Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 11 (21): 3600-3606, 2011
ISSN 1812-5654 / DOI: 10.3923/jas.2011.3600.3606

Heat Integration Study on Biomass Gasification Plant for Hydrogen Production

Murni M. Ahmad, Mohd F. Aziz, Abrar Inayat and Suzana Yusup
Centre of Biofuel and Biochemical Research, Green Technology Mission Oriented Research,
Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia

Abstract: The world is facing global warming crisis and environmental problem due to usage of fossil fuels as major energy source. Therefore, the potential of hydrogen as an alternative, sustainable, renewable source of clean energy is highly regarded. This project aimed to develop a process simulation model of a heat-integrated flowsheet for a biomass gasification plant for hydrogen production using ASPEN PLUS software. Heat integration study has been performed on the plant flowsheet using pinch analysis and was carried out in SPRINT, The University of Manchester Process Integration Software. The minimum temperature difference was set to be 10 K. Based on the study, it was found that the minimum hot utilities required was 0.1642 kW while the minimum cold utilities required was 0.0545 kW. The maximum heat recovery from the process was 0.8413 kW. Using problem table algorithm, the pinch temperature was determined to be at 628.5°C. Three heat exchangers were proposed in the heat exchanger network design. Calculations recorded savings of approximately 72% in hot utilities and 88% in cold utilities via the heat integration analysis.

Key words: Hydrogen, biomass, gasification, heat integration, energy efficiency

INTRODUCTION

Hydrogen is considered as a promising fuel for the twenty-first century, due to its environmental-friendly combustion. Moreover, production of hydrogen from renewable biomass has a lot of advantages compared to that of fossil fuels. Currently hydrogen is mostly extracted from natural gas i.e. with an average of 90% formed by steam reformation of naphtha or natural gas with approximately 80% efficiency and has been commercially used in various industries as stated before (Nath and Das, 2003). Steam-methane reforming which is widely used in United States is a process in which high-temperature steam around 700-1000°C is used to produce hydrogen from a methane source from natural gas (Padro and Putsche, 1999). Today, a lot of research has been carried out on developing the production of hydrogen from renewable sources in the effort to reduce the demand on fossil fuels throughout the world.

Renewable sources of energy such as wind, geothermal and solar hold promise as clean sources of energy but face significant difficulties before they become economically viable. Meanwhile, generating hydrogen from renewable biomass may be more viable, efficient and appealing as a potentially carbon neutral option. In Malaysia, biomass has the potential to become the main source of energy based on high resources obtained from agricultural or industrial process in Malaysia (Hassan and Yacob, 2005; Kelly-Young *et al*., 2007); more specifically from oil palm residues, wood residues, paddy residues, sugar cane residues and municipal solid wastes (Hashim, 2005). Abdullah and Yusup (2010) screened and evaluated eleven types of Malaysia biomass for a suitable solid gasification fuel for hydrogen production. In another study, Muis *et al*. (2010) reported a work that solved for the optimal usage of agriculture residues in Malaysia for electricity generation with targeted CO_2 emission reduction.

Two main thermochemical processes to produce hydrogen from biomass are pyrolysis and gasification. Hydrogen production from catalytic steam gasification has been shown to be more efficient and economically viable than conventional gasification. Hydrogen yield can be improved by using CO_2 sorbent that captures CO_2 on site, promoting the reaction forward to produce more hydrogen (Inayat *et al*., 2010a, c; Ahmad *et al*., 2011; Florin and Harris, 2008).

