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Review

Advances in the HTAG technology and process of biomass

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High Temperature Air/Steam Gasification (HTAG) is a process in which a highly preheated air/steam is utilized as the oxidizer. The HTAG process follows the developments in the High Temperature Air Combustion (HiTAC), which has shown to be superior in energy saving and pollution reduction compared to the conventional combustion technology. The preheated oxidizer provides additional energy into the gasification process that enhances thermal decomposition of the gasified solid feedstock. Consequently, the HTAG increases both the calorific value of the producer gas, and the cold gasification efficiency. In this work, the advantages of the HTAG processes is presented by considering performance influencing parameters that include materials quality, oxidizer type, equivalence ratio (ER), gasification temperature, and bed additives.

Key words: High temperature air/steam gasification (HTAG), biomass gasification, updraft/downdraft gasifier, fluidized bed gasifier.

INTRODUCTION

The development of advanced combustion technologies is a result of the need for quality and competitive products (Ruth, 1998; Long et al., 1978) reduced energy and materials cost (Gielen and Moriguchi, 2002; Polenske and McMichael, 2002; Chan et al., 2005), and is necessary for meeting stringent environmental requirements (Kyoto Protocol). One of the recent advanced combustion technologies is the High Temperature Air Combustion (HiTAC). This technology is also referred to as mild combustion, colourless combustion, flameless combustion, excess enthalpy combustion or distributed combustion. Advantages of the HiTAC technology compared to conventional combustion include: up to 30% energy savings, equipment downsizing about 20%, and 50% pollution reduction (Tshuji et al., 2002).

High temperature air combustion takes place under moderate and intense oxygen dilution of up to 3%, which is achieved by high flue gas and heat recirculation rates. Achieving flame stability in the HiTAC condition requires a careful control of the auto ignition process, which is mainly a function of mixture (species concentration, flow velocity, flow field) and temperature (Wünning and Wünning, 1997). At higher flue gas recirculation rates, a region of stable combustion is experienced at higher temperatures. Particularly, temperatures in excess of 1,400 K must be obtained to achieve stable conditions for all air/fuel rates. However, temperatures in the region of about 1,000 K mixtures twice as rich as the stoichiometric C/O ratio are high enough to sustain stable combustion (Joannon et al., 2005).

Regenerative burners or recuperative burners are utilized to recirculate the flue gas and heat. Effectiveness of the generator or recuperator is based on its ability to withstand the harsh and high temperature gas while at the same time achieving acceptable heat exchange efficiency. Widely used are the honeycomb regenerators made of ceramic materials such as Al_2O_3/SiO_2. Honeycomb regenerators have a larger heat exchange surface area per unit cross section area. Consequently, their heat exchange efficiency is more than 85%, which is two-fold larger than those of conventional recuperator systems (Suzukawa et al., 1997; Nishimura et al., 1997; Rafidi and Blasiak, 2005). They can preheat the combustion air up to 50^{o} below the furnace operating temperature. On the other hand, recuperative burners can only preheat the combustion air up to 600ºC (Nicholson, 1983; Taylor and Wadkin, 1986).

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Performance studies on the HiTAC reveal enhanced temperature and heat flux uniformity over larger furnace volume coupled with low combustion intensity (Blasiak et al., 2004; Rafidi and Blasiak, 2006; Tiwari et al., 2005), which are key parameters for improved furnace performance and for low thermal NOx emissions respectively.

Nishimura et al. (1997) reported a test result of a regenerative type HiTAC burner that achieved low NOx emissions while saving 55% fuel energy at a forge plant. The work of Suphansomboon et al. (2004) showed that HiTAC could effectively utilize low calorific value gas fuel from incineration plants for improving the plant's emission performance and thereby reducing energy consumption. Similarly, research carried out at the Royal Institute of Technology (KTH) in Sweden has shown promising results in the application of the HiTAC technology in biomass gasification. In the process known as High Temperature Air/Steam Gasification (HTAG), high temperature air/steam is utilized as the oxidizer in gasification. The highly preheated air/steam provides additional energy into the gasification process that enhances thermal decomposition of the gasified solid feedstock. HTAG increases calorific value of the producer gas, increases cold gasification efficiency and specific gas production rate.

