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Foreword

The 18th International Conference on Sustainable Energy Technologies was a significant international academic event in the domain of world sustainable energy technologies with a theme of '*Sustainable Energy Towards the New Revolution'*. The conference aimed to provide a forum for the exchange of latest technical information, the dissemination of up-to-date research results, and the presentation of major topics including sustainable energy, low carbon technologies, eco-cities, energy security and environmental policy.

Held from August 20th – 22nd 2019 in Kuala Lumpur, Malaysia, the conference was a collaboration between the World Society of Sustainable Energy Technologies (WSSET), the Universiti Sains Malaysia and University of Nottingham. World-renowned experts and scholars in the area, representatives of prominent enterprises and universities attended to discuss new developments and achievements in the field, as well as promoting academic exchange, application of scientific results, university-industry collaboration and government-industry collaboration.

The papers contained in these proceedings focus on topics such as Energy Storage for the Age of Renewables; Research, Innovation and Commercialisation in Sustainable Energy Technologies; Integrating Planning & Policy, Architecture, Engineering & Economics; Energy and Environment; Engineering Thermo-physics; and Systemic Change for Cities.

About 230 delegates from 30 countries attended SET2019; nearly 400 abstracts were received and 190 papers have been published in the conference proceedings. The proceedings have therefore been divided into three volumes. I hope you enjoy as much as I did the breadth of work you will find in these proceedings.

We would like to thank all participating authors for their contributions to both the conference and to the publishing of this book. We are also indebted to our international scientific committee for their advice and seemingly endless review of papers. We would also like to thank unreservedly Celia Berry, Zeny Amante-Roberts, Dr Mardiana Idayu Ahmad and Professor Dr Norli Ismail for their tireless efforts in making SET2019 one of the most successful conferences we have held. Also a huge thanks to our sponsors First Solar, PCM Products Ltd and Professor Terry Payne.

Professor Saffa Riffat
Chair in Sustainable Energy Technologies
President of the World Society of Sustainable Energy Technologies
Fellow of the European Academy of Sciences
SET 2019 Chairman

CONTENTS

Paper Number **Title** **Page**

#273: Performance modelling and validation on the co-gasification of coal and sawdust pellet in research-scale downdraft reactor

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Co-gasification of fossil fuel with biomass is considered a very promising clean energy option in reducing greenhouse gas emissions and non-renewable energy dependency. The main objective of this research was to develop a simple and reliable model as a preliminary tool to evaluate the performance of co-gasification of sub-bituminous coal with densified biomass (sawdust pellet). The simulation model was validated experimentally to ascertain the performance parameters. The model, which included the minimization of the Gibbs free energy, was simulated using Aspen Plus as the modelling tool. Experimental investigations were carried out under controlled conditions of the electrically-driven externally-heated fixed bed downdraft gasifier in the Biomass laboratory in the Department of Mechanical Engineering, Universiti Teknologi Petronas. The operating parameter of the biomass blending ratio, gasification temperature and equivalence ratio (ER_{air}) on the co-gasification performance parameter were analysed. Three performance parameters, calorific value of the syngas (CV_{syngas}), syngas yield (Y_{syngas}) and gasification efficiency (ŋGE), were studied. The experimental works of the co-gasification took place with air, at the various sawdust pellet blending ratios of 0, 25, 50, 75, 100% w/w, in a gasification temperature ranging from 650 to 850°C, and various air equivalence ratios ranging from 0.1 to 0.4 and under atmospheric pressure.

The increase of the biomass blending ratio denoted a decrease of the calorific value (CV_{syngas}), syngas yield (Y_{syngas}) and gasification efficiency (ŋGE). On the contrary, effects of the gasification temperature at the various blending ratios exhibited an increase for all the performance parameters. In addition, ER_{air} resulted in the decline of the syngas yield (Y_{syngas}), the calorific value of the syngas (CV_{syngas}) and gasification efficiency (ŋGE).

Meanwhile, as the ER_{air} increased, the syngas yield (Y_{syngas}) also increased. Furthermore, it was found out the result obtained from the developed model agreed well with the experimental data conducted in replicate. Thus, the model was validated and considered reliable for predicting the co-gasification performance parameter on the coal and sawdust pellet.

