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Technical Challenges of Utilizing Biomass Gasification Gas for Power Generation: An Overview

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Abstract

Biomass stores solar energy during its growth by photosynthesis reaction and releases the equivalent amount of energy during its thermochemical conversion. The storage energy in biomass can be effectively utilized for heat and power generation by gasification. However, the commercial application of biomass gasification technology, especially for power generation suffers from a number of technological challenges. In this review, the challenges related to the gasification of biomass to produce clean gas for internal combustion engines and gas turbines are highlighted. Gas cleaning is one of the most challenging issues related to the biomass gasification based power generation. Among the gas impurities, tar is the most problematic one which is difficult to remove to an acceptable range for internal combustion engine or turbine. For running engine or gas turbine for electricity generation, the gasification gas requires to have a specific gas composition with an acceptable range of impurities. A number of gas cleaning methods including physical filtration, thermal cracking and catalytic reforming of tar removal have been developed. However, the most efficient and popular one is yet to be developed for commercial purpose. Based on the literature, the efforts related to tar separation affect burnable gas composition and heating value, which are the most important terms define the overall efficiency of biomass gasification based power generation. In this review different gas cleaning methods will be summarized and highlighted how it affects the gas composition and cold gas efficiency.

Keywords: gasification gas, producer gas, gas cleaning, catalytic gas cleaning, cold gas efficiency

1. Introduction

Biomass gasification can be considered as one of the promising technologies to utilize renewable energy. Biomass includes forest residues such as dead trees and wood chips, agricultural residues, municipal organic wastes, and animal wastes, which are abundantly available all over the world. The advantages of utilizing these biomasses for energy could be accounted as they are carbon neutral and homogeneously distributed all over the world. Thus, the utilization of biomass energy can provide dual benefits: it can reduce carbon dioxide (CO_2) emission as well as it can increase fuel security as it is produced locally. Despite many advantages of biomass energy, it is not being used in commercial scale because of many challenges associated with mostly gas cleaning technologies (Dong et al., 2013; Zhang et al., 2013).

Biomass gasification gas, often termed as producer gas, is a mixture of CO, CO_2, H_2, CH_4 and N_2 along with some C_2 and C_3 hydrocarbon gases. Some impurities such as tar, particles and gases including NH_3, NO_x, SO_x and HCl are also formed during gasification. These impurities create problems in downstream application of producer gas. Among the impurities, tar is the most notorious one, which are chemically polyaromatic hydrocarbons. Under the gasification temperature, it exists as gas, while it condenses under ambient conditions and deposites in the downstream equipments, bloking the narrow pipeline. Particles also cause the blocking and abrasion problem in the engine and turbine. Therefore, for downstream application of producer gas the impurities concentration must be bellow the maximum acceptable range for individual application (Asadullah, 2014).

Different types of gasifier have been developed in order to produce quality gas for downstream applications (Buragohain et al., 2010). Among the gasifiers, down draft, updraft and fluidized bed gasifiers are well developed; however, none of them can produce suitably cleaned gas. Therefore, to keep the reasonable concentration of burnable gas in the producer gas with minimum tar, the secondary filtration or hot gas cleaning of gas is essential.

Simple filtration of the sticky tar blocks the pores of the filter and creates pressure drop. In addition, since tar consists of toxic chemicals, handling and disposing of it is a health and environmental issue. The catalytic hot gas cleaning is the most promising method, which provides multiple advantages such as (1) tar can be almost completely removed (Schmidt et al., 2011), (2) tar can be converted to product gas (Rapagnà et al., 2010) and (3) other contaminants can also be trapped in the catalyst bed. However, the catalyst deactivation due to carbon build up and poisonous gas adsorption on the catalyst surface is often considered as a serious issue.

Efficient catalyst which has perfect redox properties can effectively reform tar to gas as well as can remove the deposited coke like materials by oxidation. Comprehensive researches have been conducted for catalyst development in order to reform tar to gases over the last couple of decades. The tar is a mixture of wide range of aromatic hydrocarbons and their derivatives. In principle, these aromatic hydrocarbons can undergo reforming or cracking reaction on some catalysts to form gaseous products (Xu et al., 2013). At the same time ammonia can also be decomposed on the Fe, Ni and Ru based catalysts (Yin et al., 2004). However, HCl, H_2S and SO_2 do not decompose on the catalyst, instead they are highly soluble in water, and hence they can be separated by water scrubbing (Vaselli et al., 2006).

