Materials Research Proceedings 29 (2023) 439-445 https://doi.org/10.21741/9781644902516-50

Preliminary study for catalytic gasification of water hyacinth for syngas production

APRIL LING KWANG Chee[1,a], BRIDGID LAI FUI Chin[1,b*], SHAHARIN ANWAR Sulaiman[2,c], YEE HO Chai[3,4,d], AGUS Saptoro[1,e], HADIZA AMINU Umar[2,5,f], MAN KEE Lam[3,4,g], CHUNG LOONG Yiin[6,7,h]

[1]Department of Chemical and Energy Engineering, Faculty of Engineering and Science, Curtin University Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia

[2]Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 32610, Seri Iskandar, Perak Darul Ridzuan, Malaysia

[3]Chemical Engineering Department, Universiti Teknologi PETRONAS, 32610, Seri Iskandar, Perak Darul Ridzuan, Malaysia

[4]HICoE-Centre for Biofuel and Biochemical Research, Institute of Self-Sustainable, Building, Universiti Teknologi PETRONAS (UTP), 32610 Seri Iskandar, Perak Darul Ridzuan, Malaysia

[5]Mechanical Engineering Department, Bayero University Kano, PMB 3011 Kano, Kano State Nigeria

[6]Department of Chemical Engineering and Energy Sustainability, Faculty of Engineering, Universiti Malaysia Sarawak (UNIMAS), Kota Samarahan, 94300, Malaysia

[7]Institute of Sustainable and Renewable Energy (ISuRE), Universiti Malaysia Sarawak (UNIMAS), 94300, Kota Samarahan, Sarawak, Malaysia

[a]aprilchee@postgrad.curtin.edu.my, [b]bridgidchin@curtin.edu.my, [c]shaharin@utp.edu.my, [d]yeeho.chai@utp.edu.my, [e]agus.saptoro@curtin.edu.my, [f]hadiza_16000717@utp.edu.my, [g]lam.mankee@utp.edu.my, [h]clyiin@unimas.my

Keywords: Gasification, Biomass, Water Hyacinth, Syngas, Downdraft Gasifier

Abstract. Water hyacinth being one of the top invasive aquatic plants has brought upon various challenges towards the humanity and the environment. The magnitude of the menace of uncontrollable growth and spread of water hyacinth has sparked the interest of researchers in identifying its potential as a biomass feedstock for biofuel production. Biomass gasification is deemed as a promising green technology which is capable of converting biomass into value-added commodity. Conversion of such large quantity of biomass into biofuel via gasification does not only help to promote sustainable resource utilization but also facilitates the reduction of global carbon impacts and engender socioeconomic development. The addition of catalysts to the gasification process could enhance the formation of gaseous products where the gas composition may be altered. This study aims to present the preliminary study on the gasification performance of water hyacinth biomass in a lab scale fixed-bed downdraft gasifier (67 mm diameter and 750 mm height), with the use of air as the gasifying agent in a batch feeding of 50 grams for each run. The results showed that temperature has a substantial effect on the gasification of water hyacinth whereby hydrogen produced was raised from 2.92 vol.% to 11.19 vol.%. Further gasification tests are expected for the optimization of the main process parameters such as biomass particle size and catalyst loading.

Introduction

Water hyacinth, with its scientific name known as *Eichhornia crassipes*, is regarded as a potential and economically viable feedstock for biofuel production via thermochemical conversion. It was reported that water hyacinth comprises of higher cellulose and hemicellulose contents in comparison to algae [1]. Water hyacinth has been perceived to be one of the worst aquatic weeds due to the tremendous challenges brought upon the urban management as a result of its abundance and rapid reproduction rate. In fact, water hyacinth has been a major encumbrance to fishing and hydroelectric schemes while also causing disruption to navigation and irrigation systems [2]. Biomass gasification would be an appropriate alternative solution for managing such large amount of aquatic plant biomass and help to eradicate the excessive amount of water hyacinth present in the ecosystem. Meanwhile, such initiative could also facilitate the paradigm shift to alternative renewable energy sources and possibly reducing the heavy reliance on the dwindling supply fossil fuels for most industrial activities [3,4,5,6,7,8,9,10,11]. Utilization of conventional fossil fuel resources often times contribute a huge share to the net greenhouse gas emission. Hence, exploration of potential alternative renewable and sustainable energy resources is much needed not only for reducing the global carbon footprint but also be able to meet the ever-increasing energy demand by the rapid population growth.