Keywords: co-gasification; coal; wood pellet; Aspen Plus; performance

1. INTRODUCTION

Coal, the third primary energy resources after natural gas and crude oil, accounted for about 16k tonnes of oil equivalent (toe) of the total primary energy supply in Malaysia, and was predicted to increase by 23% over the year in Malaysia (Energy Commission, 2016). Apart from the issue of depletion of fossil fuels reserves, the primary concern of the usage of coal is the production of greenhouse gas emissions and other toxic gases such as CO_2 and NO_x eventually causing global warming and acid rain (Alauddin *et al.*, 2010)**.** Thus, it has heightened the need to search for promising solutions that are renewable, environmentally friendly, sustainable, economical and lessen the current environmental issues. Recent research has proven that co-utilization of coal and biomass was a development of sustainable bioenergy network between a renewable and non-renewable resource, especially in co-gasification to produce syngas and electricity in a sustainable manner (Paiman *et al.*, 2018). Co-gasification technology aids in potentially reducing the exploitation of conventional coal resources, assists in lowering greenhouse gases (GHG) emissions, but also boosts the overall gasification process efficiency (Ali *et al.*, 2016). It has been discovered that the co-gasification of these two fuels exhibited synergism reaction that reduced GHG emissions without reducing the energy content of the product gas (Ciferno and Marano, 2002). Furthermore, biomass characterization and the percentage mixture of biomass with coal plays an essential role as it is directly associated with the fuel gas composition. The co-gasification process between biomass and fossil fuels significantly reduces the carbon footprint on the environment and enhances the H_2/CO ratio in the produced syngas, which is essential in liquid fuel synthesis. Another crucial point, it has been discovered that the inorganic matter present in biomass functions as a catalyst for coal gasification (Satyam Naidu, Aghalayam and Jayanti, 2016). Thus, production of superior gas quality by using coal-biomass blends at different operating conditions and temperatures and ER_{air} have gained interest among researchers (Sarker, 2016). A number of research projects on co-gasification of the various blending ratio of biomass with coal have been conducted with the results indicating that blending coal with biomass eventually enhances the gasification beyond levels that were possible by gasifying these feedstocks alone (Valdés *et al.*, 2016). Most of the studies were focused on the raw biomass co-gasified with coal; however, the co-gasification on the pre-treated biomass, especially pelletization, is still lacking. Dafnomilis *et al.* (2018) expressed the opinion that the pre-treatment of biomass in the form of pelletized or otherwise densified resulted in better fuel operability in terms of handling, transportation, storage, and feeding compared than raw biomass. Gasification of pellet fuel has been widely applied in commercial gasification resulting in syngas composition being much more stable by maintaining a more steady and efficient gasification; the uniform shape and density of the pellet fuels aids in smooth feeding by making less of a biomass bridge and gasification reaction (Yoon *et al.*, 2012). It has been discovered by a number of researchers that the co-gasification of biomass pellets/coal resulted in a promising efficient production of syngas. Although pelletized biomass has been utilized as a co-feed in gasification or combustion systems, the reason for the improvement in the efficiency of the pelletized case gasification is not apparent (Pradhan, Mahajani and Arora, 2018). The development of a fuel-flexible gasification in the pellet form co-gasified with coal remains a challenge, and the field requires further attention. Hence, this study attempts to simulate a co-gasification model of the downdraft fixed bed gasifier with the application of the Aspen Plus® software environment.

Much research has been conducted in modelling the downdraft gasification on various feedstocks either using agricultural residue or forestry residue. This is due to the application of software serving as an alternative to minimize experimental costs and time (Monir *et al.*, 2018). Able to simulate the gasifier by breaking gasification into the drying zone, the pyrolysis zone, the oxidation zone and the reduction zone as well as considering the heat and mass transfer in the model, this tool is capable of predicting gasification performance effectively. Subsequently, the performance of a gasifier system at the different operating and design parameters which can be validated from the optimal model allows designers to speculate the effects of parameters even without any further experimental data (Ismail and El-Salam, 2017). Keche *et al.* (2015) built the developed model with the different biomass fuels in an atmospheric fixed bed reactor to investigate the syngas composition. A model developed by Gao *et al.* (2017) investigated the production of H_2 from the co-gasification of coal and biomass in the presence of CaO as a sorbent. Co-gasification of the charcoal with EFB was developed by Monir *et al.* (2018) that found out that the highest mole fraction of H_2 and CO occurred at a temperature of 975°C and pressure of 35 bar. Ali *et al*. (2016) developed a simulation model of the rice-husk and coal that indicated the model capable of serving as a reliable benchmark for revamping an existing Egyptian natural gas-based power plant. Kuo and Wu (2015) designed the co-gasification of coal with pre-treated biomass, which was the torrefied woody biomass as a substitution to the raw woody biomass. The simulation noted that the utilization of the torrefied woody biomass significantly improved syngas yield. Meanwhile, according to the power generation's view, the co-gasification of coal and torrefied biomass resulted in an optimal input condition in terms of power generation and system efficiency. As far as the authors are aware, there is still limited modelling of co-gasification of coal with pre-treated biomass, especially densified biomass using the Aspen Plus® software.

The objective of this study was to investigate the co-gasification of sub-bituminous coal (CL) with sawdust pellet (SP) by modelling and simulate a kinetic free equilibrium model of fixed-bed downdraft gasifier in Aspen Plus®. The sawdust pellet (SP) blending ratio, gasification temperature and air equivalence ratio were varied to predict the calorific value of the syngas (CV_{syngas}), syngas yield (Y_{syngas}) and gasification efficiency (ηGE). Furthermore, the results obtained from the experimental measurement were used to verify the simulation result obtained from the developed model. The results acquired through this study will serve for preliminary investigation on gasification performance of the pre-treated biomass co-gasified with coal.

2. METHODOLOGY

2.1. Aspen Plus simulation model

In modelling the co-gasification process, a kinetic free equilibrium model is developed using Aspen Plus® software (ver. 8.6). The major chemical reactions that occurred in the gasifier are listed in Table 1 (Kuo and Wu, 2015). The co-gasification process was divided into three sub-systems to form a downdraft gasifier system. The drying sub-system minimized the moisture content of the feed before being fed into the next reactor. The second sub-system aided in decomposing the feed into volatile components and char. Moreover, the FOTRAN statement will be included to specify the yield distribution for each conventional components. Next, the RGibbs sub-system simulated the partial oxidation and gasification process by minimizing Gibbs free energy. In carrying out the modelling, some assumptions were made. The assumptions applied in the model were:

- The process occured in a steady state with kinetic free and the residence time was not considered.
- Atmospheric pressure was assumed in all sub-system.
- Air was introduced in the RGibbs to enhance the co-gasification process at ambient temperature and pressure.
- The gasification agent mixed homogenous and reacted with feed instantly in the reactor.
- All sulphur was produced in the H_2S form; meanwhile no oxide of nitrogen was formed as only NH_3 was produced.
- Tars were assumed to be negligible in the syngas.

