Vol. 1(1), pp. 1-8, December 2022
DOI: 10.0001/AJPC2021.0207
ISSN 2021-xxxx

ASEAN Journal of Process Control

Research Article

Comparative analysis of agile control system for a downdraft gasification with CHP system

Nur Alia Farhana R. M., Low Y. H., Nursyuhada' K., Norhuda A. M.*

Department of Chemical and Environmental Engineering, Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia
*Corresponding Author: norhuda.kl@utm.my
Academic Editor: Syamsul Rizal Abd Shukor
Received: 17 October 2022; Published: 1 December 2022

Abstract: Biomass gasification features a feasible and sustainable option to move forward as a net carbon-negative energy technology. Its maturity and capability to produce hydrogen-rich syngas make it sensible to supersede conventional fossil fuel as clean energy source. In this work, a previously developed empirical model of biomass gasification with CHP system is embedded with PID and MPC algorithms. The agility and robustness of the proposed PID and MPC are demonstrated through the servo and regulatory problems which translated by the intermittent power output. MPC exhibits superior control performance with minimal overshoot and diminutive oscillation compared to PID controller. The outcomes obtained from present study are valuable in identifying the feasibility of PKS gasification with CHP system as a sustainable and clean technology.

Keywords: Model predictive control, Proportional integral and derivative, Agile control, Hydrogen energy, Biomass gasification

1. Introduction

Global energy demand has been heavily reliant on fossil fuels for ages. Recent anthropogenic global warming and climate change phenomena are apparent to put coercive transition to clean and renewable energy. Bioenergy emerges as an alternative and greener option to overcome this daunting issue. This evident with the emphasis on the bioenergy movement in Net Zero Emission by 2050 Scenario [1]. Concomitantly, interest in second generation of biomass originating from non-food source contributes to the stimulation of national policies support and massive activities of agriculture and forestry sectors [2], thus promoting waste-to-energy technology [3].

From gasification technology, biomass can be converted into gaseous, liquid, and solid fuels via thermochemical conversion. Integration of biomass gasification with combined heat and power (CHP) emerges as an alternative approach towards sustainable development, which focuses on the energy security, environmental protection, and social well-being. Thereby, gasification with the CHP system not only offers the benefit of mitigating the greenhouse gas emissions but also the omission of the electricity transmission and distribution network, which contributes to reduction in energy costs for consumers. However, a major problem of biomass gasification is its bulkiness and inconvenient form of biomass. Most of the biomass has a low energy density in comparison to fossil fuels. For instance, the low energy density of palm kernel shell is at 18 MJ/kg while natural gas has an energy density of 55 MJ/kg [4].

Biomass gasification is a complex chemical process that involves gas-solid two-phase flow, heat and mass transfer, cracking and steam reforming of tar vapour, heterogeneous gas-solid reactions, and homogeneous gas phase reactions. Moreover, the amount of syngas heating value is dependent on many variables including raw material, gasifying agents, design of gasifier, and catalysts, thus enhancing the complexity and contributing to the extreme condition of the gasifier [5]. Due to the dynamics imposed on the gasification system with consideration of CHP hybrids, an agile and robust control system is important to accommodate and stabilize the plant operation to ensure it achieve the product portfolio (in this case, power generation) and meeting the energy demand and operational safety. The aforementioned scenarios underpin that much effort need to be exerted to comprehend the dynamic of biomass gasification with CHP and their large-scale suitability [3], whereby plant-wide control strategy play significant measure to it.