GASIFICATION TECHNOLOGY

Biomass gasification produces synthesis gas through thermochemical conversion of biomass. Its advances to date are history long but renewed interest as a source of renewable energy is formidable. The renewed interest in biomass gasification is a result of their potential to increase in biomass to-power (electricity) conversion efficiency. While the direct combustion with a conventional Rankine cycle reaches efficiency of about 30%, integrated gasification combined cycle can attain efficiency of up to 50% (Bridgwater, 1995). Furthermore, gasification produces a clean burning fuel gas that can be used with new or retrofit gas burners. The gas is easily transported in pipelines and can be used in the production of fine chemicals, liquid fuels or fertilizers. Other attractiveness of the biomass gasification technology is from the fact that the gasification process and temperature can be controlled to as low as 600 – 650°C. This prevents sintering and agglomeration of the ash that causes operation problems in combustion processes.

The current large scale development of biomass gasification is mainly an output of the Bioenergy Agreements number 1 – 11, whose tasks were carried out since 1970s under the aegis of the International Energy Agency – IEA (Brown, 1993; Babu and Whaley, 1992). The agreements involved 14 countries and their objectives were to encourage cooperative research, development and demonstration activities in new technologies that will enable more efficient use and increased utilization of alternatives to oil. Biomass gasification was c arried out under task number 7 and 10 namely biomass conversion, and biomass utilization respectively. Activities under task 7 and 10 therefore promoted further the already existed large scale commercial gasifiers with capacities 20 – 35 MWth for firing kilns and boilers in the countries of Sweden, Finland and the U.S.A. Tasks under the Bioenergy Agreement translated further into implementing countries' programs that led to the existing rapid development of the gasification technology.

PHYSICAL FACILITIES AND LAYOUT

There are many types of gasifiers with varying schemes for both reactor design and reaction media in a wide range of operating conditions. Generally, gasifiers are commonly classified into fixed bed and fluidized bed. Other gasifier classifications are moving bed, rotary kiln and cyclonic reactor.

Fixed bed gasifiers (Figure 1) are classified further into counter-current (updraft) and co-current (downdraft) gasifiers. On the other hand, fluidized bed gasifiers (Figure 2) are divided into bubbling and circulating gasifiers and can either be pressurized or atmospheric installations. The fluidized bed gasifiers are usually applied for capacities higher than 5 MWth where as fixed bed gasifiers are suitable for small scale ranges.

Typical processes taking place in these gasifiers are drying, pyrolysis, gasification and gas phase reactions. Drying is responsible for evaporating the moisture bound to biomass cell wall. At the bed bottom, air flow meets the hot char first and burns rapidly. Because of the high temperature and excellent conditions of heat and mass transfer, the combustion reaction is so fast that almost all of the oxygen is consumed in this zone. Consequently, the temperature becomes high and meets the demands of pyrolysis process in the next zone. During pyrolysis, volatile matters that contain higher hydrocarbons (C_mH_n) and gas phases that include CO, CO_2, H_2, and CH_4 are formed from the biomass leaving a hot solid carbon (char). Most of fuel gas forms in this pyrolysis zone. A well controlled pyrolysis zone is therefore important in performance of the whole gasification process. Further to the outgoing gasification processes, the gas phase reactions involve gases formed in the first stages. The tar cracks and the char is reduced simultaneously resulting in the production of more CO and H_2. Some C_mH_n also cracks at the same time. The gas phase reactions are dominant at relatively elevated temperatures of about 1000°C required for breaking down the existing higher hydrocarbons and gas phases and to sustain endothermic reactions. Important gasification reactions are shown in equations 1 through 10.