The gases involved were in compliance with the Peng-Robinson equation of state with Boston-Mathias alpha function (PR-BM) to estimate all physical properties of the conventional and non-conventional components at the multiple phase in the gasification process (Yu *et al.*, 2015)

Table 1: Chemical reactions that occur in gasifier.

Reaction number	Reaction name	Reaction equation
1	Combustion reaction	$C + O_2 \rightarrow CO_2$
2	Bourdouard reaction	$C + CO_2 \leftrightarrow 2CO$
3	Water gas shift reaction	$C + H_2O \rightarrow CO + H_2$
4	Water gas shift reaction	$CO + H_2O \rightarrow CO_2 + H_2$
5	Methanation reaction	$C + 2H_2 \leftrightarrow CH_4$
6	Methanation reaction	$2C + 2H_2O \rightarrow CH_4 + CO$
7	NH_3 formation reaction	$0.5N_2 + 1.5\ H_2 \rightarrow NH_3$
8	$H2_S$ formation reaction	$H_2 + S \rightarrow H_2S$

2.2. Model development

The simulation model flowsheet used in the developed model is shown in Figure 1. Firstly, the stream of feed consisted of a mixture of sawdust pellet and coal, with a ratio blend of of 0, 25, 50, 75, 100% w/w, respectively was fed into the system. The sawdust pellet blending ratio was defined as the mass ratio of sawdust pellet to the total of biomass and coal, therefore, 0, 100% of sawdust pellet blending ratio refers to the pure coal and pure sawdust pellet, respectively. The feed stream was passed through all blocks with different reaction temperatures. The feedstock was specified as a non-conventional component in Aspen Plus and was defined by their ultimate and proximate analysis present in Table 2. In addition, Table 3 provides the operation model that was used in this study. The drying process that removed the residual moisture in the feed was simulated in the 'RStoic' block by including the FOTRAN statement in the calculator block to control the drying operation. After drying, the feed decomposed into its constituent components (C, H, O, S and N) by specifying yield distribution in the block 'RYield'. The feed needed to decompose as the 'RGibbs' block cannot calculate the feed due to its non-conventional components. In the 'RYield' block, the yield distribution of the feed was specified by FOTRAN statement in a calculator block into its components. The total yield of volatiles was assumed to be equal to the volatile content of the parent fuel by taking into account the proximate analysis of the fuel. The co-gasification process was simulated in 'RGibbs' block by minimizing the Gibbs free energy assuming the complete chemical equilibrium calculations. The gasifying agent, which was air, was introduced into the block where partial oxidation and gasification reactions took place. Furthermore, the 'RGibbs' block was capable of calculating the syngas composition as it can generate light gases such as CO, CO_2, H_2, H_2O, N_2, CH_4, and H_2S. H_2S in the gases were considered negligible due to the lower content of sulphur in the fuel. In addition, considering that only NH_3 formed in the gasifier without any formation nitrogen oxide has already been used by other researchers (Schuster *et al.*, 2001). The outlet stream of the 'RGibbs' passed through the 'Sep' block to separate gases from ash according to the specified splits fractions as desired. The 'Sep' in the Aspen Plus model was simulated for the functioning in ash separation from the syngas.

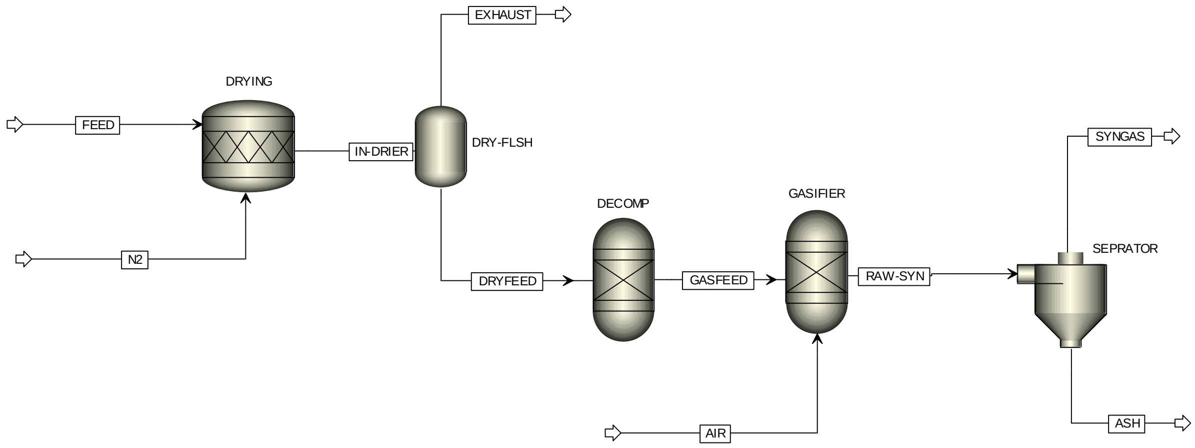


Figure 1: ASPEN Plus simulation model of co-gasification on coal with WP.

Table 2: Proximate, ultimate and calorific value of the coal and WP

Components	Coal	Sawdust
Proximate analysis (wt %)		
Moisture content	8.18	9.19
Volatile matter	39.79	79.00
Fixed carbon	33.81	10.16
Ash content	18.22	1.65
Ultimate analysis (wt %)		
Carbon (C)	52.58	44.28
Hydrogen (H)	5.90	6.09
Nitrogen (N)	1.49	1.05
Sulphur (S)	1.14	0.28
Oxygen (O)	38.90	48.62
Calorific value (MJ/kg)	20.19 ± 0.082	17.46 ± 0.085

Table 3: List of ASPEN Plus unit operation model.