Gasification process involves the conversion of organic or carbonaceous materials into gaseous products such as carbon monoxide, hydrogen, methane and carbon dioxide via high temperatures for wide application such as power generation, liquid fuels, production of hydrogen, ethanol, and methanol [12]. Partial oxidation reaction is involved where the amount of oxygen/air, steam or combination of these two oxidizing agents is controlled and introduced into the system. Gasification outweighs other thermochemical conversions in terms of syngas production as it is capable of transforming biomass into syngas with low net CO_2 emissions. There are some studies on the gasification of water hyacinth in the literature. [13] studied on the supercritical water gasification of water hyacinth and examined its potential against biomethanation. Results showed that gasification offers better conversion and energy efficiency of 64.8%. However, it was lack of in-depth study on the thermal degradation behaviour and kinetic parameters related to the gasification of water hyacinth.

Most researchers investigating on conversion of water hyacinth have mostly employed the pyrolysis process. Study conducted by [13] involved catalytic pyrolysis of water hyacinth using KCl, MgO and CaO catalysts whereby the optimum conditions for attaining maximum syngas were studied. [14] reported on the maximum bio-oil yield of 44.9 wt% achieved at 350ºC with heating rate of 30ºC/min and particle size of less than 0.5 mm via pyrolysis of water hyacinth. [15] found that the optimum concentration of ferric chloride solution for maximum syngas production from pyrolysis of water hyacinth at 540ºC was 2M with syngas composition of 42% H_2 and 22% CO. Notably, these studies have converted water hyacinth into valuable commodity via pyrolysis but yet to investigate on the kinetic parameters of the thermal degradation of water hyacinth. However, [16] had evaluated on the bioenergy potential and kinetic parameters of the pyrolysis of water hyacinth. Nonetheless, there was no studies reported on the catalytic gasification of water hyacinth biomass for syngas enriched hydrogen production and hence this preliminary study intends to investigate on the effect of temperature on the gasification of water hyacinth.

This research involves gasification of water hyacinth biomass for producing syngas enriched hydrogen. It could be a solution to the major issue of the abundance of water hyacinth especially in Malaysia and thereby possibly alleviating the negative impacts of water hyacinth brought to both human and local ecosystems. For instance, the removal of water hyacinth which occurred to be nutrient extraction tool in Lake Victoria was found to have reduced algal blooms as nutrients level in its surrounding was decreased. Furthermore, the rate of disease spreading could be reduced as schistosomiasis and malaria were found to be associated to the spread of water hyacinth [17,18].

Moreover, production of syngas by gasification of water hyacinth could be used for multiple applications such as electricity generation as it can be directly used in engine, steam or gas turbines as well as fuel cells. Syngas could also be employed to produce chemicals for commercialization such as ammonia, methanol and Fischer Tropsch diesel [19].

This study may offer a solution by utilizing the wet biomass found in ASEAN countries and thereby encourage the development of renewable and sustainable energy while also resolving the negative ecological impact brought by the aquatic weeds such as water hyacinth. Furthermore, this could be part of the initiatives for attaining a circular bioeconomy approach in phytoremediation through gasification or pyrolysis of biomass. For instance, production of biochar may be applied for multiple applications such as conductor or electrode in fuel battery, adsorbents to remove the aquatic pollutants and catalysts in green industry. Furthermore, gasification technology is deemed to possess better carbon sequestration potential (146–264 kg C/ton) when compared to combustion (~87 kg C/ton) and anaerobic digestion (146 kg C/ton) [20]. This would aid in achieving low carbon footprint as well as reduction in greenhouse gas emissions.