The integrated gasification combined cycle which was originally developed for fossil fuels, had been used as promising ways of opportunities for achieving higher efficiencies for combined heat and power plant from biomass waste (Sadhukhan *et al*., 2009; Jurado *et al*., 2003; Steinwall, 1997). However, gasification of biomass produced tar and char which need to be removed to

Corresponding Author: Murni M. Ahmad, Centre of Biofuel and Biochemical Research, Green Technology Mission Oriented Research, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia

obtain clean and low environmental impact gas. Therefore, the low heating value of the gas generated from biomass gasification imposes major barriers for gasification plant for power plants to be utilized (Sadhukhan *et al*., 2009). Furthermore, intensive studies had been carried out to analyze and control such problem from biomass gasification plant along with several integration strategies in view to maximize heat recovery. Heyne *et al*. (2010) reported a study on synthetic natural gas production from biomass gasification using integrated process design in ASPEN PLUS. They applied pinch analysis for the optimal internal heat recovery calculation within the process. Smejkal *et al*. (2009) presented a model for energy production from biomass gasification using process integration approach. The model predicted high efficiency and low operating cost of process. Pavlas *et al*. (2010) also applied heat integration methodology for a biomass gasification process design to deal with the heating and cooling streams involved in energy recovery.

Current proposed method to produce hydrogen via biomass gasification is an endothermic reaction that requires a lot of energy. Hence, the objective of this study is to improve the efficiency of a selected biomass gasification plant in terms of energy consumption and recovery. Pinch analysis technique has been used to determine hot and cold utilities needed by the process and obtain maximum energy recovery. Furthermore, possible heat exchanger network has been design and proposed. Moreover, evaluation on energy savings has been carried out on the heat integrated flowsheet.

MATERIALS AND METHODS

The process flow diagram for the biomass gasification for hydrogen production process is based on the process reported by Inayat *et al*. (2010b). Water is heated from room temperature of 298 K until superheated condition (523 K) under atmospheric pressure. Dry biomass enters the gasifier along with sorbent, CaO as a catalyst. Both are fed at room temperature and under atmospheric pressure. Heat is supplied to the gasifier in order to increase the temperature up to 1073 K with enthalpy energy value of 8681 kJ h^{-1} (Inayat *et al*., 2010b). A mixture of gas exit the gasifier containing H_2O, H_2, CO, CO_2, CH_4 and ash goes through a filter where ash is removed. The remaining components in the gas mixture enter a scrubber to remove most of the water and condensable gasses in the product gas using water. The product gas temperature is reduced from approximately 1004 K down to 298 K by removing 1521 kJ h^{-1} of energy. The remaining gas exits the scrubber to enter an adsorption unit where H_2 is purified up to 99.9% (Inayat *et al*., 2010b).

Table 1: Reactions occurring in the gasifier

Reaction	Kinetics constant	Reference
$C+H_2O \rightarrow H_2+CO$	2.0×10^5 exp (-6,000/T)	Corella and Sanz (2005)
$C+2H_2 \rightarrow CH_4$	4.40 exp (-1.62×10^8/T)	De Souza-Santos (1989)
$C+CO_2 \rightarrow 2CO$	0.12 exp (-17,921/T)	De Souza-Santos (1989)
$CH_4+H_2O \rightarrow CO+3H_2$	3×10^5 exp (-15,000/T)	Corella and Sanz (2005)
$CO+H_2O \rightarrow CO_2+H_2$	10^6 exp (-6,370/T) K_w= 520 exp (-7,230/T)	Corella and Sanz (2005)
$CO_2+CaO \rightarrow CaCO_3$	10.20 exp (-44.5/T)	Lee *et al*. (2006)

The gasification process is integrated with CO_2 adsorption step and there are six major reactions assumed to occur in the gasifier (Inayat *et al*., 2010a). The list of reactions is listed in Table 1.

Biomass is assumed as char to simplify the simulation. Tar formation in the gasification process is negligible (Nikoo and Mahinpey, 2008; Shen *et al*., 2008), isothermal condition, constant volume and atmospheric pressure (Nikoo and Mahinpey, 2008; Shen *et al*., 2008; Chejne and Hernandez, 2002; Choi *et al*., 2001; Zhang *et al*., 2009).

RESULTS AND DISCUSSION

Process simulation in ASPEN PLUS: A process simulation of the gasification process flowsheet is carried out using ASPEN PLUS software. ASPEN is a standard process flowsheet simulation tool which is suitable to simulate gasification based process system (Sadhukhan *et al*., 2009; Emun *et al*., 2010; Heyne *et al*., 2010). From the process simulation, the mass and energy balances for the flowsheet had been established. Then, data extraction had been carried out from the energy related data from the heat source, sinks processes and streams in order to apply heat integration approaches afterwards.