Aspen Plus Model	Operation	Description	Function
RStoic	Drying	Conversion reactor with known stoichiometry	Reduce the moisture content of the wet feed
RYield	Decomposed	Yield reactor with known products yield	Decomposed non-conventional feed into its element constituents applying FOTRAN statement
RGibbs	Gasifier	Multiphase chemical equilibrium reactor (non-stoichiometry)	Models gas-phase chemical equilibrium and aids in calculating the syngas composition by minimizing Gibbs free energy
Sep	Separator	Split a stream into two stream or more by specifying split fractions	Separates gas from ash

2.3. Model verification

In order to demonstrate the validity of the proposed model, the experimental measurement of co-gasification of coal with SP was carried out in a lab-scale electrical downdraft gasifier, as shown in Figure 2. The system was custom-fabricated and located in the Biomass laboratory under the Department of Mechanical Engineering of Universiti Teknologi Petronas, Malaysia. The reactor was a cylindrical tube made up of stainless steel class SS316 consisting of an internal diameter of 80mm and 500mm long. The gasifier was positioned vertically as a function in a free-fall, gravity-fed reactor. About 100g of the feed was then loaded into the gasifier with the different mixture ratio of SP at 0, 25, 50, 75, 100% w/w. The electrical downdraft gasifier was heated with a WATLOW 240V, 1300W ceramic-embedded radiant tube heater with a maximum heating temperature of 1000°C on continuous duty. Furthermore, the operating temperature varied from 650°C to 850°C and was measured by an external PID controller coupled with a K-type thermocouple mounted on the gasifier reactor. Meanwhile, a stainless steel grate was held at the centre inside the gasifier acting as the feedstock holder and also as the reactor bed where the thermal conversions took place. Air as an oxidizing agent was distributed in the gasifier by the compressed air through a 5mm welded connection situated slightly below the top of the gasifier and controlled by a rotameter. The equivalent ratio of air fixed at 0.20, 0.25 and 0.30 were varied using the airflow rate from 2 L/min - 4L/min. The gasifier had two threaded openings at the top and bottom for the feedstock loading and for ash removal and cleaning access respectively. Gases flowed to the bottom of the reactor, certifying a downdraft fixed bed configuration (Susastriawan, Saptoadi and Purnomo, 2017). The gases then flowed to a gas conditioning unit before entering the online gas analyzer for gas composition measurement.

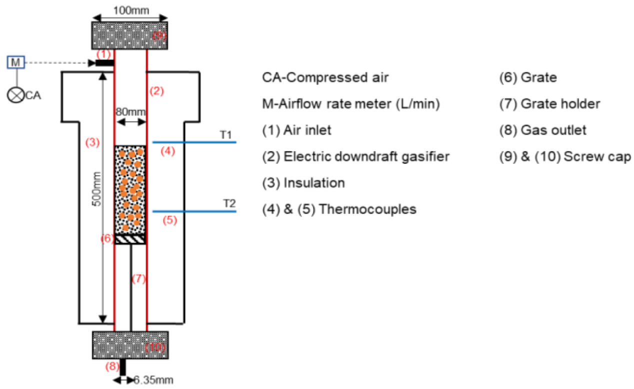


Figure 2: Schematic diagram of laboratory scale electrical downdraft gasifier used for the model validation.

The developed simulation model for co-gasification of coal and SP was used to perform the sensitivity analysis. The effect of the sawdust pellet (SP) blending ratio, gasification temperature and air equivalence ratio (ER) on each syngas composition, the calorific value of the syngas (CV_{syngas}), syngas yield (Y_{syngas}) and gasification efficiency (ŋGE) was investigated. The calorific value of the syngas (CV_{syngas}) was calculated as it was an important output parameter that defined the quality of syngas produced from gasification in terms of energy content per unit volume or mass. The calorific value of the syngas (CV_{syngas}) was calculated by taking into account the volume percentage of combustible gas components in the syngas (CO, H_2 and CH_4) produced from the co-gasification experiment with their specific calorific value obtained from the US National Renewable Energy Laboratory (NREL) in the unit of MJ/Nm^3 as per standard value (Basu, 2010b). The equation is expressed in Equation 1*Equation*.

Equation 1: Calorific value of the syngas (CV syngas). $$CV_{syngas} = (V_{CO} \times 12.63) + (V_{CH_4} \times 39.82) + (V_{H_2} \times 12.74)$$

Where:

- CV_{syngas} = calorific value of the syngas (MJ/Nm^3)
- V = volumetric percentage for each of CO, CH_4 and H_2 obtained from online gas analyzer measurements (%)

Meanwhile, the syngas yield (Y_{syngas}) in the unit for each experiment took into account the volume of syngas produced per unit mass of feedstock consumed in the gasifier by considering the nitrogen balance method that was proposed and applied by several authors (Atnaw, Sulaiman and Yusup, 2011). It was applied by taking into account the continuous exposures of the high temperatures as well as the tar depositions in the measuring equipment causing the inaccuracy of the reading. The calculated value is given in Equation 2.

