Journal of Energy Technologies and Policy
ISSN 2224-3232 (Paper) ISSN 2225-0573 (Online)
Vol.3, No.11, 2013 – Special Issue for International Conference on Energy, Environment and Sustainable Economy (EESE 2013)

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

Mohammad Asadullah*

Faculty of Chemical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

*Email address of corresponding author: asadullah@salam.uitm.edu.my; asadullah8666@yahoo.com

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

1.1 Problem Statement

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 problems associated with mostly gasification gas (producer gas) cleaning technologies (Dong et al., 2013; Zhang et al., 2013).

1.2 Exploration of the Importance of the Problem

Producer gas (a mixture of CO, CO_2, H_2, CH_4 and N_2) cleaning is important because it contains some impurities such as tar, particles and toxic gases including NH_3, NO_x, SO_x and HCl. These impurities create problems in downstream application of producer gas. Among the impurities, tar is the most notorious one, which are chemically polyaromatic hydrocarbons (Virginie et al., 2012; Hernández et al., 2013; Baumhakl & Karellas 2011). 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; Spath & Dayton, 2003; Bui et al., 1994).

1.3 Description of the Relevant Work

Different attempts have been taken to produce clean gas previously. The attempts include the development of different types of gasifier (Buragohain et al., 2010), cold gas filtration (Akay et al., 2013), hot gas filtration (Simeone et al., 2013), catalytic gas cleaning (Simell et al., 1996) and etc.

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.

1.4 Hypotheses and Their Correspondence to Solve the Problems

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. In principle, the aromatic hydrocarbons in tar 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. Method

In this study, the challenges related to the gasification gas production and cleaning are summarized and critically analyzed. The efforts so far contributed to overcome the challenges related to biomass gasification and gas cleaning is categorized in three sections such as (1) gas impurities level and their effects to the downstream applications, (2) impurities content based on operating variables of gasification and (3) cleaning of gas impurities. The gas cleaning is further subdivided in to (1) physical gas cleaning (simple filtration), (2) thermal gas cleaning and (3) catalytic gas cleaning. Each of the section and subsection is critically reviewd in the subsequent sections.

3. Results

3.1 Gas impurities, their level and effect to the downstream applications

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. 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).

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, 2013)
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)

3.2 Critical Review on 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 °C: (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 °C. However, the tar yield from the gasification bellow 1000 °C 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.

3.3 Critical Review on 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.

3.3.1 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.

3.3.2 Thermal Gas Cleaning Method

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.

3.3.3 Catalytic Gas Cleaning Method

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 (≈ 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, ^{o}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).

4. Discussion

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. 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).

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).

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.

Three types of gas cleaning methods are usually applied to produce quality gas. However, the simple filtration and thermal craking of tar are not technically, economically and environmentaly viable because of numerous complexicity as discussed in the earlier sections. The catalytic tar cracking is more advantageous because it converts tar to burnable gas at reasonably low temperature. Two major benefits of catalytic tar removal are that it increases the burnable gas composition, thereby increases the overall thermal efficiency and it simultaneously decreases the particls and poisonous gas composition by adsorbing them into the catalyst bed.

In conclusion, the gasification gas usually contains several impurities which are essential to remove for downstream applications. Among the impurities, tar is the most notorious one which is difficult to remove to an acceptable range. Several gas cleaning methods such as physical filtration, thermal tar cracking and catalytic tar reforming are widely investigated. The 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. The char supported iron catalyst seems to be more effective for tar removal because it is quite active for tar reforming to gas as well as resistive against deactivation. In addition, both support material (char) and active ingredient (iron compound) are quite cheap, which can provide the economic viability to entire process.

Acknowledgements

The author is greatful to the Research Management Institute, Universiti Teknologi Mara and Ministry of Higher Education, Malaysia for financial support under the Project no. 600-RMI/DANA5/3/RIF(110/2012) and 600-RMI/PRGS/5/3(3/20/ 2011).

References

Akay, G., Jordan, C. A., Mohamed, A. H. (2013). Syngas cleaning with nano-structured micro-porous ion exchange polymers in biomass gasification using a novel downdraft gasifier. *Journal of Energy Chemistry, 22,* 426-435.

Aljbour, S. H., Kawamoto, K. (2013). Bench-scale gasification of cedar wood – Part II: effect of operational conditions on contaminant release. *Chemosphere, 90*, 1501-1507.