Simulation of the process flowsheet in ASPEN PLUS is shown in Fig. 1. The fluidized bed gasifier is modelled as an RGibbs reactor with the assumption that the six reactions in Table 1 occur simultaneously. By controlling the temperature, pressure and steam-to-biomass ratio entered the gasifier, the product gas composition can be predicted. The RGibbs reactor is chosen to be used in the process as it can represent the overall biomas gasification process with biomass being represented as its major element i.e. C and the reactions involve the elements present in the process as pure components (C, H, O, N and S).

Based on the simulation results from ASPEN PLUS, H_2 is obtained at the mass flow rate of 0.01499 kg h^{-1} from 72 g h^{-1} of char. A portion of water present is removed from the product gas using a scrubber (Pavlas *et al*., 2010). The remaining amount of water is separated out using a pressure swing adsorption column along with other by-products which are CO, H_2, CH_4 and CO_2.

Table 2: Hot and cold streams data

Stream name	Supply temp. (°C)	Target temp. (°C)	ΔH (kW)	CP (kW K^{-1})
H1 (VAPORS-TOP)	1026.85	226.85	0.89102	1.11E-03
C1(MIX-VAPORS)	623.54	1026.85	0.6022	1.49E-02
C2(H2O/ STEAM)	24.85	249.85	0.1719	7.64E-04
C3(SORBENT/ MIX)	24.85	623.544	0.2265	3.78E-04

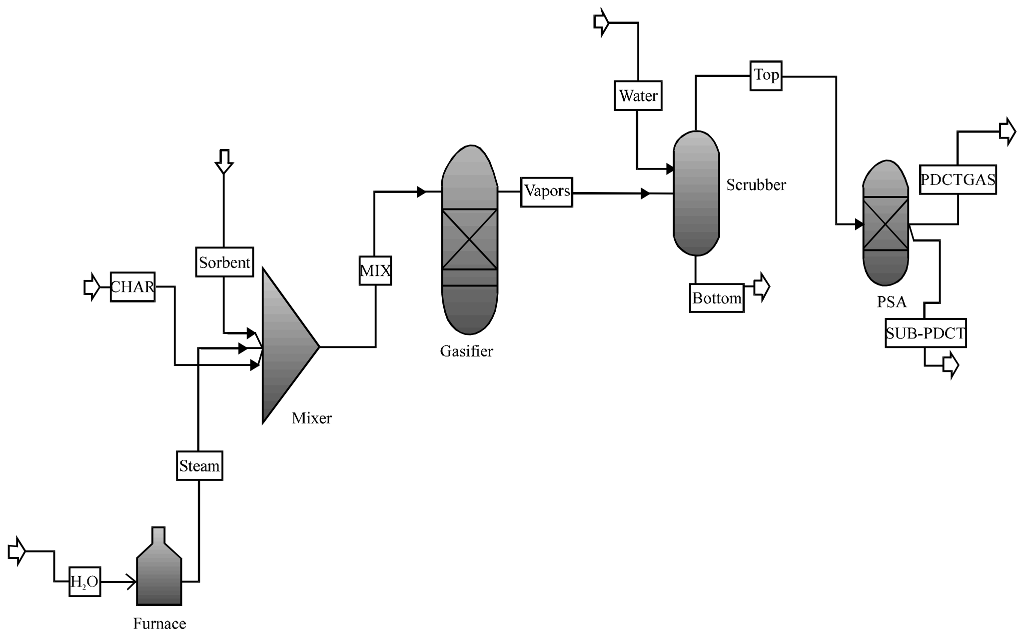

Fig. 1: Simulation of the biomass gasification flowsheet in ASPEN PLUS

In this simulation model, a furnace is to generate steam required at a temperature of 523 K. Excess steam from the gasification process also can possibly supply some amount of energy that can be considered in heat integration study.

Heat integration study: Heat integration is carried out to recover the maximum amount of energy and minimize the usage of utilities. The approach to achieve this objective is pinch analysis. The first step is to identify the hot and cold streams in the process flowsheet carried out in ASPEN. The data extraction is show in Table 2.