Equation 2: The syngas yield (Y_{syngas}) from the co-gasification of coal and SP. $$Y_{syngas} = \frac{Q_a \times 79\%}{m_{feed} \times N_2}$$

Where:

- Y_{syngas} = syngas yield (Nm^3/kg)
- Q_a = volume flow rate of air (Nm^3/h)
- m_{feed} = mass flow rate of the feedstock in the gasifier system (kg/h)
- N_2 % = volumetric percentage of N_2 in the dry fuel gas

Furthermore, the gasification efficiency (ŋGE) can be calculated either from the cold gas efficiency or hot gas efficiency (Kumar et al., 2014). It is possible to define the cold gas efficiency as the ratio between the chemical energy leaving the system associated with the cold and tar-free syngas and the chemical energy entering the system related to the biomass (Inayat *et al.*, 2016). Thus, the gasification efficiency was calculated by considering the specific gas production and the energy content of the biomass. The gasification efficiency (ŋGE) was calculated using Equation 3.

Equation 3: The gasification efficiency from the co-gasification of coal and SP.

$$\eta GE = \frac{CV_{syngas} \times Y_{syngas}}{CV_{feed}} \; x \; 100$$

Where:

- ηGE = gasification efficiency (%)
- CV_{syngas} = calorific value of the syngas (MJ/Nm^3)
- CV_{feed} = calorific value of the feed (MJ/kg)
- Y_{syngas} = syngas yield (Nm^3/kg)

The comparison between the predicted data from the simulation model and the experimental data for the co-gasification of coal and SP were discussed on the gasification performance in term of CV_{syngas}, Y_{syngas} and ηGE. In addition, the root mean square error (RMSE) was calculated using Equation 4 for each gasification performance at different gasification conditions to measure the error between simulation and experimental.

Equation 4: Calculation of RSME at every gasification performance.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}$$

Where:

- P = predicted value
- = observed value
- n = number of dataset

3. RESULTS AND DISCUSSION

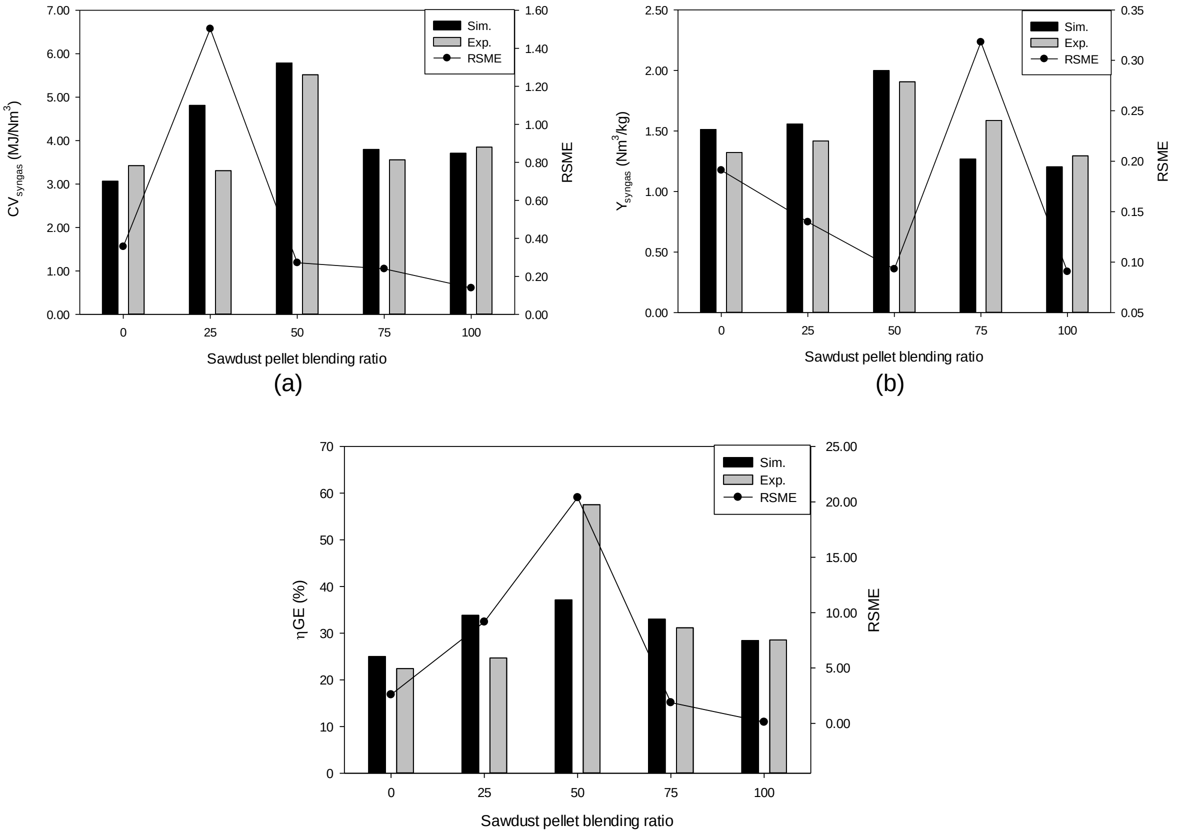
A sensitivity analysis was performed in the GASIFIER block by varying the gasification temperature and airflow parameter at different sawdust pellet blending ratios. This was to investigate the effect of sawdust pellet blending ratio, gasification temperature and air equivalence ratio on the gasification performance. In ASPEN Plus, this tool helped in determining the gasification performance on the varying input parameters. Table 4 shows the input parameters of the temperature and airflow applied in the model.

Table 4: Variable set in the GASIFIER block of the model.