Methodology and Methods

Water hyacinth (WH) was extracted from the lake of Curtin University, Malaysia. WH biomass was dried under sunny days for 36-48 hours and further dried in oven at 105^{o}C for 4 hours. The dried biomass was then grounded and sieved to particle size of 4 mm for preliminary gasification experiment.

Gasification Experimental Setup

The gasification system consists of a gasifier, a temperature controller, an air compressor and a cleaning system. The gasification experiment was conducted in a lab-scale gasifier which operates in allothermal mode. The gasifier is composed of a vertical cylindrical casing of 750 mm height and 67 mm internal diameter, which is enclosed within a ceramic electric heater of 1.25 kW. Prior to the 50 g batch feeding of each experimental run, the gasifier has to be cleaned. The temperature microcontroller which employs the Type-K thermocouple is responsible for the temperature adjustment. The gasification temperature used for this study is range from 600 to 800^{o}C. An air compressor is connected to the gasifier for air supply which is regulated by a rotameter. A constant air flow rate of 2 L/min was supplied to the gasifier. A 4.0 µm ceramic filter is affixed for filtering possible particulate matter in the gas sample prior to entering the gas analyzer. The gaseous products exit from the bottom of the gasifier and flows through a tube connected to the cooling and filtering unit and enters the gas analyzer (X-STREAM X2GP model). The gas analyzer provides information on the gas constituents in terms of volume percentage.

Results and Discussion

The operating temperature employed to gasify water hyacinth biomass for investigation purposes range from 600 to 800^{o}C. As illustrated in Table 1, the gaseous products generally increase alongside with the increment of temperature except for carbon dioxide (CO_2) content.

Table 1: Gas composition from gasification of water hyacinth at different temperatures

Temperature (^{o}C)	CO [vol.%]	CO_2 [vol.%]	CH_4 [vol.%]	H_2 [vol.%]	H_2+CO [vol.%]	H_2:CO
600	4.59	14.6	4.56	2.92	7.51	0.389
700	9.10	22.48	5.07	5.74	14.84	0.631
800	15.06	20.48	8.63	11.19	26.25	0.426

A huge leap in hydrogen (H_2) and carbon monoxide (CO) content, from 2.92 to 11.19 vol.% and 4.59 to 15.06 vol.% respectively, is observed when temperature is raised from 600 to 800ºC. Study conducted by [21] have shown similar trend in the hydrogen content which was increased from 7.28 to 14.59 vol.% when temperature was increased from 700 to 900ºC. It was reported that the gasification of cellulose with temperature increasing beyond 930ºC was found to cause the decline in hydrogen (H_2) production [22]. However, the desirable gasification temperature range for maximizing hydrogen production is also subjected to the gasifier, gasification agent and biomass feedstock used. [22] reported that a reduction in H_2 composition was observed from the gasification of rice husk and rice straw while corn cob exhibited greater amount of H_2 production, when pure steam was employed as the gasifying agent.

Due to the increasing trend of carbon monoxide (CO) and hydrogen (H_2), the syngas produced, which is mainly the sum of CO and H_2, from the gasification process shows significant increase from 7.51 to 26.25 vol.%. The proportional relationship between the H_2+CO composition and temperature could be attributed to the endothermic reactions (primary and secondary water gas reactions, Eq. 1-2, and Boudourd reaction, Eq. 3) which may have prevailed over the methanisation reaction (Eq. 4) [23-25]. This is because high temperatures favours the right side of the equilibrium reactions for endothermic reactions and hence promotes the formation of H_2 and CO.

$$C + H_2O \leftrightarrow CO + H_2 \qquad \Delta H_r = 131.3 \text{ kJ/mol} \tag{1}$$

$$C + 2H_2O \leftrightarrow CO_2 + 2H_2 \qquad \Delta H_r = 90.2 \text{ kJ/mol} \tag{2}$$

$$C + CO_2 \leftrightarrow 2CO \qquad \Delta H_r = 172.5 \text{ kJ/mol} \tag{3}$$

$$C + 2H_2 \leftrightarrow CH_4 \qquad \Delta H_r = -74.9 \text{ kJ/mol} \tag{4}$$

Based on the tabulated results in Table 1, it can be deduced that the temperature of 700ºC could be the ideal gasification temperature for high quality syngas due to the high H_2:CO ratio of 0.631 which is a significant increment of 62.2% compared to the H_2:CO ratio at 600ºC.

