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Modelling and Control Analysis of Bamboo-based Gasification: Towards the Modern Renewable Energy

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Rapid population growth and expeditious economic development have provided significant influence on the increase of global energy demand. This has contributed to the extreme greenhouse gas emissions and anthropogenic climate change. Innovation in bamboo-based gasification with combined heat and power (BG-CHP) system emerges as a potential modern waste-to-energy (WtE) technology to overcome those environmental and energy challenges. In this study, an empirical model is built to evaluate the transient behaviour of BG-CHP system. The empirical model has described the transient variables of a downdraft gasifier equipped with a spark fired internal combustion engine (ICE). A pilot plant dynamic data obtained from the Aspen Dynamic flowsheet model were employed to build a data-driven/empirical model of the gasification based-CHP plant in Simulink, MATLAB. Process control analysis is then conducted based on set point trajectories for 10 h operation via model predictive control (MPC). A control pairing involves syngas flowrate with power output as the manipulated and control variables. A closed-loop analysis revealed that MPC performed well under the intermittent set points 15-18-12-15-20 kW with root mean square error (RSME) of 0.018. The modelling and control results obtained in this study can provide insight into the feasible and flexible operation of a large-scale BG-CHP plant and contribute to the minimization of food and energy competition with the utilization of bamboo as a new-modern energy source.

1. Introduction

The quest for renewable and sustainable energy resource has created looming competition in waste-to-energy technology focusing agriculture and forest residues. This is inline with the Sustainable Development Goals' agenda with the main objective to avoid energy insecurity (imbalance of electricity demand-supply) and extreme climate change. In this case, biomass based energy generations emerge as a reliable and feasible approach towards the movement of modern renewable energy technology (Sun et al., 2014). Bamboo biomass has become an emerging renewable fuel due to its abundancy and its utilization as energy source which may significantly minimize the food and commodity competition, especially in Southeast Asia countries. Several works have been conducted related to the bamboo gasification for energy generation. Those works mostly used simulation-based approach to analyse plant performance and characteristics of plant variables. Kuo et al. (2014) analysed the performance of gasification system using Aspen Plus software, subjected to three different types of bamboo such as raw bamboo, torrefied bamboo at 250 °C and torrefied bamboo at 300 °C. Their result indicated that the used of torrefied bamboo (at 250 °C) as a feedstock exhibited optimal gasification performance (maximum yield of syngas) at an equivalence ratio of 0.28 and steam supply ratio at 0.9. Al-Zareer et al. (2018) analysed three different types of biomasses in the gasification process via Aspen Plus software. They identified that bamboo produced maximum hydrogen gas compared to rice husk and corn straw due to its high volatile matter at the optimum flowrates of air and steam. Experimental analysis was underpinned the aforementioned simulation-based studies, where Zheng et al. (2016) found that the best quality of syngas can be obtained using

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bamboo at optimal gasification temperature of 700 °C. This reflected by the high carbon content exhibited in bamboo biochar which can be exploited for energy source (Hernández-Mena et al., 2014). Based on existing studies, optimal operation of gasification is vital to ensure high quality and quantity of syngas (hydrogen content), since it may affect the energy production.

Major problem of general biomass gasification is its bulkiness and inconvenient form along with the multifaceted process behaviour, which require understanding of the dynamics and robust control system to ensure plant feasibility and flexibility. Vijay and Sanjeevi (2017) studied mathematical modelling and biomass gasification control system. A Proportional, Integral, Derivative (PID) controller was used to control the temperature to achieve an optimal result by manipulating the airflow. Their analysis showed that PID controller is able to improve the performance of the plant in terms of setpoint tracking, regulatory changes and provides optimum stability. Huang and Shen (2019) carried out a study by manipulating the amount of water to improve the output of syngas and reduce the slag in the gasification system by using an adaptive control design. From the study, combination control of MANFIS and PSO is useful to increase the hydrogen production efficiency by 25.43 % and reduced slag formation by 36.8 %. Elmaz and Yücel (2020) designed a model predictive control (MPC) system for biomass gasification with the objective to maximize energy production. It was observed that MPC was able to reach maximum energy generation and stabilizing the high heating value by manipulating the equivalence ratio. This work extends existing research studies by analysing the dynamic behaviour of integrated bamboo gasification with a combined heat and power system (BG-CHP) embedded with MPC strategy. Whereas scarce study explored the plant model and control boundary up to CHP system with the targeted objective is power output. The objective of this study is to understand the plant dynamics and assess the capability and flexibility of BG-CHP system to operate under plant perturbation at designated energy output. Findings from this study contributes to technical insights for commercial scale of BG-CHP plant. Whereas application of robust control system is important not only at the operational level but also impacting the plant's profit and safety.