Variable	Type	Block/stream	Variable	Unit	Limits	Increment
Temperature	Block-var	GASIFIER	TEMP	°C	600-1000	50
Air flow	Stream-var	AIR	MASS-FLOW	kg/hr	0.1-0.4	0.025

3.1. Effect of sawdust pellet blending ratio

Figures 3 (a), (b) and (c) present the effect of the sawdust pellet at blending ratio of 0, 25, 50, 75, 100% w/w on the $CV_{syngas,}$ Y_{syngas} and ηGE, respectively. The gasification temperature and the ER_{air} was fixed at 750°C and 0.25, respectively. It can be seen that all the gasification performance increased with the increasing of the sawdust pellet blending ratio from 0 to 50%. The range of the $CV_{syngas,}$ Y_{syngas} and ηGE calculated were 3.00 – 6.00 MJ/Nm^3, 1.00 – 2.00 Nm^3/kg and 25% - 37%, respectively. It was found that the maximum value of the $CV_{syngas,}$ Y_{syngas} and ηGE from the simulation was calculated at 5.78 MJ/Nm^3, 2.00 Nm^3/kg and 37%, respectively that occur at 50% of the sawdust blending ratio. However, as the amount of the sawdust pellet blending ratio increased to 75%, all of the gasification performance dropped down by an average of 30%. A similar trend was found by Seo *et al.* (2010) who noted that increasing the Y_{syngas} at all temperatures together with an increase in biomass ratio was due to the transfer of hydrogen radicals in biomass to coal that resulted in higher decomposition of coal. The suggested minimum blend of 40% pine chips to 60% Sabero refuse coal with the value of 1.78 Nm^3/kg by Pan *et al*. (2000) was quite similar to those for the highest yield of syngas obtained from this study when assessing influence of the biomass blending ratio on the Y_{syngas}. In term of the RSME value, both of the CV_{syngas} and Y_{syngas} were in the range of the 0 to 1.60, being relatively low and generally well aligned with the experimental result. Hence, this denoted that the purpose model was validated and reliable. In contrast, the RSME value of the ηGE was in the range of 0 to 21, in which the highest was recorded at 50% of the sawdust pellet blending ratio. This deviation might be due to the equilibrium condition that was applied in the gasification model that eliminated insignificant reaction between the coal and biomass (Ghassemi and Shahsavan-markadeh, 2014).



(c)

Figure 3: Effect of the sawdust pellet blending ratio with calculated RMSE value on (a) CV_{syngas} (b) Y_{syngas} and (c) ŋGE at gasification temperature and E_{air} fixed at 750°C and 0.25.

3.2. Effect of gasification temperature

The influence of the gasification temperature from 650 to 850°C on various sawdust pellet blending ratio with the ER_{air} fixed at 0.25 on the gasification performance is illustrated in Figure 4. Figures 4(a), (c) and (e) show the CV_{syngas}, Y_{syngas} and ŋGE as a function of gasification temperature, respectively. Meanwhile, the RSME value for every gasification performance in terms of CV_{syngas}, Y_{syngas} and ŋGE are illustrated in Figures 4(b), (d) and (f), respectively. Altogether, it can be seen that the gasification temperature at the various sawdust pellet blending ratio exhibited an increase for all the performance parameters. The range of the CV_{syngas} was from 2.00 to 6.00 MJ/Nm^3, and Y_{syngas} ranged from 1.00 to 2.00 Nm^3/kg. Furthermore, ŋGE ranged from 18% to 37%. The maximum of each of the gasification performances occurred at 50% of the sawdust pellet blending ratio. It can be concluded that the optimum blending ratio for the sawdust pellet with coal was 50%. A study conducted by Masnadi *et al*. (2014) assessed that the increase of the CV_{syngas} was associated with higher gasification temperatures resulting in the endothermic gasification reactions (Adeyemi *et al.* 2017). Complementary to this higher gasification temperature, there were more heat losses of the system and eventually the gasification process on the syngas production was improved. Meanwhile, increasing the gasification temperature enhanced the release of gaseous products from the pyrolysis, steam reforming, gasification and cracking reactions inside the gasifier and contributed to the high total amount of Y_{syngas} (Patel and Narnaware, 2018). These results were also recognised by several researchers who attributed the influence of temperature on Y_{syngas} in co-gasification (Fermoso *et al.*, 2009). Considering the rising of the gasification temperature improved the endothermic char reactions in the gasifier, it can be concluded that the increase of the Y_{syngas} was expected due to the increasing concentration of gaseous product (Ahmed *et al.* 2015). It was seen that the increase of ŋGE as the gasification temperature increased was mainly due to the rise in CV_{syngas}. As previously mentioned, the lower RSME value indicated the least error between simulation and experimental. It can be seen from the RSME value for each the gasification performance parameter against the gasification temperature was lower than 20. Consequently, the model was suitable to serve as a preliminary for the co-gasification of coal with pellets.