Different types of catalysts have been proven to be active for tar and ammonia decomposition. The utilization of catalyst in the primary bed is problematic because it deactivates rapidly due to the fouling of ash and carbon on the surface (Barisano et al., 2012). The non-metallic catalysts such as dolomite and olivine show longer activity in the primary bed; however, they are eroded and elutriated from the bed. It is reported that the noble metal catalysts such as rhodium (Rh) can almost completely convert tar and char at unusually low temperatures (500-700 ^{o}C) both in primary and secondary bed reactors (Asadullah et al., 2001a; 2001b; Asadullah et al., 2002a; 2002b; Asadullah, et al., 2003a; Asadullah et al., 3b; Asadullah et al., 2004a; 2004b). However, it was sintered during reaction. The sintering problem was overcome when CeO_2 and Rh was loaded on porous silica sequentially as $Rh/CeO_2/SiO_2$. Nickel based catalysts are widely investigated for tar cracking in the secondary bed reactor (Koike et al., 2013). These catalysts show superior activity for tar destruction; however, the catalysts cannot sustain until desired length of time. Char supported iron catalysts have recently been developed, which have shown superior activity in tar reforming. The tar concentration reduced to bellow 100 mg/Nm^3 (Dong et al., 2013).

From the above study, it can be realized that the cleaning of producer gas is essential and challenging where the catalytic destruction of tar is the most convenient way, which is supposed to provide higher overall efficiency of the process. However, the selection of catalyst is a real challenge, because of the numerous criteria to be considered. This review highlighted the advantages and disadvantages of different gas cleaning methods including physical filtration, thermal hot gas cleaning and catalytic hot gas cleaning in order to meet the quality of producer gas to be used in different downstream applications.

2. Gas impurities, their level and effect to the downstream applications

In the gasification of biomass, tar, particulate matter, NH_3, HCl, NO_x, H_2S, and SO_x are generally form as impurities in the producer gas. The concentration of impurities in the producer gas depends on many factors; however, the reactor types and the gasification conditions are two major factors that control the producer gas quality. Table 1 summarizes the composition of product gases and tar content in the raw producer gas produced from different types of gasifiers. It is reported that the maximum tar yield can go up to 6 g/Nm^3 for air blown fixed bed co-current reactor, while it is 10-33 g/Nm^3 for counter current reactor (Aljbour & Kawamoto, 2013). Meanwhile, the particulate matter content in the producer gas is lower in the case of counter current reactor than that of co-current one. On the other hand, the gas composition also differs from each other. Because of the higher burnable gas composition, the HHV of producer gas produced in co-current reactor is higher (5.0 MJ/Nm^3), compared to the counter current reactor (3.5 MJ/Nm^3) (Chen et al., 2012; Song et al., 2012).

Compared to fixed bed gasifier, fluidized bed gasifier, especially circulating fluidized bed gasifier needs high speed of air. Because of short residence time of tar molecules in the reactor, the unconverted tar is much higher in the case of circulating fluidized bed reactor than that of fluidized bed gasifier (Meng et al., 2011). However, compared to counter current fixed bed reactor, the tar is lower in producer gas from both fluidized bed gasifiers. The dust particles loading in the producer gas are normally high for fluidized bed gasifiers. Because of the fineness of the particles, it is very difficult to effectively separate from the product gas by conventional cyclone separator. When the producer gas is used for internal combustion engine, the particles deposit in the nozzle and other places and block the system. For turbine application the particles adversely affect the turbine blade due to abrasion effect. The internal combustion engine can satisfactorily accept the particle concentration <50 mg/Nm^3 with size of <10 μm, while it is <30 mg/Nm^3 for gas turbine (Hasler & Nussbaumer, 1999).

Tar forms during the secondary reaction of volatiles with gasifying agents. The turbine is not very sensitive to tar because it can accept hot gas for combustion and since the temperature of the hot gas is higher than the dew point of tar it can stay as vapor form. However, the temperature above 400 °C, the tars can undergo a subsequent dehydration reaction to form solid coke that not only further causes of fouling and plugging but also causes abrasion of turbine blade. Therefore, the safe level of tar concentration required is even lower than that of internal combustion engine (Hasler & Nussbaumer, 1999).