Pertaining to the composition of carbon dioxide (CO_2), it shows an increase from 14.6 to 22.48 vol.% when temperature was raised from 600 to 700ºC which later decreases to 20.48 vol.% when the gasification temperature was further increased to 800ºC. It was presumed that the decline in CO_2 content would be due to the prevalence of Boudourd reaction (Eq. 3) at higher temperature which consumes the CO_2 produced from partial oxidation (Eq. 5), secondary water gas (Eq. 2) and water gas shift (Eq. 6) reactions [24,26,27].

$$C + O_2 \leftrightarrow CO_2 \qquad \Delta H_r = -394.1 \text{ kJ/mol} \tag{5}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H_r = -41.2 \text{ kJ/mol} \tag{6}$$

With regards to methane (CH_4) content, Fig. 1. shows a rather relatively minor increment in the CH_4 composition as the temperature increases when compared to the other gases. Regardless, the increasing trend is also observed in the study conducted by [23] whereby grapevine pruning waste was gasified using air as the gasifying agent which is also employed in the present study. Despite so, it can be construed that CH_4 production is not greatly affected by the gasification temperature but rather due to the pyrolysis process as minor changes in CH_4 composition was observed in several studies [24,28,29] . The slight change is attributable to the formation and displacement of CH_4 involving exothermic reactions (methanation, Eq. 7 [30], methane steam reforming reaction, Eq. 8 [24], and combustion reaction, Eq. 9 [30]) which are favoured at low and high temperatures respectively [23,24,31].

$$C + 2H_2 \leftrightarrow CH_4 \qquad \Delta H_r = -74.9 \text{ kJ/mol} \qquad (7)$$

$$CH_4 + H_2O \leftrightarrow CO_2 + 3H_2 \qquad \Delta H_r = 206.2 \text{ kJ/mol} \qquad (8)$$

$$CH_4 + 2O_2 \leftrightarrow CO_2 + H_2O \qquad \Delta H_r = -802.3 \text{ kJ/mol} \qquad (9)$$