Combustion zone:

$$CH_aO_b + O_2 \rightarrow CO + H_2 + CO_2 + H_2O \quad (1)$$

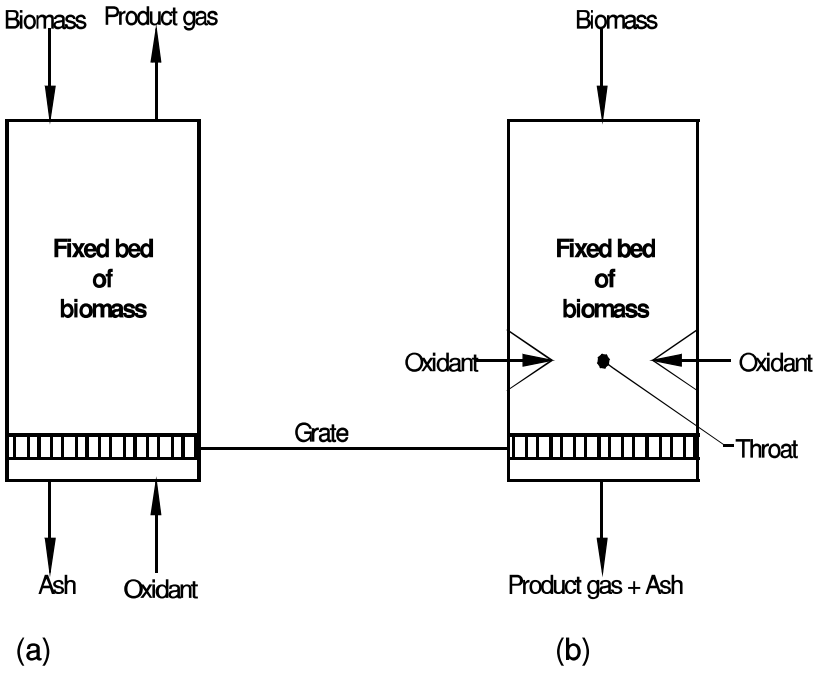


Figure 1. Schematic diagrams of: (a) Updraft, (b) Downdraft gasifiers.