SPRINT software package by University of Manchester, UK, is used to construct composite curves and grand composite curve based on the data listed in Table 2. A delta T_{min} is of 10°C that gives optimum value of minimum hot and cold utilities needed after several trials using 20, 30 and 40°C. The composite curve and problem table algorithm are given in Fig. 2 and Table 3.

Based on Fig. 2, it is shown that the minimum hot utility requirement (Q_{Hmin}) is 0.1641 kW, the minimum cold utility requirement (Q_{Cmin}) is 0.0545 kW and the maximum heat recovery ($Q_{recovery}$) is 0.8413 kW. The pinch temperature is 628.54°C with the pinch for hot streams at 633.54°C and for cold streams at 623.54°C. Problem table algorithm developed is shown in Table 3, verifying the findings in Fig. 2.

The Grand Composite Curve (GCC) for the system is illustrated in Fig. 3 which plots the results from the problem table cascade in terms of shifted temperature. Above the pinch temperature is the section of heat sink while below the pinch temperature is heat source or heat generated during the process. The area in Fig. 3 indicated by the arrows is known as pockets, representing the additional process-to-process heat transfer. The balance of the heat generated below the pinch i.e., 0.05456 kW is released to the cooling water. For hot utility, the use of flue gas generated from a furnace at a theoretical flame temperature of 2000°C is proposed (Fig. 3).

Design of heat exchanger network: The proposed Heat Exchanger Network (HEN) design for the biomass gasification plant is shown in Fig. 4.

In Fig. 4, one heater with the heat duty of 0.16416 kW and one cooler with the heat duty of 0.05456 kW are proposed to be used in the process in addition to three heat exchangers to minimize the utility requirement. A heat exchanger can be used to integrate heat of 0.4366 kW between the VAPORS and MIX streams. A heat duty of 0.2263 kW can be recovered from the VAPORS stream to heat up the STEAM stream. The third heat exchanger is proposed to superheat the fresh water feed using the VAPORS stream from the gasifier for the duty of 0.1719 kW. Based on the HEN, the modified design of process flowsheet is simulated in the ASPEN PLUS and shown in Fig. 5.

Energy savings: Total energy required before heat integration is 0.6009 kW of hot utilities and 0.4514 kW of cold utilities. Energy savings of 72.2% of hot utilities and 88.2% of energy savings of cold utilities are predicted to be achieved via the heat integration analysis.

Comparison of these findings with previous studies is not straight forward as the processes under investigations are based on different flowsheet designs, feedstocks and/or products and having different capacities. A few works focusing on improving energy requirement of selected biomass gasification plants are summarized in Table 4, to report improvement in energy requirement using heat integration approach.

Table 3: Problem table algorithm

Interval temperature (°C)	Enthalpy (kW)
1031.85	0.1641
1021.85	0.1492
628.54	0.000 (Pinch)
254.85	0.2748
221.85	0.2738
29.85	0.0545