2. Methodology

2.1 Dynamic flowsheet of BG-CHP system

A steady state flowsheet model of BG-CHP system is built in Aspen Plus before exported to Aspen Dynamics for simulation in dynamic mode. Steady-state BG-CHP model is directly adopted from a study conducted by (Najwa Annuar et al., 2021) which include unit operations (downdraft gasifier equipped with spark fired internal combustion engine (ICE)) with identified operating conditions. Proximate and ultimate analyses for gasification feedstock (bamboo) is adopted from (Mahanim et al., 2011) to reflect the actual characteristic of local bamboo in Malaysia. Initially, valves are added in the steady state flowsheet of BG-CHP system and a pressure-driven configuration was selected before being exported to the Aspen Dynamics. In this work, syngas composition produced from bamboo gasification process (in Aspen Plus model) is directly used as the inlet for dynamic mode, since Aspen Dynamics does not support any component in solid phase as illustrated in Figure 1. Here, the model consists of 5 inputs and 1 output as shown in Figure 2.

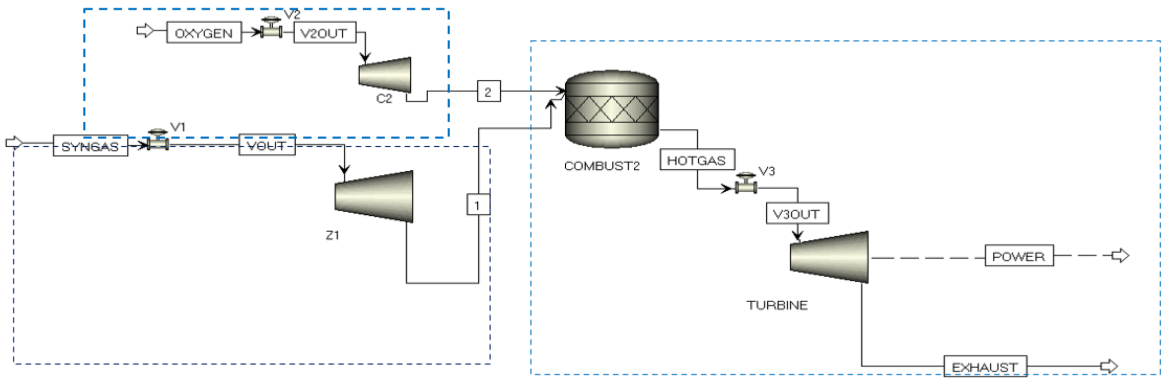

Figure 1: A dynamic BG-CHP flowsheet model in Aspen Plus workspace and model boundaries for NLRAX model

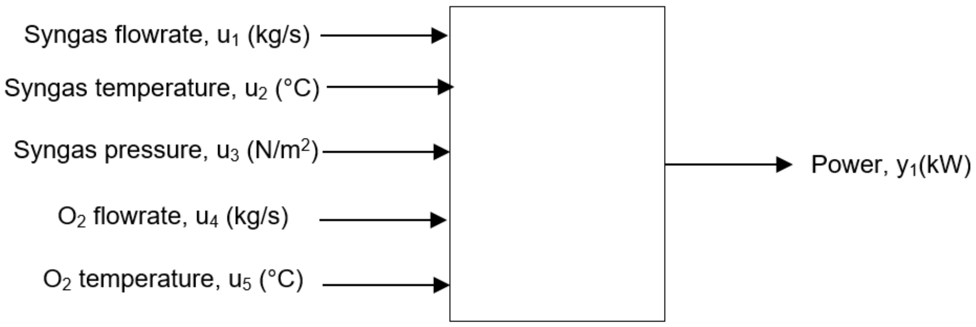

Figure 2: Input-output block diagram for BG-CHP plant

2.2 Empirical model of BG-CHP system

A set of plant data generated from the dynamic BG-CHP flowsheet model is obtained comprised of 21,601 data set at 30 mins interval time for each individual inputs and output. This dynamic data was obtained by changing the valve opening at random percentages. Data is then exported to MATLAB workspace for empirical model development. A data-driven model based on non-linear autoregressive with exogenous input (NLARX) technique is developed using System Identification Toolbox, in MATLAB environment. The NLRAX-BG-CHP model in first built based on plant boundaries as drawn in Figure 1. These three-individual data-driven models is integrated in the Simulink environment via NLARX Toolbox. Please take note that the integrated models is available under the mask of BG-CHP block model as illustrated in Figure 3.