Seepersad *et al.* (2015) [5] have carried out a study on the Proportional, integral (PI) controller of steam methane reformer tubes in a gasifier radiant syngas cooler. In their study, both counter-current and co-current flow configurations were compared to obtain the performance objectives. As a result, changing the tube flow rate and the steam-to-carbon ratio affects the tube gas exit temperature and CH_4 slip. The counter-current configurations of the control system exhibited a lot better performance than the co-current configurations in terms of control error and settling time. Mary *et al.* (2015)[6] used a Proportional, integral and derivative (PID) controller with a filter to analyze the gasifier dynamics when the variations in coal quality are applied to the design value. It deals with the pressure control, temperature, and syngas calorific value with a sink pressure disturbance and sinusoidal disturbance at a rate of 18%. As a result, the PID controller with filter gives the best performance compared to other control approaches deployed in their study. Prior to that, Gong (2014) [7] investigated the gasifier temperature and oxygen content of flue gas that was affected by the change of biomass calorific value, material feed flow, and primary air flow of the biomass gasifier. A PID controller has been developed by using a fuzzy neural network control algorithm and the traditional fuzzy control system. The results showed that the fuzzy neural network control gave a better control effect than the traditional one. Because of its performance, it provides a stable control in improving the gasifier temperature and oxygen content of the gasification product.

Vijay and Gandhi (2017) [8] have studied a design of mathematical modelling and control of downdraft biomass gasifier. PID controller was used to control the temperature to achieve an optimal result by manipulating the airflow. It was observed that the PID controller was able to improve the performance of the downdraft gasifier in terms of time-domain specifications, set point tracking, and regulatory changes and also provides optimum stability. Nevertheless, their study only focused on the gasifier performance without considering the CHP system. Recently, Huang and Shen [9] have carried out a study by adjusting the amount of water to improve the output of syngas and reduce the slag in an updraft gasifier based on the adaptive control design. From their study, a combination of multiple adaptive neural fuzzy inference systems (MANFIS) and particle swarm optimization (PSO) was useful to improve the hydrogen production efficiency by 25.43% and reduction of slag formation of the gasifier by 36.8%.

An advanced and intelligent control approach features significant elements in the modern and high-end industrial plant due to its capability to accommodate robust operation, generate feasible income and provide plant safety. MPC exhibits several advantages including the process model capable to capture the dynamic and steady interaction between input, output and disturbance variables. Additionally, control calculations can be coordinated with the calculation of optimum set points thus providing early warnings of potential problems [10]. Li *et al.* (2018) [11] have studied on MPC of biomass/coal co-gasification. The control objective is to control the co-gasification system at the most sustainable operating region via syngas production rate and H_2/CO ration while manipulating the coal flow rate, oxygen flow rate and water flow rate. MPC can stabilize the output at desired level where all the set points are attainable MPC can also keep the system in a pre-defined set point in transient scenarios.

He and Lima (2019) [12] have studied set point tracking for power generation by simulating a step increase and rejecting the disturbance in the coal feed quality. It was observed that the proposed non-linear MPC has the shortest settling time compared to the dynamic matrix controller (DMC). NLPC can process the demand change quickly at approximately 4 times steps faster while other suggested controllers featured sluggish performances with some overshooting. Moreover, NLPC can stabilize the power generation back to its original set point quickly after introducing disturbance in about 4-time steps when compared to PID and other suggested controllers. Elmaz and Yücel (2020) [13] have presented a MPC system for biomass gasification in a downdraft gasifier to maximize energy production. Their study focused on controlling syngas composition and stabilizing high heating value (HHV) output at 10 MJ/kg by manipulating the equilibrium ration (ER) variable. MPC was able to reach and stabilize a high heating value at the desired level in steady-state successfully. MPC approach for real-time control of the biomass gasification process has obtained a satisfactory result due to its high consistency with the experiment data and its success as a controller.

Based on the existing studies, most researchers only focused on the plant-wide control of gasifier reactors without consideration of the down-stream process, such as CHP system. Therefore, this wok performs a control analysis (closed loop analysis) of biomass gasification with CHP system to evaluate the plant behaviour under the intermittent power output (known as plant control objective). Here, the objective is to evaluate the plant's feasibility and overall operability of this conceptual device. Since many studies have focused on syngas composition and yield [14] and not many realize the significance of understanding the process or the attribution of syngas to energy and heat generation.