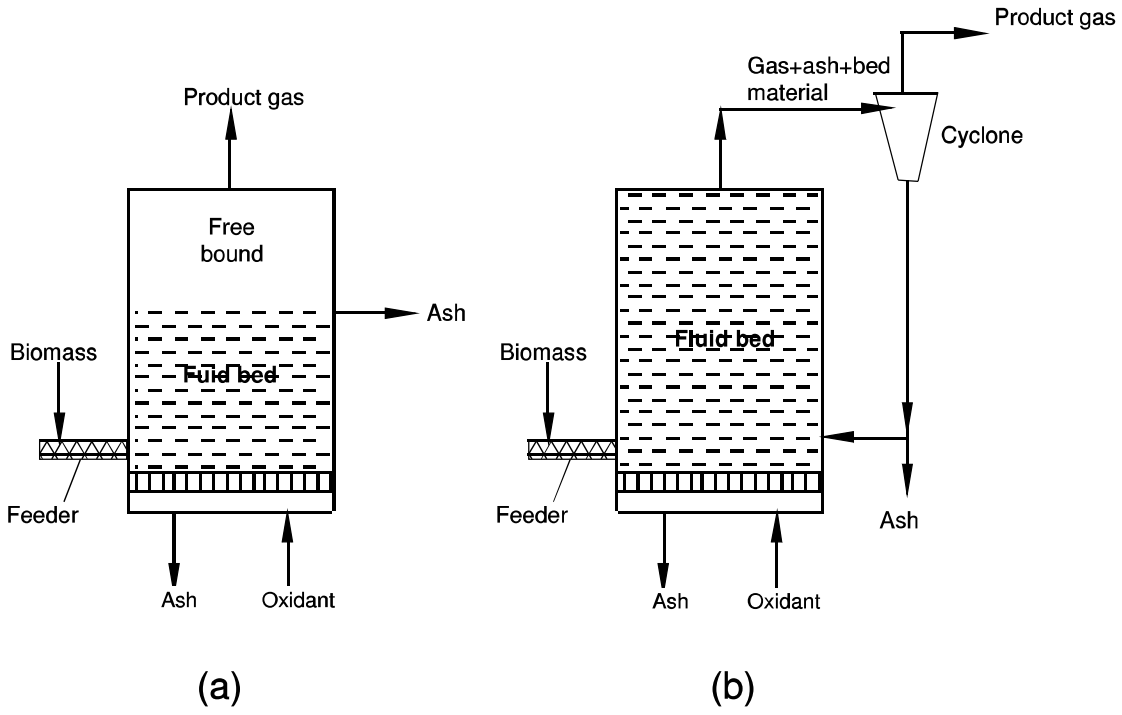


Figure 2. Schematic diagram of: (a) single (bubbling) fluidized bed and (b) circulating fluidized bed gasifiers.

$C + O_2 \rightarrow CO_2$ (2)

$H_2 + O_2 \rightarrow H_2O$ (3)

Pyrolysis:

Biomass $\rightarrow$ char + tar + gases (CO, CO_2, H_2, H_2O, CH_4, C_mH_n) (4)

Where C_mH_n are higher hydrocarbons with m and n > 1

Gas phase reactions (reduction and cracking):

$C + CO_2 \rightarrow CO$ (Boudouard reaction) (5)

$C+H_2O \rightarrow CO+H_2$ (Primary water-gas reaction) (6)

$CO + H_2O \rightarrow CO_2 + H_2$ (Water-gas shift reaction) (7)

$C_xH_y + xH_2O \rightarrow (x+y/2)H_2 + xCO$ (Steam reforming of tars) (8)

$Tar \rightarrow CH_4 + H_2O + C_mH_n + H_2$ (Cracking of tars) (9)

$C_xH_y + xCO_2 \rightarrow (y/2)H_2 + 2xCO$ (Dry reforming of tars) (10)

Updraft and downdraft gasifiers

Counter-current gasifier is a vertical reactor where the feedstock enters from the top and the gasifying media (air, oxygen, steam) enters from the bottom. The raw gas rises inside the reactor bed and leaves at the top section, hence the designation updraft gasifier. The counter-current gasifiers can handle feedstocks with high ash and moisture content and they do not require any special feedstock preparation, thus gasifying a wide range of biomass types (Spliethoff, 2001). Through forced convection, the gas heated by oxidation in a bottom zone rises and transfer heat to the fuel. The gas leaves the gasifier with relatively low temperature, which indicates its high gasification efficiency. However, the volatile matters produced in the pyrolysis zone are carried in the rising gas stream leading to its high tar content. Consequently, the gas is best suited for close coupling to a firebox for direct burning.

In co-current (downdraft) gasifiers, feedstock and gasifying media move in the downward direction. Drying and pyrolysis stages take place in upper zones, resulting solids proceed downward to the hot oxidation zone where they are transformed into char and ash, and latter falling into the reduction zone at the bottom. The gases produced in the pyrolysis zone are heated to over 1000°C on reaching oxidation zone. As a result, high-tar gas phases are thermally cracked into simple gas phases which react with char in the reduction zone and thereby producing more gases. In contrast to the counter-current gasifier, the heat transfer between feedstock and gasifying media is low as indicated by the high tempera-ture of the raw product gas. However, the product gas is clean enough to be utilized in small-scale electricity generation with internal combustion engine. The physical limitation of its diameter and feedstock particle size limits the use of practical higher capacity engine configurations with this type.

Fluidized bed gasifiers (FBG)

In this gasification technology most of the conversion of feedstock to product gas takes place in a bed of inert material (fluidizing material), which is usually of silica sand, alumina or refractory oxide. The presence of fluidizing material enhances high rates of heat and mass transfer and good mixing of the solid phase. These features lead to high reaction rates. The bed temperature can also be controlled into isothermal conditions. Despite of the requirement of relatively small particle size feed-stock, FBG have better performance and their high volumetric capacity allows scaling up to higher capacities.

The fluidizing velocity in the circulating fluidized bed gasifier (CFBG) is high enough to entrain large amounts of solids with the product gas. The recycling of entrained materials improves the carbon conversion efficiency compared to the bubbling fluidized bed gasifiers. In other types of fluidized bed gasifiers, no inert material is present but a finely reduced feedstock is entrained. They operate at relatively higher temperatures, and hence the product gas has low concentrations of tar and condensable gases.