Table 1 – Gas composition and tar content in the product gas from different biomass gasification in different gasifier

Gasifier	Biomass	Gas composition	Tar content g/Nm^3	HHV MJ/Nm^3	Ref.
Updraft	Cedar wood	--	10.0-33.2	--	(Aljbour & Kawamoto, 201
Updraft	Mesquite wood	CO (13-21), H_2 (1.6 -3), CH_4 (0.4-6), CO_2 (11 -25), N_2 (60-64)	--	2.4-3.5	(Chen et al., 2012)
Updraft	--	CO (15-20), H_2 (55-60), CH_4 (8-10), CO_2 (15-18), N_2 free	6.5-9.0	--	(Song et al., 2012)
Updraft	Willow	CO (20-25), H_2 (30-45), CH_4 (8-12), CO_2 (15-20), H_2S (2300 ppmv), COS (200 ppmv), N_2 free	2.0-12.0	--	(Meng et al., 2011)
Downdraft	Bagasse	--	0.37-0.40	--	(Jordan & Akay , 2012)
Downdraft	Hazelnut shells	H_2(13), CO (23), CO_2 (11), CH_4	--	5.0	(Olgun et al., 2011)

Ammonia and sulfur compounds are usually formed from the inherent content of nitrogen and sulfur compounds in biomass. Ammonia is also formed from nitrogen and hydrogen in the pressurized reactor.

Although these compounds do not affect the engine and turbine operation the presence of them in the exhusat gas is environmentaly unacceptable.

3. Operating variables and impurities content

Gasification temperature affects the gas composition, tar concentration, reaction rate, ash build-up and etc (Taba et al., 2012). The low temperature gasification is attributed to high tar and low CO and H_2 yield, while the high temperature leads to high yield of CO and H_2 with low tar. However, two major problems limit the high temperature gasification above 1000 ^oC: (1) the ash melting, and (2) the requirement of stringent reactor specification. Therefore, a numerous studies have been conducted to investigate the gas composition, tar concentration and other requirement within the temperature range of 750 – 900 ^oC. However, the tar yield from the gasification bellow 1000 ^oC is significantly higher than the acceptable range, and thus it needs gas cleaning.

Most of the gasification system operates under ambient pressure, while some gasifiers operates under pressurized condition. Increasing of gasifier pressure reduces the tar yield in the product gas. However, some investigations conducted in fluidized bed gasifier have shown that the concentration of tar, mainly naphthalene, increased with increasing gasifier pressure from 0.1 to 0.5 MPa, and thus the concentration of CO decreased.

Air, steam, carbon dioxide and pure oxygen are commonly being used as gasifying agents. Utilization of air as a gasifying agent produces gases with lower concentration of H_2 and CO, because air also brings nitrogen. In addition, some of the H_2 and CO takes part in complete combustion, and thus it increases the CO_2 concentration. Addition of external steam with air increases the H_2 concentration, because of the water-gas shift reaction. It assists to balance CO and H_2 ratio for Fischer-Tropsch synthesis. However, addition of steam reduces the thermal efficiency of the gasification. Pure oxygen is suitable to produce gases with high concentration of CO and H_2 and low tar; however, pure oxygen itself is an expensive gasifying agent. Carbon dioxide also acts as a gasifying agent to react with carbon to produce carbon monoxide; however, the reaction is slow. Air to fuel ratio can control the gas composition. Higher ratio generates more oxidation environment in the gasifier, and thus attributed to lower calorific product gas. On the other hand, lower ratio results higher calorific product gas; however, the tar yield is considerably higher. Therefore, the lower ratio in combination of suitable gas cleaning system is desirable for quality gas production.

4. Gas cleaning

The gas from the conventional gasification systems developed so far generally contains the impurities above the acceptable ranges of downstream applications. It seems that without cleaning of gas especillay tar and particulate matter separation, the gas can not be utilized in any downstream application. Over the last years, numerous efforts have been given to separate impurities from producer gas in order to make it quality gas for those applications. The efforts can be categorized in three types namely physical filtration, thermal process and catalytic process as described detailed in the subsequent sections.

4.1. Physical gas cleaning method

The gas cleaning by physical method is a simple filtration or wet scrubbing of product gas in order to remove the tar and particulate matter from the gas stream through gas/solid or gas/liquid interactions. The process may be conducted either at high temperature or at ambient temperature, while the scrubbing is usually conducted at ambient temperature. The high temperature filter must be consisted of temperature tolerable materials, for example, ceramics, fiber glass, sand and etc. On the other hand, the low temperature filter may be consisted of cotton fibers, charcoal, and etc. However, in either case, the fouling of particulate matter and sticky tar has been considered as a crucial problem. The filter pores are often blocked by the deposition of particles and tar, so as to generate the huge pressure drop. The water scrubbing on the other hand can scavenge particulate matter and tar; however, handling of huge amount of contaminated water is unhealthy and it contaminates environment. A high temperature granular bed filtration has been investigated and several field tests were conducted at about 550 °C (Stanghelle et al., 2007). This filter is comparatively better than that of the bag filtration method. Tar can be termed as heavy tar and light tar and both of them were removed by a combination of vegetable oil scrubber and a char filter. The turbulence of oil increased the heavy tar absorption (Paethanom et al., 2012). However, the author did not mention post operative treatment of vegetable oil. A ceramic filter has been developed for cleaning of hot producer gas from steam-O_2 gasification of biomass at Delft University of Technology and it was used more than 50 h in the temperature range between 600 and 800 °C.