2. Materials and Methods

2.1 Dataset acquisition

A set of data based on the dynamic simulation of biomass gasification with the CHP system was obtained and adopted from a previous study conducted by our research team [15]. Present work used PKS as the feedstock rather than empty fruit bunches (EFB) and oil palm frond (OPF) since it has the highest lignin content which is proven to be the most preferred fuel for thermal combustion [16]. The adopted dynamic flowsheet model PKS gasification with CHP system flowsheet model consists of a downdraft gasifier equipped with spark fired internal combustion engine (ICE), cyclone, air filtration, flare system and process control unit (PCU) which is based on the actual pilot plant purchased from All Power Labs, Berkeley, CA. A total of 21,601 data with 6 mins interval time was generated from the Aspen Dynamic simulation [15].

2.2 System Identification

A data-driven model is conducted using System Identification Toolbox via the non-linear autoregressive with exogenous input (NLARX) technique. A data-driven model of PKS gasification with a CHP system built in Simulink, MATLAB 2020b is shown in Figure 1 via 4 inputs (u) and 1 output (y) model with model ranges described in Equation 1. Detail of this model development can be referred to [15]. For the preliminary control study, an NLRAX model was linearized based on tangent around the operating point.

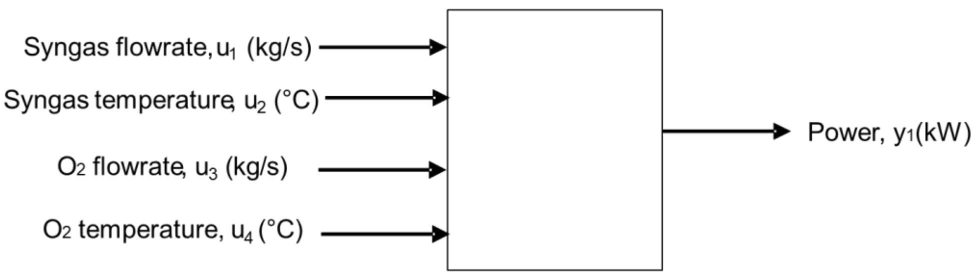


Figure 1. A simplified 4 x 1 NLARX model of PKS gasification with CHP system.

$$u = \begin{bmatrix} 2 & \ll & u_1 & \ll & 4\left(\frac{kg}{hr}\right) \\ 500 & \ll & u_2 & \ll & 800(℃) \\ 680 & \ll & u_3 & \ll & 2200\left(\frac{kg}{hr}\right) \\ 500 & \ll & u_4 & \ll & 700(℃) \end{bmatrix}$$

$$y = [15 \quad \ll \quad y_1 \quad \ll \quad 25\,(kW)] \tag{1}$$

2.3 Agile control system

This work uses the Simulink environment as the control analysis platform due to its computational efficiency in evaluating and simulating the controller performance with more realistic plant dynamics [17]. A conventional feedback PID controller and MPC algorithm are deployed to evaluate the agility (robustness) of the proposed control strategy via servo and regulatory problems. For simplification and a quick evaluation process, a control pairing for the PID controller and MPC is set between the syngas flow rate (as the manipulated variable) and power output (as the control variable). This pairing was based on the previous study conducted by Ashok and Siby [18]. Furthermore, this study can highlight the influence of syngas on energy and heat generation [14].