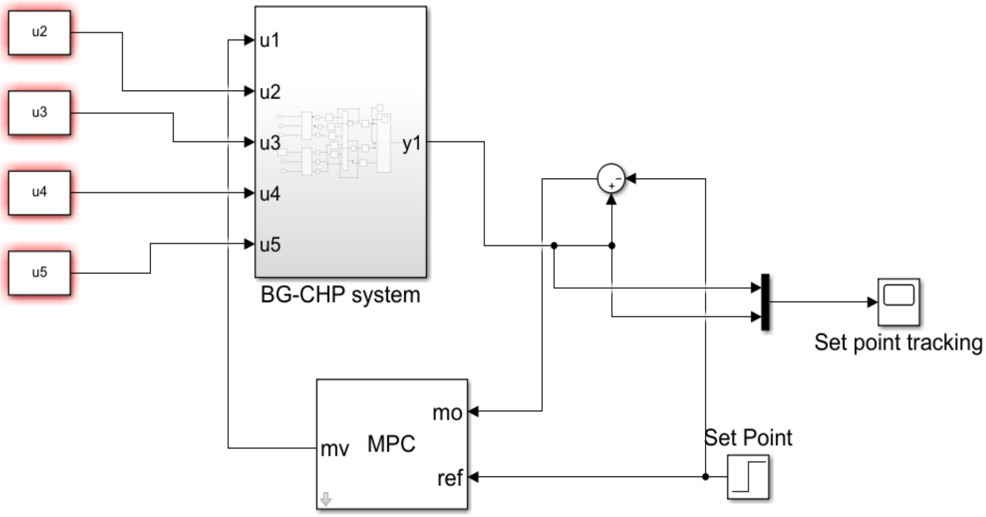

Figure 3: An NLARX-BG-CHP mode embedded with MPC in Simulink/Matlab environment

2.3 MPC design for BG-CHP system

MPC is an advance control algorithm that capable to handle complex and highly dynamic plant without risking the plant's robustness. The MPC's control objective is to evaluate the plant's feasibility and capability subjected to intermittent power output. To reflect this, MPC is designed to control energy generation (power output, y_1) from the BG-CHP plant at intermitted setpoint (15-18-12-15-20 kW) by manipulating the syngas flowrate (u_1). These intermitted set points are analyzed to mimic the hypothetical operation of actual biomass gasification-CHP plant. The perturbation might contribute from the operational problem such as replacement of air separation unit (Dean et al., 2010) and segregation time due to the hybridization of coal-combustion and steam biomass-gasification stages in the same reactor (Chen and Wang, 2013). This control analysis is simulated for 10 h operation and evaluated based on the root mean square error (RMSE).

3. Result and discussion

3.1 Open-loop dynamic analysis

The objective of open-loop dynamic analysis is to appraise and understand the behaviour of the BG-CHP plant when encounter with external perturbation and plant uncertainty. This analysis offers important insights into understanding the plant's behaviour by providing information on sensitivity of variables as well as plantwide control, start-up and shutdown (Abdul Manaf et al., 2016). Open-loop analysis is conducted by applying positive and negative step changes in the input variables which are syngas flow rate (u_1) and syngas temperature (u_2). The step change was instigated after 5 h operation where single input is altered and the other remain constant. These two inputs variables are selected due to its significant influence on plant dynamics and power output for gasification system integrated with CHP. To simulate the open loop dynamic simulation, the process model was initialized using nominal operating condition as used by Najwa Annuar et al. (2021).
Figure 4 shows the output response (y_1) when introduced with positive and negative step changes of u_2. It can be seen that the power output changed swiftly at the onset of the disturbances, before it gradually decreased and stabilized at 20 kW. A similar power output trend was observed under the positive and negative step changes of syngas temperature, revealing changes of syngas temperature did not provide vital impact to the power output generated from BG-CHP system (Lapuerta et al., 2008). This result also indicated that bamboo can be effectively gasified at minimum temperature of 650 °C to obtain significant power output. In this case, maximum power output is at 20 kW since the empirical model was developed based on the actual 20 kW (± 5 kW) APL Power pallet located at Universiti Teknologi Malaysia, Kuala Lumpur (Najwa Annuar et al., 2021).
Figure 5 illustrates the output response (y_1) when introduced with positive and negative step changes of u_1. It was indicated that the power output rapidly changed when the syngas flowrate was varied, showing an instant reaction from the perturbation. It can be seen that the power output reduced gradually when subjected to the positive step change and vice versa when negative flowrate is introduced. At both conditions, the power output was gradually increased until is stabilized to 24 kW. This result illustrated that the quantity and quality of syngas flowrate play a significant role in energy output. Where, this reaction featured the dynamic of BG-CHP plant which requires robust control strategy to sustain the operation.