4.2. Thermal process

In thermal process of gas cleaning the heavy aromatic tar species are cracked down by thermal effect to lighter molecules such as methane, carbon monoxide and hydrogen. The tar is generally refractive in nature, and thus it needs high temperature to crack down. The efficient tar cracking is usually achieved at temperatures higher than 1000 ^{o}C (Stanghelle et al., 2007). However, the operation at such a high temperature is challenging. The most challenging aspects of high temperature tar cracking are: (1) the cracking equipment must be constructed of high temperature tolerable expensive alloys, (2) it needs highly controllable complex heating system, (3) the ash melts at this temperature, and (4) the product gas needs intensive cooling system.

4.3. Catalytic hot gas cleaning

The effective use of gasification gas, especially for gas turbine or internal combustion engine, needs to meet some stringent requirement, such as the tar concentration must lie between 50-100 mg/Nm^3 and ammonia concentration must be less than 50 ppm (Milne et al., 1998). Based on the literature, the physical filtration and even high temperature thermal cracking of tar is inefficient to meet these requirements. The catalytic tar decomposition often considered as an attractive method to decrease the concentration of tar and ammonia in the product gas stream. More advantageously, the catalytic tar and ammonia decomposition often occurred at much lower temperatures (600-800 ^{o}C), compared to thermal cracking ($\approx$ 1200 ^{o}C). In addition, for physical cleaning process, the product gas is needed to be cooled down to ambient temperature, and thus decreases the thermal efficiency. Interestingly, the catalytic reforming unit can be integrated very close to the main gasification unit, and hence the raw producer gas can be immediately entered into the reforming unit without cooling down the gas, operating at the same temperature of the exit product gas temperature, and thus it does not need to heat up or cool down. Furthermore, it converts tar to CO and H_2, so as to increase the burnable gas composition. The other impurities can also be trapped in the catalytic bed, so as to provide almost completely clean gas for downstream application.

Based on the literature, a comprehensive effort has been given to the catalytic hot gas cleaning over the past years. Different types of catalysts have been proven to be active for tar and ammonia decomposition as summarized in Table 2. The catalysts have been used in different moods. Some attempts have been made utilizing the catalyst in the primary bed, where the catalyst was placed in the gasification reactor (Manuel et al., 2011). In this case, the catalyst was rapidly deactivated due to the fouling of ash and carbon on the catalyst surface (Barisano et al., 2012). The non-metallic catalysts showed longer activity; however, they eroded and were elutriated from the bed. Some precious metal catalysts such as rhodium (Rh) showed superior catalytic activity in the primary and secondary bed, converted almost all tar and char at unusually low temperatures (500-700 ^{o}C) (Asadullah et al., 2002). However, it was deactivated due to sintering of the catalyst at reforming temperature. More resistant catalyst was developed when CeO_2 and Rh was loaded on porous silica sequentially as $Rh/CeO_2/SiO_2$.

Table 2 – Effect of different catalysts on the gas composition and tar content in the product gas

Catalyst type	Catalyst bed	Temperature, °C	Tar removal, %	Reference
Dolomite	Primary	850	76	Manuel et al., 2011
Olivine	Primary	850	50	Manuel et al., 2011
Fe/Olivine	Primary	855-890	38	Barisano et al., 2012
$Rh/CeO_2/SiO_2$	Primary/Secondary	550-700	100	Asadullah et al., 2002
$Ni + MnO_x/Al_2O_3$	Secondary	550-650	100	Koike et al., 2013
Fe/Char	Secondary	500-850	95	Dong et al., 2013
Fe/Char	Secondary	900	97	Zhang et al., 2013

The nickel based and modified nickel based catalysts were widely investigated (Li et al., 2009) for tar reforming in the secondary reformer. The tars were effectively reformed on nickel based catalysts; however, the experiments were run in short reaction time. Some cheap catalysts based on char as support material and iron as an active ingredient are recently developed. The catalyst showed superior performance for tar removal. Since this catalyst is cheap, the gas cleaning technology has expedited the commercial exploitation of biomass gasification technology for power generation (Dong et al., 2013).

In conclusion, the gasification gas usually contains several impurities which are essential to remove for downstream application. Among several gas cleaning methods, catalytic hot gas cleaning is more advantageous in terms of process efficiency, environmental issues and meeting the requirement of individual downstream application. In terms of economy, the cheap catalyst with required activity and resistivity against deactivation is highly desired.

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