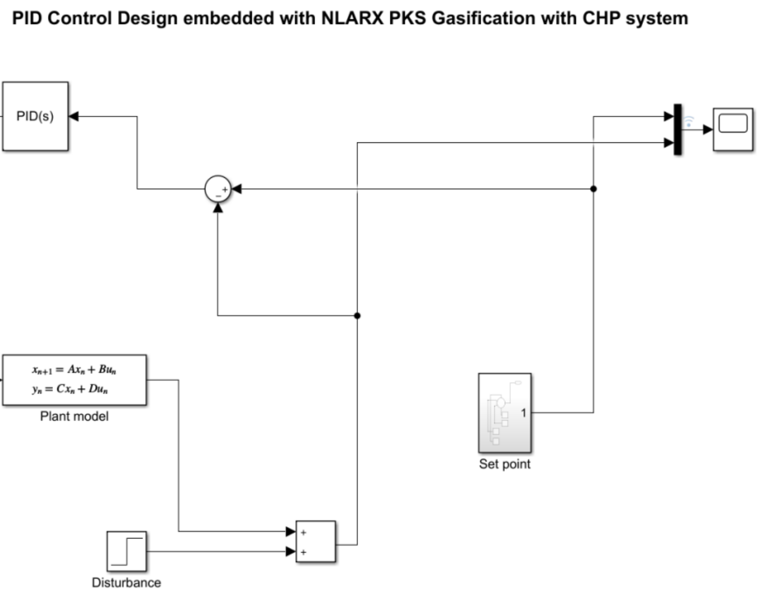
Figures 2 (a-b) illustrates the PID and MPC algorithms integrated with PKS gasification with the CHP system (plant model). A random step-wise set point (servo problem) represented by the intermittent power output at 15-18-12-15-20 kW is simulated to feature a hypothetical operation of PKS gasification with CHP system at peak and off-peak load (illustrated by the "Set point" box in Simulink platform). While disturbance is introduced in random during 10-hour simulation period to illustrate the regulatory problem. In this analysis, perturbation is featured by the "Step-change" box. A 10-hour simulation period using a ready-to-use PID and MPC toolbox are used and embedded into the plant model with control parameter setting illustrated in Table 1. These parameter values were obtained after applying the auto-tuning method for PID and the on-line optimization method for the MPC.

3. Results and Discussion

3.1 Servo problem

Figure 3 shows the control performance of PID and MPC controllers based on the power output as the set-point trajectories (servo problem). Visually, it can be seen that both controllers feature comparable performance. However, significant performance can be observed in terms of control agility between the PID and MPC. For instance, throughout the constant set-point (power output at 12 kW), a minor oscillation was observed which showed that PID was unable to stabilize the power output as depicted in block A (Figure 2). Meanwhile, MPC was able to competently track the power output's set point without any fluctuation. This outcome exhibits the agility of MPC to explicitly predict the future behavior of the plant as well as capable of optimally reduce the process variance.

a)



b)

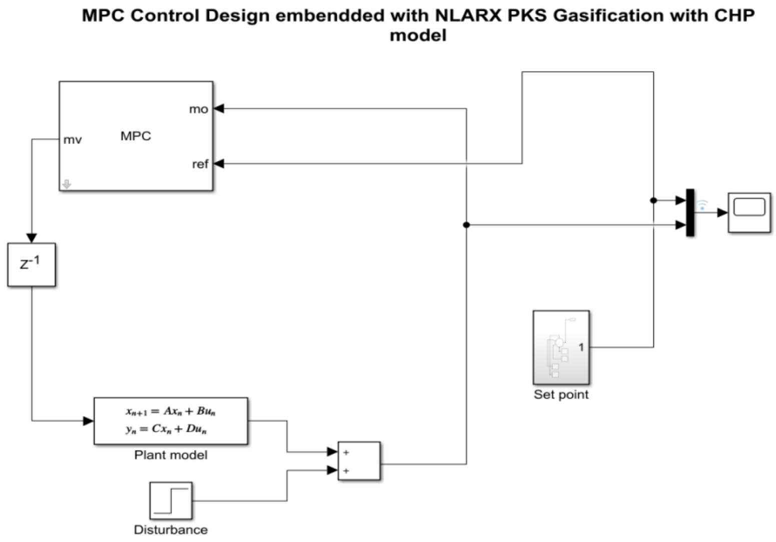


Figure 2. a) PID controller embedded with PKS gasification with CHP model, b) MPC controller embedded with PKS gasification with CHP model

Table 1. Control parameter setting in PID and MPC toolbox in Simulink, MATLAB.