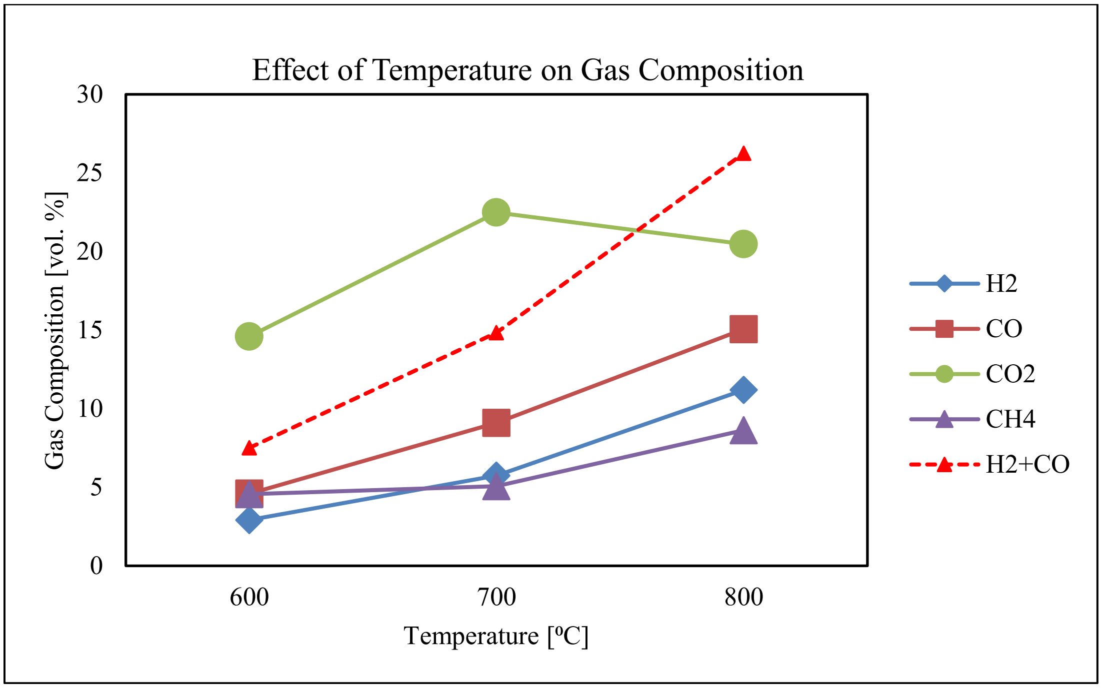

Fig. 1: Effect of temperature on gas composition

Acknowledgements

The authors would like to thank Curtin University Malaysia and Biomass Processing Laboratory, Centre of Biofuel and Biochemical (CBBR) of Universiti Teknologi PETRONAS (UTP) for the technical support. In addition, we would like to thank Curtin University Malaysia for providing the financial support on the Curtin Malaysia Research Grant (Sustainability) grant entitled, 'Conversion of water hyacinth biomass to syngas enriched hydrogen production via catalytic gasification process'.

References

[1] Q. Chen, X. Lu, J. Liu, J. Yu, J. Gu, P. Ning, R. Miao, Q. Guan, Recycling water hyacinth by gasification in supercritical water, Fresenius Environ. Bull. 26 (2017) 2163–2170.

[2] D. Güereña, H. Neufeldt, J. Berazneva, S. Duby, Water hyacinth control in Lake Victoria: Transforming an ecological catastrophe into economic, social, and environmental benefits, Sustain. Prod. Consum. 3 (2015) 59–69. https://doi.org/https://doi.org/10.1016/j.spc.2015.06.003

[3] B.L.F. Chin, A. Gorin, H.B. Chua, F. Twaiq, Experimental invesigtation on tar produced from palm shells derived syngas using zeolite HZSM-5 catalyst. J Energy Inst. 89(4) (2016) 713-724. https://doi.org/10.1016/j.joei.2015.04.005

[3] A.L.K. Chee, B.L.F. Chin, S.M.X. Goh, Y.H. Chai, A.C.M. Loy, K.W. Cheah, C.L. Yiin, S.S.M. Lock, Thermo-catalytic co-pyrolysis of palm kernel shell and plastic waste mixtures using bifunctional HZSM-5/limestone catalyst: kinetic and thermodynamic insights, J. Energy Inst. 107 (2023) 101194. https://doi.org/10.1016/j.joei.2023.101194

[4] Y.H. Chai, S. Yusup, W.N.A. Kadir, C.Y. Wong, S.S. Rosli, M.S.H. Ruslan, B.L.F. Chin, C.L. Yiin, Valorization of tropical biomass waste by supercritical fluid extraction. Sustainability 13 (2021) 233, https://doi.org/10.3390/su13010233

[5] H.Y. Lim, S. Yusup, A.C.M. Loy, S. Samsuri, S.S.K. Ho, A.S.A. Manaf, S.S. Lam, B.L.F. Chin, M.N. Acda, P. Unrean, E. Rianawati. Review on conversion of lignin waste into value-added resources in tropical countries. Waste and biomass valorization 12 (2021) 5285-5302, https://doi.org/10.1007/s12649-020-01307-8

[6] D.K.W. Gan, B.L.F. Chin, A.C.M. Loy, S. Yusup, M.N. Acda, P. Unrean, E. Rianawati, Z.A. Jawad, R.J. Lee. An in-situ thermogravimetric study of pyrolysis of rice hull with alkali catalyst of CaCO3. IOP Conf. Ser.: Mater. Sci Eng. 458 (2018) 012085. https://doi.org/10.1088/1757-899X/458/1/012085

