composition of final product was depend on series of complex and competing reactions.

Moist feedstock + Heat → Dry feedstock + H₂O  \hspace{1cm} (5.1)

Feedstock → Solid (char or carbon) + Liquid (tars, heavier hydrocarbons, and water) + Gas (CO₂, H₂O, CO, C₂H₂, C₂H₄, C₂H₆, C₆H₆, etc.)  \hspace{1cm} (5.2)

The reaction rate of the most important gasification reaction depends mainly on pressure and temperature inside the reactor, which is affected by the reactivity of fuel. Furthermore, the reactivity of any fuel depends upon its molecule structure [Lapuerta et al., 2008]. The lignite structure has C-C bonds while wood structure has R-O-R bonds. The C-C bonds in lignite basically derived from its heavy polycyclic aromatic hydrocarbons (PAH’s) content and breaking of this bond requires high activation energy while R-O-R bonds in wood derived from cellulose and lignin content and requires less energy to break up [Lapuerta et al., 2008; Ahmed et al., 2011]. The gasification reaction rate is influenced by the nature of feedstock and addition of wood to lignite can change the reaction rates due to their interactions [Saw and Pan, 2013]. Such interaction between wood and lignite is due to the changes in microstructure, which influences the mass transfer and intrinsic reaction rate [Saw and Pan, 2013]. Therefore, addition of wood to lignite makes gasification reactions more efficient [Lapuerta et al., 2008].
Overall thermal efficiency of the gasifier is greatly influenced by the temperature inside the gasifier at different zones. The temperature profile was measured by a set of type K (Chromel-Alumel) thermocouples installed at different height along the gasifier. As shown in Figure 5.6, the temperatures were measured at different points T1, T2, T3, and T4. The temperature measuring points T1, T2, T3, and T4 were at the height of 1170 mm, 775 mm, 300 mm and 150 mm above the grate respectively. Additionally, the temperature (T5) of producer gas before cooling and temperature (T6) of producer gas after cooling was also measured. Figure 5.7 shows the average gasification temperatures profile inside the gasification system for various wood-lignite ratio. A typical temperature profile during this co-gasification inside the gasifier with time is shown in Figure 5.8.
Different reactions took place in the different zones, as the solids and gases moved in the downward direction in the downdraft gasifier. The feedstock was loaded at temperature T0 - an ambient temperature. The drying of feedstock took place first about 120 °C at T1. Then, the devolatilization or pyrolysis occurred at temperature T2 (about 400 °C). The major products of pyrolysis are solid (char or carbon), liquid (tars, heavier hydrocarbons, and water) and gas (CO₂, H₂O, CO, C₂H₂, C₂H₄, C₃H₆, C₆H₆, etc.). These pyrolysis products were oxidized in oxidation zone at temperature T3 (about 900 °C) and reduced in to producer gas in reduction zone at temperature T4 (about 500 °C). The raw gas was at temperature T5 (about 300 °C) at gasifier exit. The producer gas was cooled down in the water scrubber system located at the exit of the gasifier and cooled gas was entered into first filter at temperature T6 (about 40 °C). From the Figure 5.7, it can be concluded that the feedstock with higher wood content had a higher average temperature profile. Figure 5.7 indicated that the average temperature in oxidation and reduction zone increased by approximately 61 °C and 46 °C respectively when wood content increased from 0 to 30%. This higher temperature was attributed to higher HHV (Higher heating value) [Vélez et al., 2009] and reactivity [Fermoso et al., 2009; Pan et al., 2000; Li et al., 2010]
of wood compared to lignite. In addition, wood contains lower amount of fixed carbon compared to lignite. The amount of gasified carbon decreased as the wood percentage increased. Therefore, the heat required for gasification reactions decreased [Li et al., 2010]. The higher reactivity of wood leads to faster decomposition and generates volatile hydrocarbons, resulting in a high consumption of oxygen, higher temperatures in the oxidation zone and reduction zone. The wood displayed high reactivity with oxygen resulting in higher temperature. The increase in temperature at different gasifier zones with increase in biomass percentages is also reported by other researcher [Li et al., 2010].

![Figure 5.7. Average gasification temperature profile inside the gasification system for co-gasification.](image)

Figure 5.7 indicates the temperatures measured by the set of thermocouples installed at different locations along the height of the gasifier with time. From Figure 5.8 it can be concluded that the temperature in all zones, except drying zone, increased with increase in wood content in mixture. During gasification, the temperature of the drying and pyrolysis zone (upper part of gasifier) increased slowly due to limited heat transfer in upward direction and thermal inertia.
of gasifier. The temperature in the drying zone had no impact of wood content and found almost consistent for all experimental runs. The temperature in drying zone varied from 65 °C to 150 °C. The temperature in pyrolysis zone was in the range of 250-430 °C. It was observed that initially temperature was higher in oxidation zone. It could be due to fact that initially char is burnt resulting in to higher temperature. So, temperature dropped after 20-25 minutes as char consumed and then became steady at 800-900 °C in oxidation zone. The temperature in the reduction zone varied from 450 °C to 600 °C.