Parameter setting	PID	Parameter setting	MPC
P	0.809	Prediction horizon	10
I	0.453	Control horizon	2
D	-0.214		

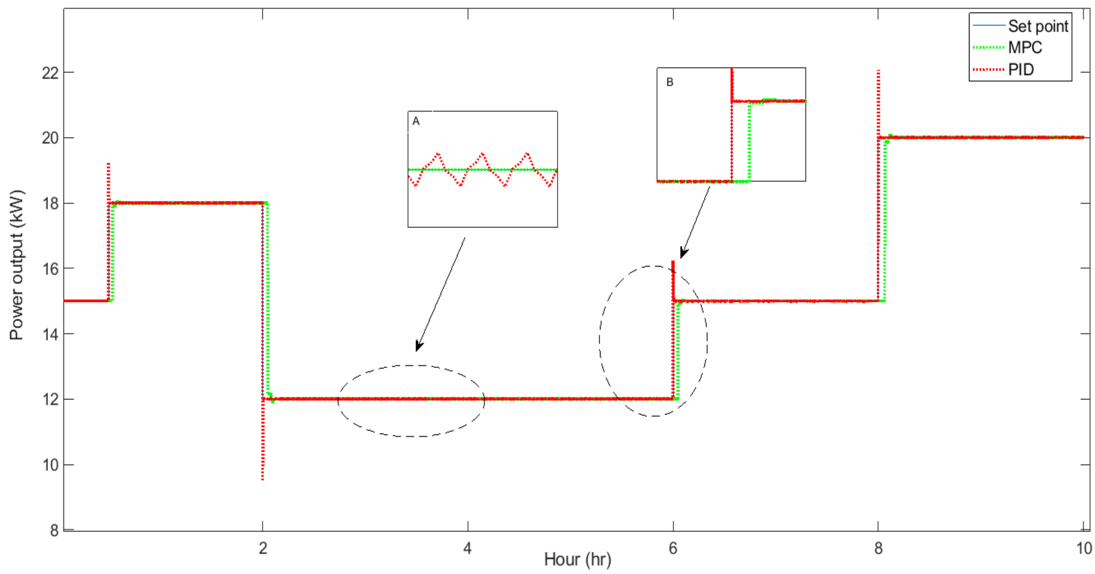


Figure 3. Control performance of PID and MPC algorithm for servo problem.

The peak and off-peak load can be reflected via the set point change as illustrated in Figure 2. It can be seen that an overshoot is displayed at the onset of the set-point change (power output changed). This performance showed the incapability of the PID controller to robustly stabilize the PKS gasification with CHP system under the unprecedented and dynamic conditions/operation.

Under a similar situation (set-point transition), MPC has ramped up the gasifier power output to the required demand whenever the set-point changes. A similar result is obtained by Ashok and Siby [18]. The MPC algorithm took around 6 minutes to respond to the changes/transition of power output with minimal overshoot. It can be observed that the MPC provides satisfactory control performance which is translated by the capability of MPC to eliminate control error with faster response, as the model did not show significant overshoot and damping when stabilizing to its set point.

3.2. Regulatory problem

Figure 4 shows the control performance of PID and MPC controllers based on the disturbance rejection scenario (regulatory problem). In this analysis, perturbation is introduced at a time of 5 hours to represent the dynamic operation of PKS gasification with the CHP system. MPC exhibits efficient disturbance rejection (green line) compared to PID controller (red line). Whereby, PID is unable to competently reject the disturbance featured by the positive/negative spike. Contrary,