PERFORMANCE INFLUENCING PARAMETERS

Performance of the high temperature air/steam gasifier is compared to the conventional low temperature counterparts by considering the main performance influencing parameters and the respective output parameters. Performance influencing parameters include: materials quality (type, size, moisture, mineral matter content); oxidizer type (air, steam, oxygen); equivalence ratio (ER); gasification temperature; and bed additives (catalysts). On the other hand, gasifiers output performance parameters forming bases for the comparative are: carbon conversion efficiency, yield and product gas composition, product gas quality (tar, particulate dust), and product gas calorific value.

Materials quality

The biomass feedstock utilized in biomass gasification has varied characteristics in terms of composition and size. While composition is mainly dominated by biomass species, geographical location and harvesting, feedstock size is determined by processing technique or knife setting.

Feedstock type and composition

Plant materials have different composition of cellulose, hemicellulose and lignin. The difference in these components influence the gasification yield and product gas composition. Hanaoka et al. (2005) investigated the gasification of cellulose, xylan, lignin, Japanese oak and Ja-

panese pine bark. Cellulose, xylan and lignin represented the model compounds of woody biomass while Japanese oak and Japanese pine bark are typical woody biomass. It was observed that carbon conversion in cellulose and xylan were much higher (97.9 and 92.2% respectively), compared to lignin (52.8%). In contrary, the carbon distribution to the char and carbon loss in lignin were much higher than respective values in cellulose and xylan.

The Hanaoka work further indicated that the product gas obtained in the air-steam gasification of Japanese oak was 39.9 mol% CO, 23.4 mol% CO_2, and 22 mol% H_2 and was similar to that of cellulose, while the respecttive gas composition from the Japanese red pine bark was 25.6 mol% CO, 34.7 mol% CO_2, and 31 mol% H_2, which was similar to that of lignin. Consequently, the gasification of individual constituent has well predicted the product gas composition of the woody biomass.

Thermogravimetric (TG) experiments were also carried out under air or nitrogen flow to study the pyrolysis behavior and the reactivity of individual feedstock and oxygen. Cellulose had higher weight decrease at lower temperatures where as the weight loss of xylan and lignin was almost indistinct. The result suggests that cellulose is mainly gasified due to pyrolysis while xylan and lignin is gasified due to pyrolysis and combustion. Consequently, the TG result suggests that in the gasification of cellulose, the main gasification pathway would be due to pyrolysis where as the gasification pathway of xylan and lignin would be due to pyrolysis and partial oxidation. Accordingly, the difference between the ratio of the pathway due to pyrolysis and that due to partial oxidation would be dependent on the type of feedstock, and would affect the product gas composition in gasification.

Feedstock size

Bridging is an operational problem that occurs in biomass processing equipment. Bridging causes stops in fuel flow in the handling systems due to the formation of stable structures across openings. There are two types of bridges, mechanical bridge and cohesive bridge.

Mechanical bridges are formed by large interlocking particles while cohesive bridges are formed by small particulate solids that continuously deposit on opening surfaces.

It has been shown by Mattsson and Kofman (2002, 2003) and Jensen et al. (2004) that particles longer than 100 mm that are hook shaped or long and thin particles are the main bridging factors. Other factors include harvesting system, storage system and processing system. On the other hand, increasing moisture content usually accentuates the bridging influence. It was proposed that in order to avoid bridging, biomass handling openings should be 10 times longer than the largest particle size. Bridging is an evident factor that limits feedstock size in downdraft gasifiers.