![Temperature profile with time in various zone for co-gasification.](image)

**Figure 5.8.** Temperature profile with time in various zone for co-gasification.

### 5.5.3. Fuel consumption

The fuel consumption rate and specific fuel consumption rate for different wood-lignite ratio is shown in Figure 5.9. It is observed that the addition of wood in fuel mixture increases the fuel consumption rate. This could be due to the fact that reactivity of wood is higher than that of lignite. Also the moisture content of the wood is quite less than the same present in lignite. The
lower moisture content requires less energy for drying and may accelerate the pyrolysis [Sheth and Babu, 2009]. The higher reactivity of wood resulted into better conversion into combustible gases. Figure 5.9 indicates that the fuel consumption increased to 11.12 kg/hr from 10.01 kg/hr for the mixture containing 30% of wood with respect to fuel consumption of 100% lignite. The specific fuel consumption was also calculated in kg/kWh using the formula suggested by Karagiannidis (2012) and same was found in the range of 1.56 kg/kWh to 1.81 kg/kWh. The reported values of the specific fuel consumption for biomass gasification is in the range of 1.7-1.9 kg/ kWh which is in line with the present results [Yin et al., 2002; Mansaray et al., 1999].

![Graph showing specific fuel consumption and fuel consumption against W/L ratio](image)

**Figure 5.9. Fuel consumption of various W/L ratio.**

### 5.5.4. Dry gas yield

The gas yield expressed in Nm³/kg of fuel and may be defined as volume of producer gas at standard conditions per mass of feedstock supplied to the system. The gas yield is one of the important parameters which indicate the gasifier performance. Figure 5.10 shows the gas yield
obtained with different wood-lignite ratio. It is observed that gas yield increased with the increase in wood content in mixture. This increase in the gas yield could be due to following two reasons: (1) The increase in wood percentage in the mixture reduces the concentration of heavy tar. This heavy tar are very difficult to gasify and may result in to less gas yield [Kumabe et al., 2007] and (2) The higher wood ratio in mixture increases the temperature in oxidation and reduction zone due to higher reactivity. The literature also supports the fact that the gas yield is strongly influenced by the reactor temperature [Pinto et al., 2002; Rapagnà and Latif, 1997]. The increase in reactor temperature increases the thermal conductivity due to higher reactivity of wood. The higher temperature favors production of gaseous product during pyrolysis and devolatilization. The conversion of char and tar into gas take place at higher temperature through endothermic reactions (Boudouard and steam cracking and reforming reaction) [Luo et al., 2010; André et al., 2005]. Figure 5.10 indicates the gas yield obtained for different wood-lignite ratio is in the range of 2.57 to 2.81 Nm$^3$/kg which is in line with the reported value of gas yield of 2 to 3 Nm$^3$/kg for the various fuels [Martínez et al., 2012; Martínez et al., 2011].

Figure 5.10. Gas yield of various W/L ratio.
5.5.5. Gas composition

Figure 5.11 shows average gas composition of the producer gas for different wood-lignite mixture as a gasifier fuel. The concentration of \( \text{H}_2 \) and \( \text{CO}_2 \) in producer gas was significantly influenced by the increased percentage of wood in the mixture. With an increase in the wood percentage from 0 to 30\%, the concentration of \( \text{H}_2 \) increased from 10.27\% to 12.5\% and concentration of \( \text{CO}_2 \) increased from 12.12\% to 16.01\%. However, the concentration of CO and \( \text{CH}_4 \) was not much affected for different wood-lignite ratio. The content of CO and \( \text{CH}_4 \) was around 18–19\% and 1.49–1.71\% respectively. The trend obtained for CO and \( \text{CH}_4 \) concentration fairly agrees the same reported in the literature [Kumabe et al., 2007]. The increase in \( \text{H}_2 \) composition was mainly due to increase in the temperature in oxidation and reduction zone and synergistic effect between lignite and wood. Increase \( \text{H}_2 \) compound in producer gas with increase in biomass content in a mixture was previously reported for co-gasification study [Fermoso et al., 2009; Lapuerta et al., 2008; Li et al., 2010; Fermoso et al., 2010]. The observed increase in \( \text{CO}_2 \) concentration with wood may be due to two reasons: (1) a higher reactivity of biomass and (2) the main role of the water gas shift reaction [Franco et al., 2003]. The \( \text{CO}_2 \) concentration trend obtained in this work is in line with the same reported in the literature [Valero and Uso’n, 2006; Pinto et al., 2009]. As discussed earlier, the methane content does not significantly vary in the producer gas with different wood-lignite mixture. This may be due to limited methanation reaction [Fermoso et al., 2009]. The production of methane is bound to pyrolysis process. The constant \( \text{CH}_4 \) concentration with wood/biomass content in a fuel blend is also reported in the literature [Fermoso et al., 2009; Kumabe et al., 2007]. Total percentages of combustible products were approximately 30.2–32\% of total product gas.
5.5.6. Producer gas heating value