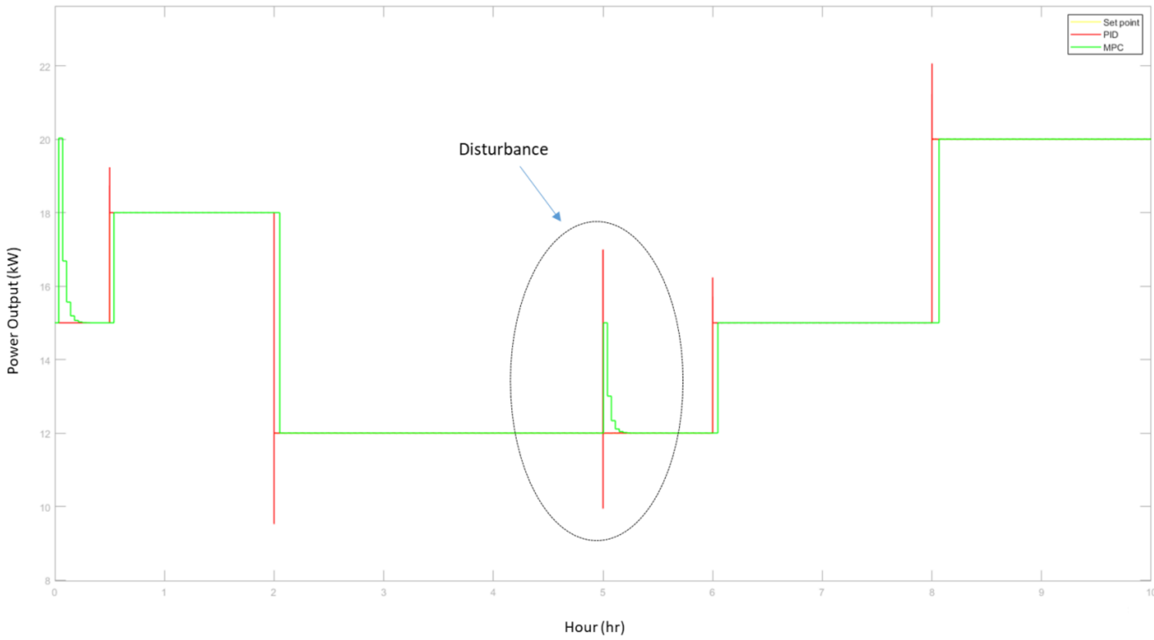


Figure 4. Control performance of PID and MPC algorithm for regulatory problem.

3.3 Root mean square error (RMSE)

The control error between both controllers are evaluated in Simulink, MATLAB by via root mean square error (RSME) as illustrated in Eq. 2.

$$RSME = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(n_p - n_a)^2} \quad (2)$$

Where n_p is the set point of power output, n_a is the actual measured power output and n is the number of measured samples. Diminutive control error was in both PID and MPC controllers were at approximately 1.978 %. Nevertheless, in this case, MPC is technically preferable to be embedded with PKS gasification with CHP system due to it robustness and agility to work under the complex process and unprecedented disturbances.

4. Conclusions

A previously developed data-driven PKS gasification with a CHP model is embedded with two different controllers, which are PID and MPC. A comparative analysis is conducted based on the servo and regulatory problems. It is evident that the MPC algorithm outperformed the performance of the PID controller, which was reflected during the constant set point trajectory, transition set point trajectory, and disturbance introduction. Minimum overshoot with stable set points trajectory exhibited when plant is installed with MPC. Results obtained in this study indicated the robustness (agility) of the developed MPC thus enhancing the dynamic performance and providing good process controllability. Nevertheless, present work possesses some limitation where it only represents the characteristic of gasification-based CHP system with similar operating range and plant capacity. For future research, a comprehensive model can be developed and enhanced by considering detailed composition of syngas (i.e H_2, CO, CH_4 and CO_2) and other key important parameters which are CO_2 emission reduction and cold gas efficiency. With the cooperation of sophisticated digital tools, one is able to evaluate the feasibility of gasification-based CHP system as a smart waste-to-energy technology.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