Besides the bridging problems, feedstock particle size can influence product gas yield and gas composition. It has been generally accepted that small particles with approximation of spherical shape are ideal for gasification. By modifying rice straw dimensions from φ 2 x 10 mm to φ 0.132 mm in pyrolysis of rice straw, Chen et al. (2003) found a 12.7% relative increase in gas yield where as an increase of 14% was noted by modifying 10 x 4 x 2 mm sawdust into φ 0.25 mm. Similarly, high temperature air-steam gasification produced similar results (Lucas, 2005; Lv et al., 2004). On reducing particle size from 0.75 to 0.25 mm, Lv et al. (2004) found that gas yield, product gas low heating value, and carbon conversion efficiency increased from 1.53 Nm^3/kg of biomass, 6976 kJ/Nm^3, and 77.62%, to 2.57 Nm^3/kg, 8737 kJ/Nm^3, and 95.10%, respectively. Smaller particles have larger surface area and therefore acquire faster heating rates, which produce more light gases of CH_4, CO, and H_2 while producing less CO_2, tar condensates and char. It can further be explained that for small particle sizes the pyrolysis process is controlled by reaction kinetics. In contrast, since the product gas formed inside the larger biomass particle is slowly diffusing out, the process is mainly controlled by gas diffusion.

Moisture and mineral matter content

Other qualities of biomass feedstock that influence product gas yield and the respective mole ratios include its moisture content and mineral matter content. The effect of biomass feedstock moisture content has been shown to slow the reaction front propagation since its vaporization consumes energy and lowers the reaction temperature (Horttanainen et al., 2000; Saito et al. 2001). In low temperature gasifiers, the moisture content effect is more pronounced. The evaporated moisture dilutes the product gas, which attains low heating value. Furthermore, there is an additional product gas dilution by N_2 from the air used in drying the feedstock. Brammer and Bridgwater (1999) reported that moisture content up to 20 and 50% is acceptable to downdraft gasifiers and updraft gasifiers, respectively. Fluidized bed gasifiers can gasify higher moisture content materials, up to 70% (Faaij et al., 1997). In high temperature gasifiers, the presence of acceptable levels of moisture in biomass feedstock increases combustible gas yield and its heating value. The moisture takes part in the secondary reduction and steam reforming processes that are responsible for the formation of CO and H_2 via equations 6, 7 and 8.

Different biomass feedstocks contain varied proportions of inorganic materials (minerals). Main inorganic materials are alkaline metals (Na, K), alkaline earth metals (Ca, Mg), toxic trace elements of heavy metals (Cu, Zn, CO, Mo, As, Ni, Cr, Pb, Cd, V, Hg) and others like Si, Cl, P and S. It is known that Ca, Mg, Na, K, and P elements are plant nutrients whereas Si, Ca, Mg, K, Na, S, and Cl are the main ash forming elements (Obernberger et al.,

1997; Vamvuka and Zografos, 2004). These elements influence the ash formation, ash melting behavior, as well as process equipment fouling and corrosion. Heavy metals evaporate and form gaseous emissions that are environmental hazards. The presence of N_2, S and Cl is associated with the formation of corrosive compounds of NH_3, H_2SO_4 and HCl, res-pectively, that are the major sources of damage to the process hardware.

Under the reducing environment of gasification the evaporation and transformation of inorganic elements consumes energy that would otherwise be utilized in the carbon conversion process. The overall consequence of increased mineral matter is the reduction of product gas heating value. Mineral matter content of above 20% makes it difficult for the fuel heating value from conventional gasifiers to reach medium heating value required for application in engines and turbines (Chancellor et al., 1981; Faaij et al., 1997).

High temperature steam gasification of biomass has shown the catalysis role played by the presence of alkali metals in biomass feedstocks. Elliot et al. (1984) investigated the effect of alkali (carbonates of Na, K and Cs) catalysts on the low temperature and high tem-perature steam gasification of cellulose, holocellulose Kraft lignin, and Douglas fir. Results showed little effects of alkali catalysts in the devolatilization stages of the respective materials. However, in the char gasification stage they showed both an increased rate and overall carbon conversion efficiency for cellulose, holocellulose Kraft lignin (and little effects to Douglas fir due to its high ash content).

The alkali catalysts enhance the steam reforming of carbon through the primary water gas reaction ($C + H_2O \rightarrow CO + H_2$) that increases yield and product gas heating value. There are also positive physical effects of alkali catalysis in steam gasification. The alkali induces swelling of biomass at high temperatures, which is associated with its effects on physical structure of the char. Swelling increases char surface area available for the gasification reactions.