[7] V.S.Y. Soon, B.L.F. Chin, A.C.R. Lim. Kinetic study on pyrolysis of oil palm frond. IOP Conf. Ser.: Mater. Sci. Eng. 121 (2016) 012004. https://doi.org/10.1088/1757-899X/121/1/012004

[8] Y.H. Chai, M. Mohamed, Y.W. Cheng, B.L.F. Chin, C.L. Yiin, S. Yusup, M.K. Lam, A review on potential of biohydrogen generation through waste decomposition technologies. Biomass Conv. Bioref. (2021) https://doi.org/10.1007/s13399-021-01333-z

[9] Y.H. Chan, A.C.M. Loy, K.W. Cheah, S.Y.W. Chai, L.H. Ngu, B.S. How, C. Li, S.S.M. Lock, M.K. Wong, C.L. Yiin, B.L.F. Chin, Z.P. Chan, S.S. Lam, Hydrogen sulfide (H2S) conversion to hydrogen (H2) and value-added chemicals: progress, challenges and outlook. Chem. Eng. J. 458 (2023) 141398. https://doi.org/10.1016/j.cej.2023.141398

[10] Y.H. Chan, S.S.M. Lock, M.K. Wong, C.L. Yiin, A.C.M. Loy, K.W. Cheah, S.Y.W. Chai, C. Li, B.S. How, B.L.F. Chin, Z.P. Chan, S.S. Lam, A state-of-the-art review on capture and separation of hazardous hydrogen sulfide (H2S): recent advances, challenges and outlook. Environ. Pollution 314 (2022). 120219. https://doi.org/10.1016/j.envpol.2022.120219

[11] S.W. Hii, B.L.F. Chin, F.R.S.A. Majing, H.Y. Lim, A.C.M. Loy, C.L. Yiin, S. Yusup, A.T. Quitain, M.N. Acda, P. Unrean, E. Rianawati, Chapter 12 – Isoconversional kinetic and thermodynamic analysis of catalytic pyrolysis for palm oil wastes. Value-Chain of Biofuels (2022), 277-300. https://doi.org/10.1016/B978-0-12-824388-6.00025-7

[12] Y. Matsumura, Evaluation of supercritical water gasification and biomethanation for wet biomass utilization in Japan, Energy Convers. Manag. 43 (2002) 1301–1310. https://doi.org/10.1016/S0196-8904(02)00016-X

[13] Z. Hu, X. Ma, L. Li, Optimal conditions for the catalytic and non-catalytic pyrolysis of water hyacinth, Energy Convers. Manag. 94 (2015) 337–344. https://doi.org/https://doi.org/10.1016/j.enconman.2015.01.087

[14] M.A. Rahman, Pyrolysis of water hyacinth in a fixed bed reactor: Parametric effects on product distribution, characterization and syngas evolutionary behavior, Waste Manag. 80 (2018) 310–318. https://doi.org/10.1016/j.wasman.2018.09.028

[15] T.K. Tran, N. Kim, H.J. Leu, M.P. Pham, N.A. Luong, H.K. Vo, The production of hydrogen gas from modified water hyacinth (Eichhornia Crassipes) biomass through pyrolysis process, Int. J. Hydrogen Energy. 46 (2021) 13976–13984. https://doi.org/10.1016/j.ijhydene.2020.08.225

[16] H. Huang, J. Liu, H. Liu, F. Evrendilek, M. Buyukada, Pyrolysis of water hyacinth biomass parts: Bioenergy, gas emissions, and by-products using TG-FTIR and Py-GC/MS analyses, Energy Convers. Manag. 207 (2020) 112552. https://doi.org/10.1016/j.enconman.2020.112552

[17] C.C. Gunnarsson, C.M. Petersen, Water hyacinths as a resource in agriculture and energy production: A literature review, Waste Manag. 27 (2007) 117–129. https://doi.org/https://doi.org/10.1016/j.wasman.2005.12.011