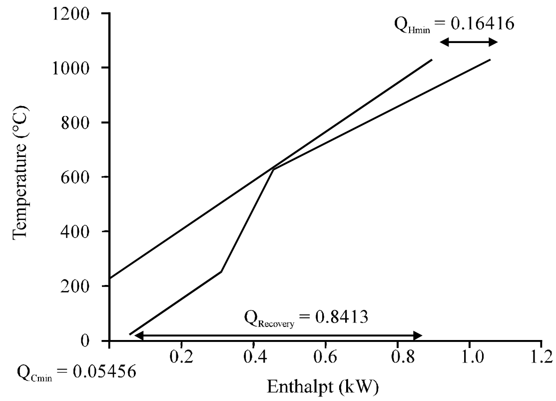

Fig. 2: Composite curve construction

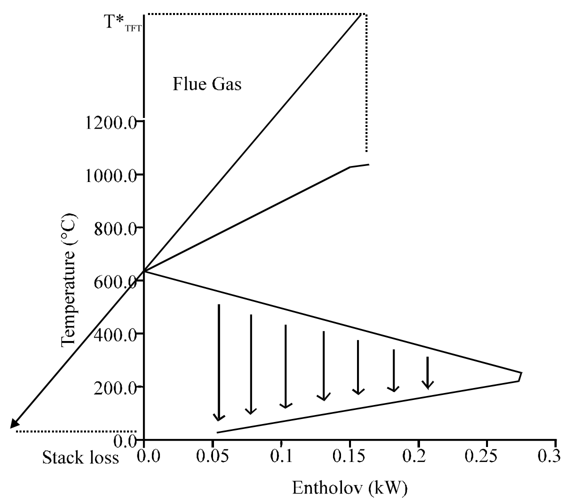

Fig. 3: Grand composite curve

Table 4: Summary of results from integration work on selected biomass/coal gasification plants

		Hot utility			Cold utility			
Process	Capacity	Actual required (kW)	After integration (kW)	Energy saving (%)	Actual required (kW)	After integration (kW)	Energy saving (%)	References
Combined heat and power from biomass waste via char combuster and steam gasification	NA	NA	124.40 MW	NA	NA	55.13 MW	NA	Sadhukhan *et al.* (2009)
Production of ethanol from corn stover via direct gasification and steam reforming (Thermo-chemical)	10.8 kg sec^{-1}	45.5 MW	17 MW	62.6	14 MW	50 MW	-57 (increase)	Cucek *et al.* (2011)
Integrated coal gasification combined cycle for electricity generation	44.3 kg sec^{-1}	NA	225 MW	94	NA	450 MW	97	Emun *et al.* (2010)
Biomass gasification process for syngas production	12.5 t/day	341.42 kW	226.6 kW (HP steam pumping)	33.6	92.38 kW	92.38 kW	0	Pavlas *et al.* (2010)
Biomass steam gasification for hydrogen production	71 g h^{-1}	0.6009	0.1641	72.2	0.4514	0.0545	88.2	Present study