Chemical pretreatment of rice straw and sawdust was done by Chen et al. (2003) so as to remove alkaline metals of Zn and K and hence investigating its effect under pyrolysis gasification. Removal of the alkaline metals rendered the gasification reaction weaker compared to the control (without removal) situation. A decrease in product gas yield of 3.9 and 1.9% was noted for rice straw and sawdust respectively.

Oxidizer

Gasifiers utilize air, oxygen and or steam as the main oxidizing agent. Gasifier performance in terms of carbon conversion efficiency, product gas composition and heating value vary considerably under different oxidizers. Despite the performance aspects, the choice of oxidizer is also influenced by economic aspects for its use. For instance, use of oxygen and steam requires additional equipments for their supply where as air is abundantly available.

Simple air blown gasifiers will produce a low heating value product gas (4 – 6 MJ/Nm^3) due to dilution by N_2 present in air that takes a lesser extent in the gasification reactions. In order to obtain a product gas with medium heating value of up to 19 MJ/Nm^3, oxygen injection or the use of steam gasification under high temperature conditions is imperative (Bridgwater, 1995). Under these conditions, there is an overall increase in gasification which is also associated with product gas heating value increment.

Equivalence ratio

The equivalence ratio (ER) expresses the variation of the ratio of air (oxidizer) to feedstock e.g. wood. ER is expressed as shown in equation 11 where the numerator is air consumed per unit of dry wood in gasification while the denominator is air consumed per unit of dry wood in complete combustion under stoichiometric conditions.

$$ER = \frac{Weight of\ air / Weight of\ wood}{Stoichiometric\ air / wood\ ratio} \quad (11)$$

The ER has been defined so as to reflect the combined effects of air flow rate, rate of wood supply and run dura - tion. It has therefore reduced the number of parameters on which the performance of biomass gasifiers depends on. The ER enables performance comparison of different gasifiers irrespective of their constructional features like size.

The gas composition of gasifiers is influenced by the ER. Incidentally, there is an optimum value of ER where a balanced value of gas composition against maximum heating value exists (Zainal et al., 2002; Prasad et al., 2004). As the ER represents the quantity of air introduced into the gasifier, high values of the ER increases the amount of oxygen with respect to gasified feedstock. As a result more char is combusted to form CO_2 at the expense of combustible gases of CO, H_2, CH_4 and higher hydrocarbons. More N_2 is also introduced in the gasifier as ER increases, which leads to increased dilution effects. In fluidized bed gasifiers, the effect of increased oxidation and product gas dilution is exaggerated further by increasing fluidization velocity (Mansaray et al., 1999).

The overall effects of increasing ER in steam gasification on gas yield, composition, and heating value is of an increasing trend of combustible gases to a maximum value after which they decrease (Lv et al., 2004). Initially, increased ER plays an important role of increasing gasifier reaction temperature that favors the formation of H_2 and CO through endothermic cracking reactions namely water-gas shift reaction ($CO + H_2O \rightarrow CO_2 + H_2$)

and the primary water-gas reaction ($C + H_2O \rightarrow CO + H_2$).

Temperature

Being a thermochemical process, gasification takes place at elevated temperatures. Thermal energy is necessary for moisture evaporation and the subsequent stages of devolatilization, char gasification and thermocracking processes. After moisture evaporation, biomass feedstock temperature raises to a point where devolatilization proceeds, which is about 200 - 300°C (Chancellor et al., 1981; de Filippis et al., 2004). Drying, devolatilization, and char gasification occurs simultaneously, and particularly a greater portion of char is gasified during the devolatilization stage.

Reaction temperature in air blown downdraft and updraft gasifiers reaches as high as 1000°C with a temperature variation of about 300 - 400°C. Conversely, fluidized bed gasifiers have reaction temperatures of about 850°C with little variation of about 5 - 7°C (Bridgwater, 1995; Mansaray et al., 1999). As indicated by low exit gas temperature (of about 250°C), updraft gasifiers have higher thermal efficiency due to their high heat exchange between products gas and the countercurrent feedstock mass. Downdraft gasifiers exit gas temperature is about 800°C where as fluidized bed gasifiers have exit gas temperatures of close to their reaction temperatures of about 850°C.