References

1. International Energy Agency (IEA). Bioenergy Power Generation – Analysis - IEA [Internet].2021.Available from: https://www.iea.org/reports/bioenergy-power-generation.
2. Nagpal, D., and Hawila, D. Renewable Energy Market Analysis: Southeast Asia [Internet].International Renewable Energy Agency. 2018. 1–168 p.Available from: www.irena.org.
3. Kumar, P., Subbarao, P. M. V., Kala, L. D., and Vijay, V. K. Real-time performance assessment of open-top downdraft biomass gasifier system. *Clean Eng Technol*. 2022.;7(10044):8,. doi:10.1016/j.clet.2022.100448.
4. Ahmad, R., Ishak, M. A. M., Ismail, N. N. K. and., Khudzir., Ahmad, R., Ishak, M. A. M., et al. Properties of Torrefied Palm Kernel Shell via Microwave Irradiation. *Biofuels - Challenges Oppor*. 2018. [cited 2022 Dec 8];Available from: https://www.intechopen.com/state.item.id. doi:https://doi.org/10.5772/intechopen.81374.
5. Seepersad, D., Ghouse, J. H., and Adams, T. A. Dynamic simulation and control of an integrated gasifier/reformer system. Part I: Agile case design and control. *Chem Eng Res Des*. 2015.;100:481–96,. doi:https://doi.org/10.1016/j.cherd.2015.05.006.
6. Mary, X. A., Sivakumar, L., and Jayakumar, J. Modelling and control of MIMO gasifier system during coal quality variations. *Int J Model Identif Control*. 2015.;23(2):131–9,. doi:10.1504/IJMIC.2015.068870.
7. Gong, Q. H. Application of fuzzy neural network in the intelligent control of biomass gasifier. *Adv Mater Res*. 2014.;1044–1045:712–5,. doi:https://doi.org/10.4028/www.scientific.net/AMR.1044-1045.712.
8. Daniel, V., and Gandhi, S. Design of Mathematical Modelling and Control of Downdraft Biomass Gasifier. *Int J Control Autom*. 2017.;10(11):175,. doi:http//dx.doi.org/10.14257/ijca.2017.10.11.16.
9. Huang, C. N., and Shen, H. T. Maximum hydrogen production by using a gasifier based on the adaptive control design. *Int J Hydrogen Energy*. 2019.;44(48):26248–60,. doi:https://doi.org/10.1016/j.ijhydene.2019.08.087.
10. Seborg, D. E., and Edgar, T. F. Process dynamics and control.John Wiley & Sons.; 2016.
11. Li, S., Ruiz-Mercado, G., and Lima, F. A novel model predictive control scheme for sustainability: Application to Biomass/Coal Co-gasification System.AIChE Annual Meeting November. Pittsburgh; 2018..
12. He, X., and Lima, F. V. Development and Implementation of Advanced Control Strategies for Power Plant Cycling with Carbon Capture. *Comput Chem Eng*. 2019.;121:497–509,. doi:10.1016/j.compchemeng.2018.11.004.
13. Elmaz, F., and Yücel, Ö. Data-driven identification and model predictive control of biomass gasification process for maximum energy production. *Energy*. 2020.;195:11703,. doi:https://doi.org/10.1016/j.energy.2020.117037.
14. Gambarotta, A., Morini, M., and Zubani, A. A non-stoichiometric equilibrium model for the simulation of the biomass gasification process. *Appl Energy*. 2018.;227:119–27,. doi:10.1016/j.apenergy.2017.07.135.
15. Kamaruzaman, N., Kok, Y. H., Manaf, N. A., Shah, K. N. A. K. A., Yusop, M. Z. M., Rohani, J. M., et al. Modelling and Control Analysis of Bamboo-based Gasification: Towards the Modern Renewable Energy. *Chem Eng Trans*. 2021.;89(November):223–8,. doi:10.3303/CET2189038.
16. Hamzah, N., Tokimatsu, K., and Yoshikawa, K. Solid Fuel from Oil Palm Biomass Residues and Municipal Solid Waste by Hydrothermal Treatment for Electrical Power Generation in Malaysia:

A Review.2019.;Available from: www.mdpi.com/journal/sustainability. doi:10.3390/su11041060.

17. Chinprasit, J., and Panjapornpon, C. Model predictive control of vinyl chloride monomer process by Aspen Plus Dynamics and MATLAB/Simulink co-simulation approach.Vol. 778, IOP Conference Series: Materials Science and Engineering. Paper presented at the IOP Conference Series: Materials Science and Engineering; 2020. doi:10.1088/1757-899X/778/1/012080.
18. Ashok, S., and Siby, J. Application of Model Predictive Controller in Gasifier Power Plant.In: System Modelling, Optimisation and Advanced Process Automation (SYMOPA-2010) Paper presented at the IOP Conference Series: Materials Science and Engineering; 2010. p. 159–64

Citation: Nur Alia Farhana R. M., Low Y. H., Nursyuhada' K., Norhuda A. M. Comparative analysis of agile control system for a downdraft gasification with CHP system. *ASEAN Journal of Process Control* **2023**, **1** (1).