NA: Not available

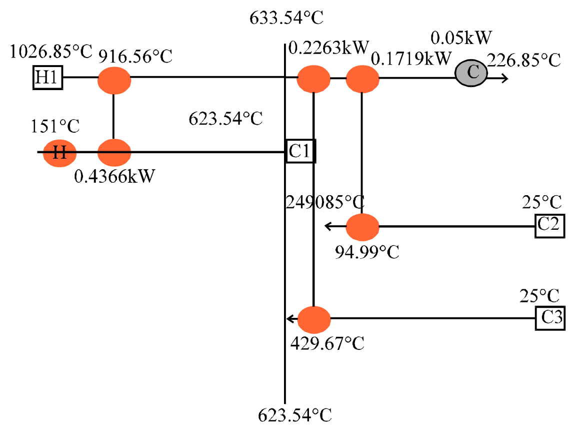

Fig. 4: The heat exchanger network design

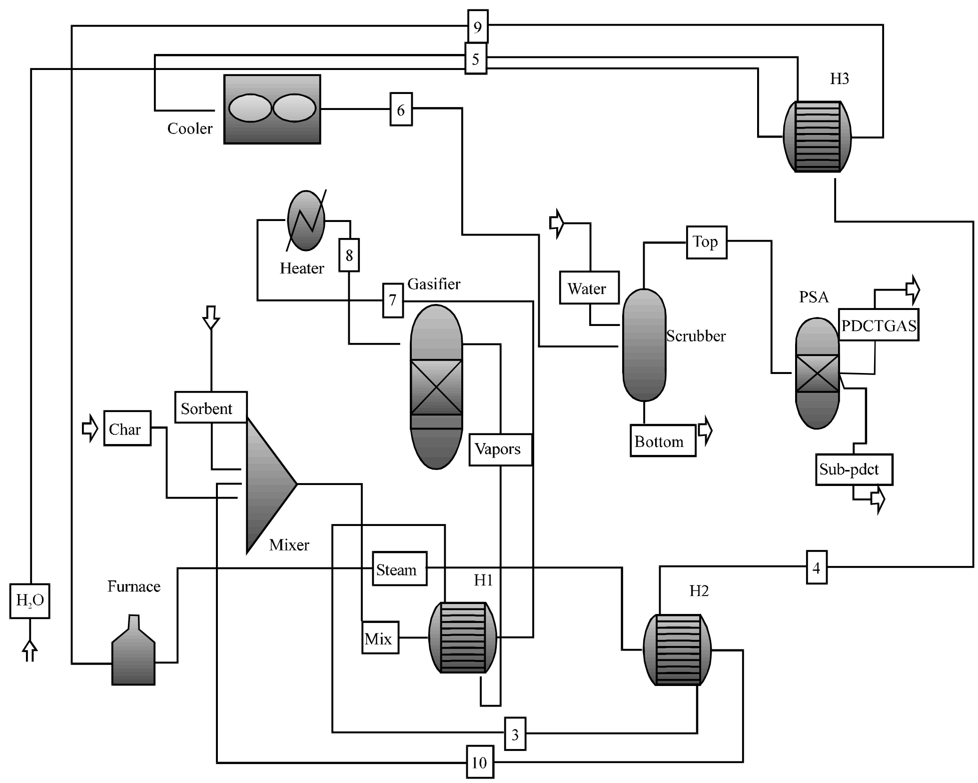

Fig. 5: Modified design for the biomass gasification process flowsheet in ASPEN PLUS

CONCLUSION

In this study, heat integration study has been performed on a biomass gasification plant for hydrogen production using pinch analysis. For the temperature difference of 10 K, it is determined that the minimum hot utility required is 0.1642 kW while the minimum cold utility required is 0.05456 kW with the maximum heat recovery of 0.8413 kW. Using the problem table algorithm, the pinch temperature is determined to be at 628.54°C. Three heat exchangers are proposed to be used based on the results from heat exchanger network development. Calculation of energy saving shows approximately 72% of hot utility and 88% of cold utility can be saved by applying heat integration technique. Further studies are recommended that the actual experimental kinetics data on the specific biomass are to be used in order to obtain more accurate simulation results. Moreover, detailed economic analysis can be performed to evaluate the result of heat integration study on the process plant.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support from Universiti Teknologi PETRONAS and Petroleum Research Fund of PETRONAS to carry out this research.

REFERENCES

Abdullah, S.S. and S. Yusup, 2010. Method for screening of Malaysian biomass based on aggregated matrix for hydrogen production through gasification. J. Applied Sci., 10: 3301-3306.

Ahmad, M.M., A. Inayat, S. Yusup and K.M. Sabil, 2011. Simulation of oxygen-steam gasification with CO_2 adsorption for hydrogen production from empty fruit bunch. J. Applied Sci, 12: 2171-2178.

Chejne, F. and J.P. Hernandez, 2002. Modelling and simulation of coal gasification process in fluidized bed. Fuel, 81: 1687-1702.

Choi, Y.C., X.Y. Li, T.J. Park, J.H. Kim and J.G. Lee, 2001. Numerical study on the coal gasification characteristics in an entrained flow coal gasifier. Fuel, 80: 2193-2201.

Corella, J. and A. Sanz, 2005. Modeling circulating fluidized bed biomass gasifiers. A pseudo-rigorous model for stationary state. Fuel Process. Technol., 86: 1021-1053.

Cucek, L., M. Martin, I.E. Grossmann and Z. Kravanja, 2011. Energy, water and process technologies integration for the simultaneous production of ethanol and food from the entire corn plant. Comput. Chem. Eng. (In Press). 10.1016/j.compchemeng.2011.02.007

De Souza-Santos, M.L., 1989. Comprehensive modelling and simulation of fluidized bed boilers and gasifiers. Fuel, 68: 1507-1521.

Emun, F., M. Gadalla, T. Majozi and D. Boer, 2010. Integrated Gasification Combined Cycle (IGCC) process simulation and optimization. Comput. Chem. Eng., 34: 331-338.

Florin, N.H. and A.T. Harris, 2008. Enhanced hydrogen production from biomass with *in situ* carbon dioxide capture using calcium oxide sorbent. Chem. Eng. Sci., 63: 287-316.