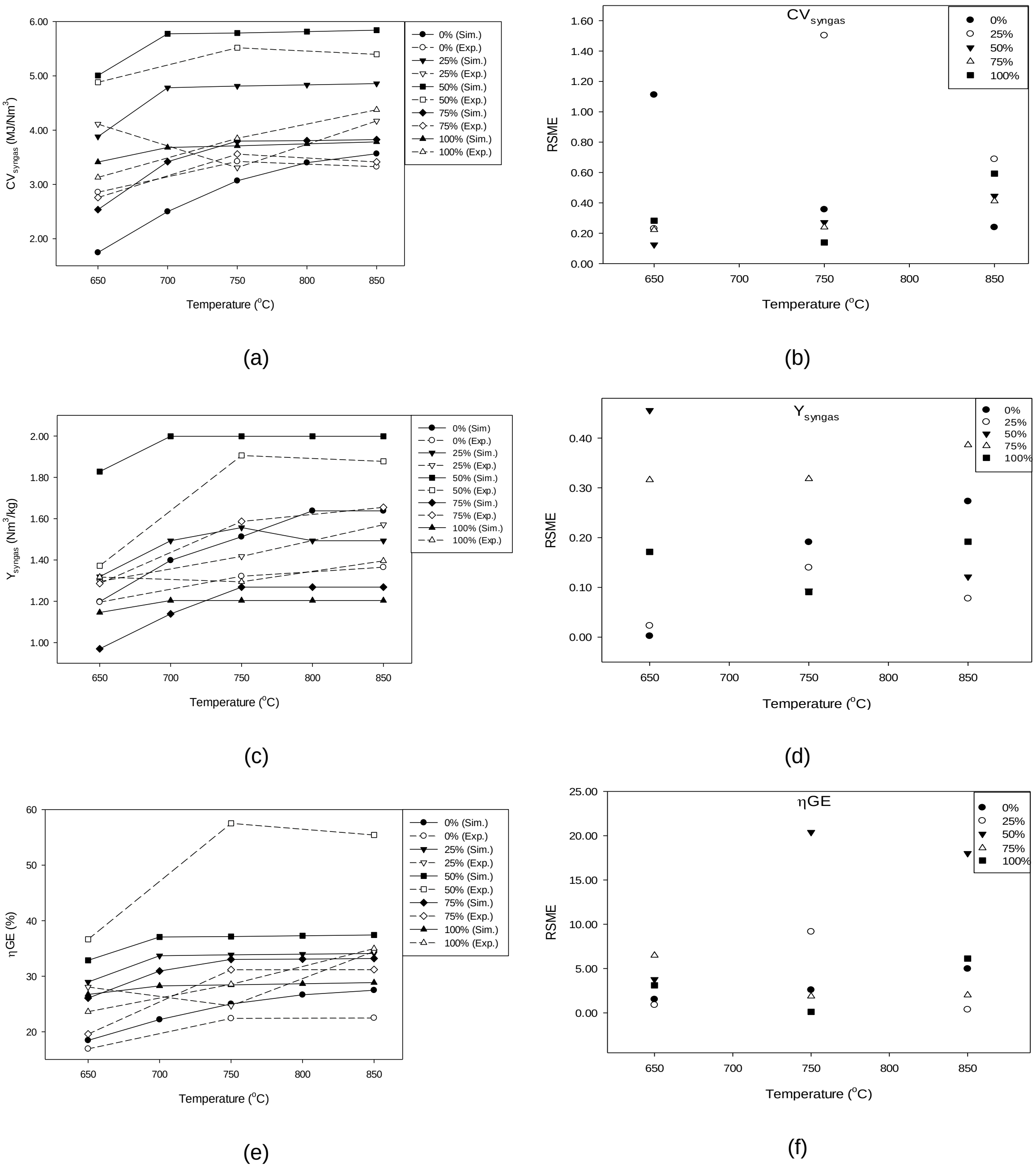


Figure 4: Gasification temperature at ER_{air} of 0.25 influence on (a) CV_{syngas} (c) Y_{syngas} and (e) ŋGE with the respectively calculated RSME (b), (d) and (f).

3.3. Effect of air equivalence ratio

CV_{syngas}, Y_{syngas} and ŋGE plot are presented in Figures 5 (a), (c) and (e), respectively for co-gasification of sawdust pellets at various blending ratio testing at gasification temperature fixed at 750°C. It can be seen that the CV_{syngas} and ŋGE gradually decreased as the ER_{air} increased to 0.4. The CV_{syngas} and ŋGE ranged from 1.6 to 8.4 MJ/Nm^3 and 14% to 51%, respectively. Both of the highest quantities of CVsyngas were recorded at pure sawdust pellet achieved at 8.369 MJ/Nm^3 and 51%, respectively. This can be predicted as the nature of the pellet form enhanced the energy density per unit volume, uniformity and defined structure of fuels thus possessed higher stability without depending on the critical variation of time (Yoon *et al.,* 2012). In addition, for other feeds, increasing the ER_{air} contributed to the higher airflow rate resulting in the lower heating values for syngas and significantly reduced the gasification process efficiency (Azargohar *et al.*, 2015; Valdés *et al.*, 2016). This was believed to occur due to the ER_{air} being related to the airflow rate, therefore increasing the airflow rate resulted in the shorter residence time of the feed to undergo reactions (Basu, 2010; Yan *et al.*, 2018). Inversely, increasing the ER_{air} value, the value of the Y_{sngas} also increased. Upadhyay *et al.* (2019) stated that the total Ysyngas was mainly associated with the fuel and air consumption rates. The study conducted on the co-gasification of lignite and sawdust briquette found that the higher gas yield reached at 2.99 Nm^3/kg obtained a high ER_{air} of 0.386. Commonly, it has been stated that for effective downdraft gasification, the ER should be between 0.2-0.4 (Basu, 2010). For the RSME value, as previously described, the RSME value for both for the CV_{syngas} and Y_{syngas} were lower, ranging from 0 to 2.3. The RSME value for ŋGE ranged from 0 to 32 which is quite high, and was calculated at 50% of the sawdust pellet blending ratio. This might be due to the kinetic reaction taking place in the gasifier during the experimental measurement.