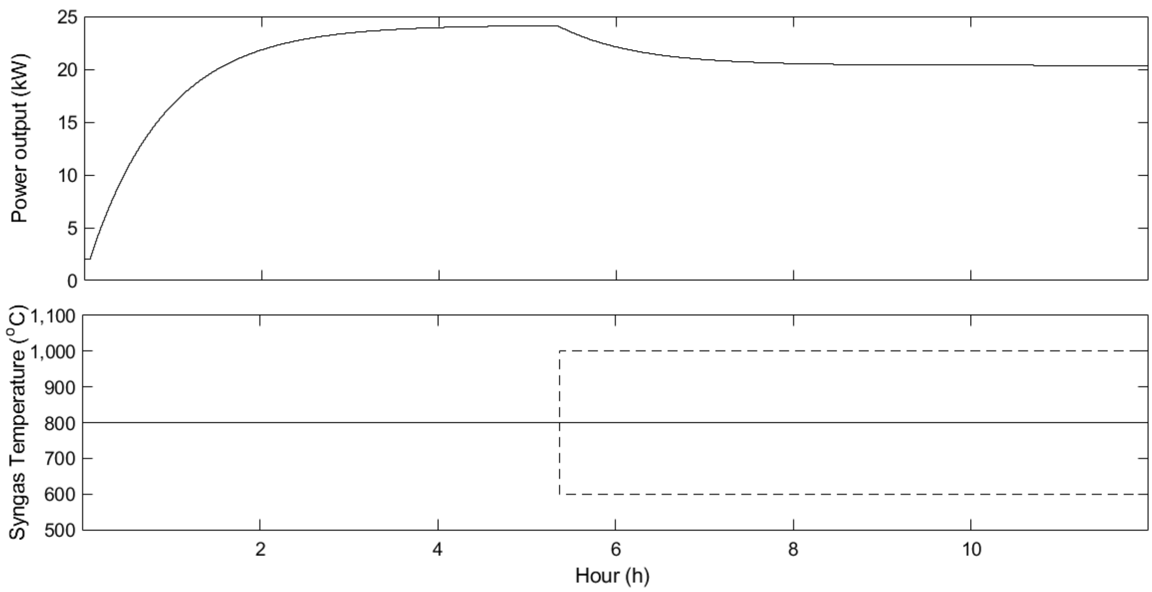

Figure 4: Output responses (y_1) due to a ± 200 point in syngas temperature (solid line: base case; dash line: positive step change and negative step change).

3.2 Close-loop analysis

Figure 6 illustrates the performance of MPC in tracking the BG-CHP plant's objective (power output). MPC is designed based on the prediction horizon, 10 and control horizon, 2 by using default tuning parameters values in the MPC toolbox (input weights = 0.3, output weight = 1). It can be observed that the MPC managed to reach the allocated stepwise-set points at 15-18-12-15-20 kW. A diminutive control error (RSME = 0.018) is exhibited with sluggish control performance (slight delay) at the transitional change of setpoint which shows the complexity of BG-CHP system thus require some time for the plant to reach its stability. A small overshoot featured during the changes of set points exhibit that MPC is capable to effectively handling the intermittent set points by manipulation the syngas flowrate. Similar control performance is seen in the study conducted by Al Seyab et al. (2006). This control performance evident the robustness of MPC to efficiently perform under the dynamic perturbation which apparent the intelligence of developed control strategy.