Hashim, M., 2005. Present status and problems of biomass energy utilization in Malaysia. Proceedings of APECATC-Workshop on Biomass Utilization, Jan. 19-21, Tokyo, Tsukuba, pp: 1-25.

Hassan, M.A. and S. Yacob, 2005. Biomass utilization in Malaysia: Current status of conversion biomass into bioproducts. University Putra Malaysia, Malaysia. http://www.biomass-asia-workshop.jp/biomassws/01workshop/material/AliHassan.pdf.

Heyne, S., M. Seemann and S. Harvey, 2010. Integration study for alternative methanation technologies for the production of synthetic natural gas from gasified biomass. Chem. Eng. Trans., 21: 409-414.

Inayat, A., M.M. Ahmad, S. Yusup and M.I.A. Mutalib, 2010a. Biomass steam gasification with *in-situ* CO_2 capture for enriched hydrogen gas production: A reaction kinetics modelling approach. Energies, 3: 1472-1484.

Inayat, A. M.M. Ahmad, M.I.A. Mutalib and S. Yusup, 2010b. Flowsheet development and modelling for hydrogen production from empty fruit bunch via steam gasification. Chem. Eng. Trans., 21: 427-432.

Inayat, A., M.M. Ahmad, M.I.A. Mutalib and S. Yusup, 2010c. Effect of process parameters on hydrogen production and efficiency in biomass gasification using modelling approach. J. Applied Sci., 10: 3183-3190.

Jurado, F., A. Canoa and J. Carpio, 2003. Modeling of combined cycle power plants using biomass. Renewable Energy, 28: 743-753.

Kelly-Young, T.L., K.T. Lee, A.R. Mohamed and S. Bhatia, 2007. Potential of hydrogen from oil palm biomass as a source of renewable energy worldwide. Energy Policy, 35: 5692-5701.

Lee, D.K., I.I.H. Baek and W.L. Yoon, 2006. A Simulation study for the hybrid reaction of methane steam reforming and in situ CO2 removal in a moving bed reactor of a catalyst admixed with a CaO-based CO_2 acceptor for H2 production. Int. J. Hydrogen Energy, 31: 649-657.

Muis, Z.A., H. Hashim, Z.A. Manan and F.M. Taha, 2010. Optimization of biomass usage for electricity generation with carbon dioxide reduction in Malaysia. J. Applied Sci., 10: 2613-2617.

Nath, K. and D. Das, 2003. Hydrogen from biomass. Curr. Sci., 85: 265-271.

Nikoo, M.B. and N. Mahinpey, 2008. Simulation of biomass gasification in fluidized bed reactor using ASPEN PLUS. Biomass Bioenergy, 32: 1245-1254.

Padro, C.E.G. and V. Putsche, 1999. Survey of the economics of hydrogen technologies. National Renewable Energy Laboratory, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/27079.pdf

Pavlas, M., P. Stehlik, J. Oral, J. Klemes, J.K. Kim and B. Firth, 2010. Heat integrated heat pumping for biomass gasification processing. Applied Thermal Eng., 30: 30-35.

Sadhukhan, J., K.S. Ng, N. Shah and H.J. Simons, 2009. Heat integration strategy for economic production of combined heat and power from biomass waste. Energy Fuel, 23: 5106-5120.

Shen, L., Y. Gao and J. Xiao, 2008. Simulation of hydrogen production from biomass gasification in interconnected fluidized beds. Biomass Bioenergy, 32: 120-127.

Smejkal, Q., M. Sarlej and P. Stehlik, 2009. New unit for clean energy production from contaminated biomass (1 to 3 MW_t)-example of process design. Chem. Eng. Trans., 18: 57-62.

Steinwall, P.H., 1997. Integration of biomass gasification and evaporative gas turbines cycles. Energy Convers. Manage., 38: 1665-1670.

Zhang, Y., J. Xiao and L. Shen, 2009. Simulation of methanol production from biomass gasification in interconnected fluidized beds. Ind. Eng. Chem. Res., 48: 5351-5359.