Asadullah, M. (2014). Barriers of commercial power generation using biomass gasification gas: A review. *Renewable and Sustainable Energy Reviews*, *29*, 201-215.

Asadullah, M., Fujimoto, K., Tomishige, K. (2001b). Catalytic Performance of Rh/CeO_2 in the Gasification of Cellulose to Synthesis Gas at Low Temperature. *Industrial & Engineering Chemistry Research, 40,* 5894-5900.

Asadullah, M., Ito, S.-I., Kunimori, K., Yamada, M., Tomishige, K. (2002a). Biomass gasification to hydrogen and syngas at low temperature: Novel catalytic system using fluidized-bed reactor. *Journal of Catalysis, 208,* 255-259.

Asadullah, M., Ito, S.-I., Kunimori, K., Yamada, M., Tomishige, K. (2002b). Energy efficient production of hydrogen and syngas from biomass: Development of low-temperature catalytic process for cellulose gasification. *Environmental Science & Technology, 36*,4476-4481.

Asadullah, M., Miyazawa, T., Ito, S.-I., Kunimori, K., Tomishige, K. (2003a). Demonstration of real biomass asification drastically promoted by effective catalyst. *Applied Catalysis A: General, 246*, 103-116.

Asadullah, M., Miyazawa, T., Ito, S.-I., Kunimori, K., Yamada, M., Tomishige, K. (2003b). Catalyst development for the gasification of biomass in the dual-bed gasifier. *Applied Catalysis A: General, 255*, 169-180.

Asadullah, M., Miyazawa, T., Ito, S.-I., Kunimori, K., Yamada, M., Tomishige, K. (2004a). Gasification of different biomasses in a dual-bed gasifier system combined with novel catalysts with high energy efficiency. *Applied Catalysis A: General, 267*, 95-102.

Asadullah, M., Miyazawa, T., Ito, S.-I., Kunimori, K., Koyama, S., Tomishige, K. (2004b). A comparison of $Rh/CeO_2/SiO_2$ catalysts with steam reforming catalysts, dolomite and inert materials as bed materials in low throughput fluidized bed gasification systems. *Biomass and Bioenergy, 26*, 269-279.

Asadullah, M,, Tomishige, K,, Fujimoto, K. (2001a). A novel catalytic process for cellulose gasification to synthesis gas. *Catalysis Communications, 2*, 63-68.

Barisano, D., Freda, C., Nanna, F., Fanelli, E., Villone, A. (2012). Biomass gasification and in-bed contaminants removal: Performance of iron enriched Olivine and bauxite in a process of steam/O_2 gasification. *Bioresource Technology, 118*, 187-194.

Baumhakl, C., Karellas, S. (2011). Tar analysis from biomass gasification by means of online fluorescence spectroscopy. *Optics and Lasers in Engineering, 49,* 885-891.

Bui, T., Loof, R., Bhattacharya, S. C. (1994) Multi-stage reactor for thermal gasification of wood. *Energy, 19,* 397-404.

Buragohain, B., Mahanta, P., Moholkar, V. S. (2010). Thermodynamic optimization of biomass gasification for decentralized power generation and Fischer–Tropsch synthesis. *Energy, 35,* 2557-2579.

Chen, W., Annamalai, K., Ansley, R. J., Mirik, M. (2012). Updraft fixed bed gasification of mesquite and juniper wood samples. *Energy, 41,* 454-461.

Dong, L., Asadullah, M., Zhang, S., Wang, X. S., Wu, H., Li C.-Z. (2013). An advanced biomass gasification technology with integrated catalytic hot gas cleaning: Part I. Technology and initial experimental results in a lab-scale facility. *Fuel*, *108*, 409-416.

Hasler, P., Nussbaumer, T. (1999). Gas cleaning for IC engine applications from fixed bed biomass gasification. *Biomass and Bioenergy, 16*, 385-395.

Hernández, J. J., Ballesteros, R., Aranda, G. (2013). Characterisation of tars from biomass gasification: Effect of the operating conditions. *Energy, 50,* 333-342.

Jordan, C. A, Akay, G. (2012). Occurrence, composition and dew point of tars produced during gasification of fuel cane bagasse in a downdraft gasifier. *Biomass Bioenergy, 42*, 51-58.

Koike, M., Ishikawa, C., Li, D., Wang, L., Nakagawa, Y., Tomishige, K. (2013). Catalytic performance of manganese-promoted nickel catalysts for the steam reforming of tar from biomass pyrolysis to synthesis gas. *Fuel, 103*, 122-129.