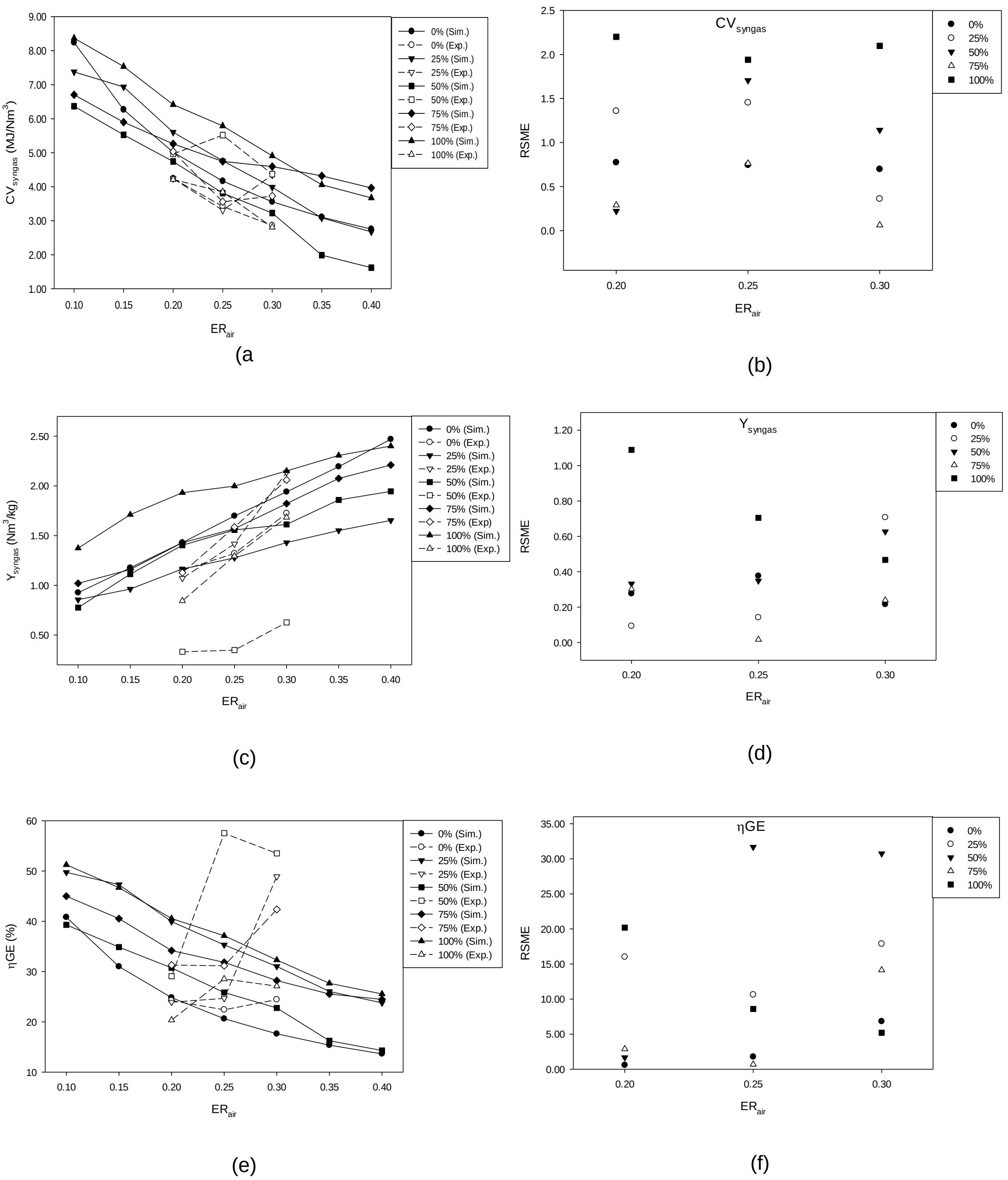


Figure 5: Influence of ER_{air} at the various sawdust pellet blending ratio from 0, 25, 50, 75, 100% w/w at gasification temperature 750 °C on the (a) CV_{syngas} (c) Y_{syngas} and (e) ŋGE with the respectively calculated RSME (b), (d) and (f)

4. CONCLUSION

Simulation modelling on the co-gasification of coal and sawdust pellets was developed using the Aspen Plus software. The effect of the sawdust pellet blending ratio, gasification temperature and E_{air} on the gasification performance were investigated. The results show that 50% of the sawdust pellet blending ratio in the co-gasification possessed the maximum CV_{syngas}, Y_{syngas}, and ŋGE at 5.84 MJ/Nm^3, 2.00 Nm^3/kg and 37%, respectively. Increasing of gasification temperature also increased the gasification performance of the co-gasification. The effect of the ER_{air} on the gasification performance was also studied. The sensitivity results indicated that the higher ER_{air} contributed to the lower value of the CV_{syngas} and ŋGE that occurred at 50% of the sawdust pellet blending ratio. The data obtained from the simulation model was validated with the experimental measurement by calculated the RSME value. The RSME showed the relatively low value of CV_{syngas} and Y_{syngas} indicating that the proposed model could be adopted to measure the gasification performance. In contrast, the RSME value on the ŋGE was quite high due to the equilibrium state assumed in the model. Hence, in future work on co-gasification of other types of sawdust pellet with coal, the same model could be used to carry out studies of the gasification performance in terms of CV_{syngas} and Y_{syngas}. To improve the model, the kinetic reaction between the sawdust pellet and coal needs to be taken into consideration and be simulated in the model.

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