The effect of the wood content on the heating value of producer gas is shown in Figure 5.12. The trend shows that the heating value (LHV and HHV) increased with increase in wood content and obtained trend was found similar to the producer gas component (H$_2$ & CO$_2$) trend. The increase in the heating value of producer gas could be due to higher concentration of hydrogen and carbon monoxide in the producer gas. The higher LHV of 4.44 MJ/Nm$^3$ and HHV of 4.75 MJ/Nm$^3$ were obtained for the 30/70 wood-lignite ratio. The LHV increased by 6.31% when 30% wood is added to lignite compared to lignite alone.
5.5.7. Cold gas efficiency

The cold gas efficiency is the percentage energy of fuel mix (lignite + wood mixture) converted into cold producer gas. The cold gas efficiency is the ratio of total energy in producer gas to total energy in fuel mix. So, the cold gas efficiency depends upon calorific value of fuel mix, consumption rate of fuel mix, calorific value of producer gas and gas flow rate.

Figure 5.13 represents the cold gas efficiency for different wood-lignite ratio. It is observed that this efficiency increased from 65.78% to 71.65% with increase in wood concentration from 0 to 30% in wood-lignite mixture. The higher efficiency with higher wood content is attributed to higher calorific value of producer gas.
5.5.8. Clinker formation

One of the major problems noticed during the gasification of lignite was the clinker formation. The ash is a by-product of gasification process [Matjie et al., 2006]. Lignite is a heterogeneous material and consist of different types of organic matters (macerals) and inorganic constituents (minerals and organically-associated inorganic elements) [Ward, 2002]. The organic matter primarily consists of carbon, hydrogen and oxygen, and lesser amount of nitrogen and sulfur. The inorganic fraction in lignite is referred to as ash after gasification. The inorganic constituents found in the lignite are of three types (1) organically associated elements (2) inherent minerals closely associated with lignite; and (3) excluded mineral matter that readily separates from lignite [Wang and Massoudi, 2013]. During the gasification, the initiation and controlling of clinker formation depends on the various factors such as the behaviors of the inorganic constituents and organic matter, operating conditions, etc. [Matjie et al., 2006].
The XRF (X-ray fluorescence) analysis of the major compounds present in the ash of each fuel is presented in Table 5.3. Sodium oxide (Na$_2$O), magnesium oxide (MgO), aluminum oxide (Al$_2$O$_3$), silicon dioxide (SiO$_2$), phosphorus pentoxide (P$_2$O$_5$), sulfur trioxide (SO$_3$), potassium oxide (K$_2$O), calcium oxide (CaO), titanium oxide (TiO$_2$) and ferric oxide (Fe$_2$O$_3$) are the major constituents of lignite and wood ash as shown in Table 5.3. The ash fusion behavior depends on the ash composition, specifically the Ca and Fe contents in the lignite [van Dyk et al., 2001]. Clinker is formed when these fluxing elements (Ca, Fe) interact with aluminium silicate present in the lignite and reduce the ash fusion temperature subsequently to form a melt [Matjie et al., 2006]. From Table 5.3, it is clear that lignite ash contains more Ca and Fe as compared to wood ash. When wood is mixed with lignite the overall percentage of ash reduces and so fluxing elements (Ca and Fe) in the ash. These factors minimize clinker formation during co-gasification of lignite and wood.

<table>
<thead>
<tr>
<th>Compound (wt.%)</th>
<th>Lignite</th>
<th>Wood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na$_2$O</td>
<td>0.69</td>
<td>0.441</td>
</tr>
<tr>
<td>MgO</td>
<td>2.627</td>
<td>6.187</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>9.664</td>
<td>33.594</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>17.676</td>
<td>35.787</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>0.237</td>
<td>3.548</td>
</tr>
<tr>
<td>SO$_3$</td>
<td>12.375</td>
<td>2.965</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.126</td>
<td>6.353</td>
</tr>
<tr>
<td>CaO</td>
<td>32.49</td>
<td>3.943</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.318</td>
<td>0.822</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>21.286</td>
<td>4.395</td>
</tr>
</tbody>
</table>

5.6. Closure

A mixture of lignite and wood waste was co-gasified in a fixed-bed reactor in order to investigate the effect of mixture ratio on the key parameters of gasification and specifically
clinker formation. The co-gasification of wood mixed with lignite seems to be promising technology and offers certain advantages over lignite gasification. The presence of wood eliminates the major problems such as clinker formation; channel burning associated with lignite gasification and also improves the process efficiency and heating value.

The following conclusions are summarized:

1. The addition of wood to lignite played a great role in reducing clinker formation. The formation of clinkers were reduced as the percentage of wood waste increased and almost vanished when wood percentage reached to 30%.
2. The temperature of oxidation and reduction zone increased with increase in wood ratio. With increasing wood waste percentage, the $H_2$ and $CO_2$ composition increased while $CO$ and $CH_4$ compositions were not affected.
3. The cold gas efficiency of gasifier increased to 71.65% from 65.78%.
4. Higher heating value of producer gas increased to 4.75 MJ/Nm$^3$ from 4.45 MJ/Nm$^3$.
5. The specific gas yield increased to 2.81 Nm$^3$/kg from 2.57 Nm$^3$/kg as the wood content varied from 0 to 30%.