Li, C., Hirabayashi, D., Suzuki, K. (2009). Development of new nickel based catalyst for biomass tar steam reforming producing H_2-rich syngas. *Fuel Processing Technology, 90*, 790-796.

Manuel, de A. J., Narros, A., Rodríguez, M. E., Behaviour of dolomite, olivine and alumina as primary catalysts in air–steam gasification of sewage sludge. *Fuel, 90*, 521-527.

Meng, X., de Jong, W., Fu, N., Verkooijen, A. H. M. (2011). Biomass gasification in a 100 kWth steam-oxygen blown circulating fluidized bed gasifier: Effects of operational conditions on product gas distribution and tar formation. *Biomass and Bioenergy, 35*, 2910-2924.

Milne, T. A., Abatzoglou, N., Evans, R. J. (1998). Biomass gasifier "tar": their nature, formation, and conversion. *NREL/TP-570- 25357*.

Olgun, H., Ozdogan, S., Yinesor, G. (2011). Results with a bench scale downdraft biomass gasifier for agricultural and forestry residues. *Biomass Bioenergy, 35*, 572-580.

Paethanom, A., Nakahara, S., Kobayashi, M., Prawisudha, P., Yoshikawa, K. (2012). Performance of tar removal by absorption and adsorption for biomass gasification. *Fuel Processing Technology, 104*, 144-154.

Rapagnà, S., Gallucci, K., Marcello, M. D., Matt, M., Nacken, M., Heidenreich, S., Foscolo, P. U. (2010). Gas cleaning, gas conditioning and tar abatement by means of a catalytic filter candle in a biomass fluidized-bed gasifier. *Bioresource Technology, 101*, 7123-7130.

Schmidt, S., Giesa, S., Drochner, A., Vogel, H. (2011). Catalytic tar removal from bio-syngas—Catalyst development and kinetic studies. *Catal Today*, *175,* 442-449.

Simell, P., Kurkela, E., Ståhlberg, P., Hepola, J. (1996). Catalytic hot gas cleaning of gasification gas. *Catalysis Today, 27*, 55-62.

Simeone, E., Siedlecki, M., Nacken, M., Heidenreich, S., de Jong, W. (2013). High temperature gas filtration with ceramic candles and ashes characterisation during steam–oxygen blown gasification of biomass. *Fuel, 108,* 99-111.

Song, T., Wu, J., Shen, L., Xiao, J. (2012). Experimental investigation on hydrogen production from biomass gasification in interconnected fluidized beds. *Biomass Bioenergy, 36*,258-267.

Spath, P. L., Dayton, D. C. (2003). Preliminary screening-technical and economic assessment of synthesis gas to fuels and chemicals with emphasis on the potential for biomass-derived syngas. NREL/TP-510-34929; 2003.

Stanghelle, D., Slungaard, T., Sønju, O. K. (2007). Granular bed filtration of high temperature biomass gasification gas. *Journal of Hazardous Matterials, 144*, 668-672.

Taba, L. E., Irfan, M. F., Daud, W. A. M. (2007). Chakrabarti MH. The effect of temperature on various parameters in coal, biomass and Co-gasification: a review. *Renewable and Sustainable Energy Review, 16*, 5584–5596.

Vaselli, O. T. F., Montegrossi, G., Capaccioni, B., Giannini, L. (2006). Sampling and analysis of volcanic gases. *Acta Vulcanologica, 18*, 65-76.

Virginie, M., Adánez, J., Courson, C., de Diego, L. F., García-Labiano, F., Niznansky, D. (2012). Effect of Fe–olivine on the tar content during biomass gasification in a dual fluidized bed. *Applied Catalysis B: Environmental, 121–122,* 214-222.

Xu, X., Li, P., Shen, Y. (2013). Small-scale reforming of diesel and jet fuels to make hydrogen and syngas for fuel cells: A review. *Applied Energy, 108,* 202-217.

Yin, S.-F., Xu, B.-Q., Ng, C.-F., Au, C.-T. (2004). Nano Ru/CNTs: a highly active and stable catalyst for the generation of CO_x-free hydrogen in ammonia decomposition. *Applied Catalysis B: Environmental, 48,* 237-241.

Zhang, S., Asadullah, M., Dong, L., Tay, H.–L., Li C.-Z. (2013). An advanced biomass gasification technology with integrated catalytic hot gas cleaning. Part II: Tar reforming using char as a catalyst or as a catalyst support. *Fuel*, *112*, 646-653.