[18] N. Minakawa, G.O. Dida, G.O. Sonye, K. Futami, S.M. Njenga, Malaria vectors in Lake Victoria and adjacent habitats in Western Kenya, PLoS One. 7 (2012). https://doi.org/10.1371/journal.pone.0032725

[19] Ö. Tezer, N. Karabağ, A. Öngen, C.Ö. Çolpan, A. Ayol, Biomass gasification for sustainable energy production: A review, Int. J. Hydrogen Energy. 47 (2022) 15419–15433. https://doi.org/https://doi.org/10.1016/j.ijhydene.2022.02.158

[20] F. Li, X. He, A. Srishti, S. Song, H.T.W. Tan, D.J. Sweeney, S. Ghosh, C.H. Wang, Water hyacinth for energy and environmental applications: A review, Bioresour. Technol. 327 (2021) 124809. https://doi.org/10.1016/j.biortech.2021.124809

[21] A.M. Ali, M. Inayat, A.A. Zahrani, K. Shahzad, M. Shahbaz, S.A. Sulaiman, H. Sadig, Process optimization and economic evaluation of air gasification of Saudi Arabian date palm fronds for H2-rich syngas using response surface methodology, Fuel. 316 (2022) 123359. https://doi.org/10.1016/j.fuel.2022.123359

[22] W. Jangsawang, A. Klimanek, A.K. Gupta, Enhanced yield of hydrogen from wastes using high temperature steam gasification, J. Energy Resour. Technol. Trans. ASME. 128 (2006) 179–185. https://doi.org/10.1115/1.2134733

[23] M. Lapuerta, J.J. Hernández, A. Pazo, J. López, Gasification and co-gasification of biomass wastes: Effect of the biomass origin and the gasifier operating conditions, Fuel Process. Technol. 89 (2008) 828–837. https://doi.org/10.1016/j.fuproc.2008.02.001

[24] L. Emami Taba, M.F. Irfan, W.A.M. Wan Daud, M.H. Chakrabarti, The effect of temperature on various parameters in coal, biomass and CO-gasification: A review, Renew. Sustain. Energy Rev. 16 (2012) 5584–5596. https://doi.org/10.1016/j.rser.2012.06.015

[25] X. Zhang, Y. Han, Y. Li, Y. Sun, Effect of Heating Rate on Pyrolysis Behavior and Kinetic Characteristics of Siderite, Minerals. 7 (2017). https://doi.org/10.3390/min7110211.

[26] J. Gil, P. Aznar, M.A. Caballero, E. France, with Steam - Oxygen Mixtures . Product Distribution for, Energy & Fuels Fuels. 11 (1997) 1109–1118.

[27] H. Zhang, X. Guo, Z. Zhu, Effect of temperature on gasification performance and sodium transformation of Zhundong coal, Fuel. 189 (2017) 301–311. https://doi.org/10.1016/j.fuel.2016.10.097

[28] W.J. Lee, S.D. Kim, B.H. Song, Steam Gasification of Coal with Salt Mixture of Potassium and Nickel in a Fluidized Bed Reactor, Korean J. Chem. Eng. 18 (2001) 640–645. https://doi.org/10.1007/BF02706380

[29] W.J. Lee, S.D. Kim, B.H. Song, Steam gasification of an australian bituminous coal in a fluidized bed, Korean J. Chem. Eng. 19 (2002) 1091–1096. https://doi.org/10.1007/BF02707238

[30] S. Pang, Fuel flexible gas production: Biomass, coal and bio-solid wastes, in: J. Oakey (Ed.), Fuel Flex. Energy Gener., Woodhead Publishing, Boston, 2016: pp. 241–269. https://doi.org/10.1016/B978-1-78242-378-2.00009-2

[31] M. Pohořelý, M. Vosecký, P. Hejdová, M. Punčochář, S. Skoblja, M. Staf, J. Vošta, B. Koutský, K. Svoboda, Gasification of coal and PET in fluidized bed reactor, Fuel. 85 (2006) 2458–2468. https://doi.org/10.1016/j.fuel.2006.04.022