Gasifier product gas yield, composition and heating value is largely dependent on the extent to which heat and mass transfer is effectively taking place in the reactor. Studies in the devolatilization process (Chen et al., 2003) have indicated that an increase in the reaction temperature coupled with high heating rates increase gas yield. Besides the fact that the devolatilization process proceeds right after the reaction temperature has been attained, higher heating rates enhance the secondary reactions that result in more gas yield. The effect of high reaction temperature is more pronounced in steam injected gasification process where prevailing endothermic reactions are responsible for producing gas with higher calorific value compared to the simple air blown gasification (Lucas et al., 2004).

Bed additives

Yield of product gas and its quality is mainly influenced by gasifier reactor geometry, feedstock type and quality, residence time, reaction temperature and heating rate. Catalysts can also be deployed in order to enhance favourable reactions that are responsible for producing gas with high calorific value. Catalysis can latter be used to upgrade the product gas into higher quality or into secondary products.

While a variety of catalyst can be adopted for enhancing biomass gasification, the oxides and salts of alkaline (Na, K) and alkaline earth metals (Ca, Mg) have higher potential for their application. Particularly, alkaline metal chlorides such as NaCl and KCl are cheap and effective. The presence of catalysts increases the gasification process rate by positively influencing pro-ducts from gas phase reactions of intermediates. Catalysts are responsible for lowering both the activation energy and the Arrhenius pre-exponential factor of steam reforming as well as the water-gas shift reactions (Rei et al., 1986; Encinar et al., 2001). These reactions are highly endothermic while at the same time are dominant in releasing combustible gases of CO and H_2. Application of catalysts therefore allows these reactions to approach equilibrium conditions even at relatively lower temperatures.

Tars and dust

The presence of tar in producer gas is undesirable since it is associated with condensation that causes blockage in the process equipment and in the engines and turbines used for gas application. It is from this reason that e.g. tar content specification for use in gas engines and turbines is limited to < 100 mg/m^3 and < 5 mg/m^3 respectively (Spliethoff, 2001). Besides the biomass feed properties, the amount and composition of tar is largely dependent on the gasifier and its operating condition. Updraft gasifiers produce the maximum amount of tar, whereas downdraft gasifiers produce the least. In general, the estimation of tar production by updraft gasifiers is around 100 g/m^3 (at STP) while that of fluidized bed and downdraft gasifiers is around 10 and 1g/m^3 respectively (Devi, 2005).

Tar removal methods can be categorized into two types, primary and secondary methods. Primary methods are taken to prevent the tar formation or to convert the tar formed into lighter compounds where as the secondary methods are used to treat product gas from the gasifiers. Primary methods are dependent on setting gasifier operating conditions in such a way that tars are thermocracked into lighter combustible gases. Since thermocracking is effective at temperatures over 700°C, high temperature gasification condition provides part of tar removal solution while simultaneously producing gas with high calorific value.

Conclusion

The HTAG process has shown promising features in terms of product gas yield, gas composition and heating value, and low tar content. The effect of its high reaction temperature is to sustain the gas phase reactions that are dominant at elevated temperatures of over 1000ºC.

While the low temperature gasifiers can process biomass feedstock with moisture content up to 50% only, HTAG can handle higher level of moisture content. The presence of moisture in the HTAG biomass feedstock increases combustible gas yield and its heating value

since the moisture takes part in the secondary reduction and steam reforming reactions that are responsible for the formation of more CO and H_2 gases.

High temperature steam gasification of biomass embraces the catalysis role played by the presence of alkali metals (carbonates of Na, K and Cs). These inorganic materials are involved in the char gasification stage where they have effects of increasing the rate and overall carbon conversion efficiency. Furthermore, the alkali metals induce swelling of biomass at high temperatures. The swelling increases char surface area available for the gasification reactions.

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