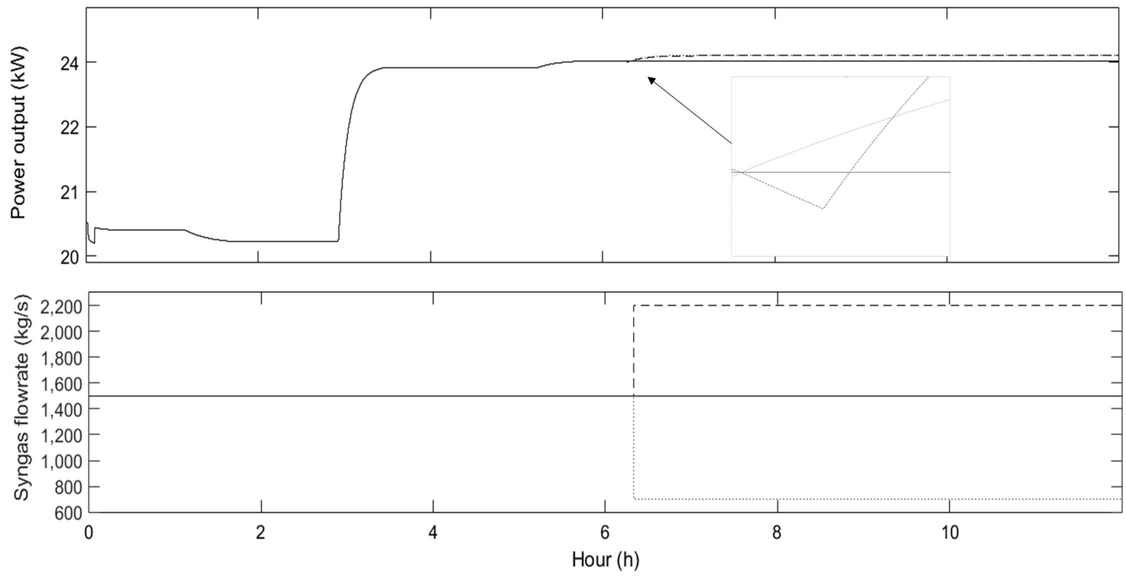

Figure 5: Output responses (y1) due to a ± 700 point in syngas flowrate (solid line: base case; dash line: positive step change, dotted line: negative step change).

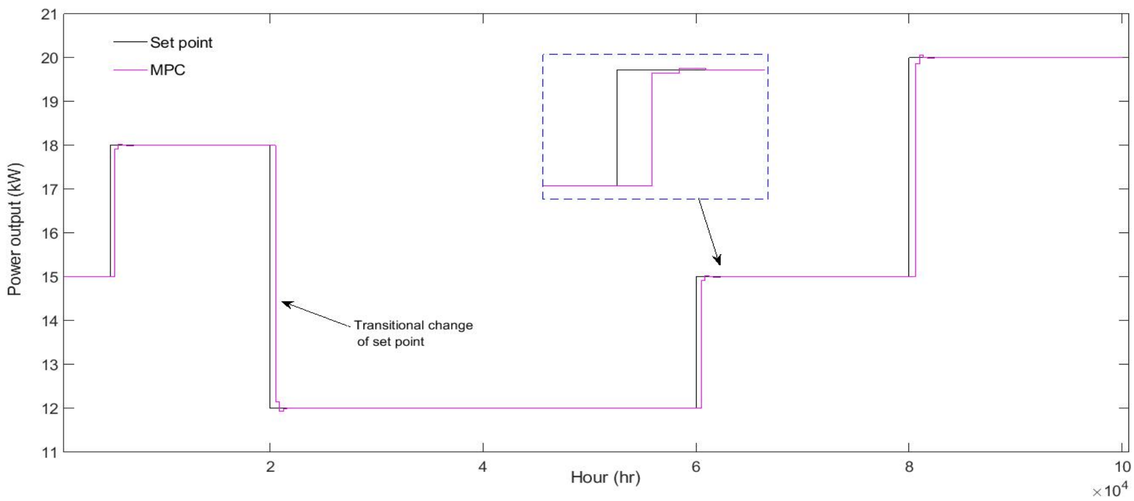

Figure 6: Profile of power output from MPC strategy

4. Conclusion

In this study, a dynamic data-driven model of BG-CHP system is built based on the plant dataset obtained from Aspen Dynamic. This NLARX-BG-CHP model is developed and validated in Simulink/MATLAB environment via System Identification toolbox. Open loop analysis shows that the variation of syngas flowrate provides significant effect to the power output compared to syngas temperature. The MPC scheme tracked the set points of power output while minimising process overshoot and delay. Preliminary finding observed in this work is beneficial towards the transition of modern renewable technology (via minimization of food and energy competition) for instance via co-gasification system, power system flexibility and energy decentralization. This work can be extended by integrating the Simulink/MATLAB with Aspen Dynamics to provide extensive modelling, control and optimization analysis prior to plant scale-up design.

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