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Research Article

A Comparative Analysis of Biomass Gasification Temperature Effect to Gasification Performance

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Abstract

Raw biomass could be converted into valuable chemicals or other high-value gases with biomass gasification technique. Considering the complexity resulting from many chemical reactions involved, it is necessary to model the gasification process. The analytical, numerical, and experimental method has been performed to build a comparative analysis in this research. The effect of temperature from biomass gasification design and operating parameters varied against the gasifier's performance (syngas mass fraction, efficiency, and syngas calorific value). The analytical method was performed with a thermodynamic equilibrium model to assess the performance of the biomass gasifier. Global gasification reaction using zero-dimensional model approach was solved with Newton Raphson method and fsolve in MATLAB. A numerical method was executed with STAR CCM+ Computational Fluid Dynamic simulation software. Complicated gasification reactions could be simulated based on the solutions for many simultaneous stages of equations, like conservation of mass, momentum, energy, also heterogeneous and homogeneous chemical reactions. An experimental method was carried out using the simplest design of the downdraft gasification reactor. The results from the experimental method were applied to validate the analytical and numerical methods obtained previously. Analysis of Root Mean Square Error performs a good agreement with another research published earlier. The optimal operation parameter was gasification temperature 800–900°C, moisture content below 20% and equivalence ratio (ratio between actual air-fuel ratio and stoichiometric air-fuel ratio) of 0.35. Gasification performance is syngas calorific value 5.69 MJ/m3, efficiency 73.71% while syngas mass fraction is 17.5% H_2, 21.3% CO, 13.3% CH_4, 3.1% CO_2, and 44.2% N_2.

Keywords: Analytical, Numerical, Experimental, Biomass Gasification

Introduction

Energy is currently being used every day since it is one of the necessities for humans. People's prosperity could be determined by the quality and quantity of energy usage. The world's economy has been supported heavily with energy to develop since the industrial revolution in the 18th century. Industrial sectors such as mining, agriculture, manufacturing, construction, housing, transportations, and many other appliances use energy extensively daily. Many countries still rely on fossil fuels like gas, oil, and coal to support their energy demands. Millions of years are needed to form fossil fuel; it cannot be filled anymore once used. Only a few decades left until fossil fuels can be used because fossil fuel is very limited and a non-renewable energy. According to some researchers like Hasan et al., [1], Ahmad et al., [2], it is estimated that within 50 to 120 years, the world will run out of fossil fuels.

Carbon emission reduction techniques have been performed by using renewable sources of energy to replace conventional fossil fuels. Renewable sources of energy could be consumed for heat and power generation in many industries like transportation, manufacturing, and so forth. Energy reduction initiative has been carried out to suppress greenhouse emissions; another idea is to use biomass as an alternative energy source.

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This research will focus mainly on biomass energy production. Biomass is carbon-neutral fuel, or no net carbon emitted from biomass usage. Plants absorb carbon during their growth and release relatively the same amount of carbon during combustion.

The palm oil tree *(Elaeis guineensis)* is one of Indonesia's main non-oil and gas commodities. The government has promoted the agricultural sector extensively to support Indonesia's economy. Along with Malaysia, Indonesia is the leading palm oil producer globally, with more than 90% global production. According to Loh [3], the oil palm industry has been mentioned as one of the most biomass producers since an abundant amount could be generated. In Indonesia, it is estimated that crude palm oil production is more than 10 million metric tons and covers more than 10 million hectares. Each kilogram of crude palm oil production will generate four kilograms of biomass. Only the fresh fruit bunch will be consumed as the desired financial part of the whole palm tree. The remaining portion could be used as a renewable source like empty fruit bunch, mesocarp fibre, palm shell, oil palm fronds, and oil palm trunks.

There are two paths of biomass conversion according to Basu [4], i.e., biochemical or thermochemical path. In biochemical conversion, biomass molecules are cracked down into much smaller molecules using bacteria or enzymes. This process does not require much external energy, but biochemical conversion takes longer than thermochemical conversion. Anaerobic and aerobic digestion, fermentation, and hydrolysis are some processes in biochemical conversion. Thermochemical conversion is much faster but requires much external energy. Dahlquist [5] reported that some processes belonging to thermochemical conversion are pyrolysis, liquefaction, combustion, and gasification. Pyrolysis occurs at a comparatively lower temperature in the absence of oxygen. Liquefaction decomposes bigger biomass molecules into smaller molecules in the liquid phase. The catalyst is used in liquefaction at a relatively lower temperature. Combustion is a high-temperature biomass conversion into carbon dioxide (CO_2) and steam with excess oxygen. Gasification engages with several chemical reactions in an oxygen-deficient environment.

Basu [6] explained that gasification is one of the most promising biomass conversions. The drying process initiates gasification and usually occurs at 200 to 300°C. Raw solid biomass always contains a certain amount of water moisture, and hence the drying process is needed to increase the gasification efficiency. The moisture content of biomass evaporates, resulting in the generation of steam. Because the temperature is considerably low to decompose the solid biomass, there will be no further biomass decomposition in this process. The pyrolysis process or thermal decomposition usually happens within a temperature range of 300 to 700°C. The pyrolysis step vaporizes the volatile components of biomass as it is heating the volatile vapour produced as a combination chemical, like tar and water vapour. Carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4), and hydrocarbon gases (HC) are also being produced. Biomass has more volatile components (70-80%) compared to coal which has only 30% volatile components. Weight reduction will occur in pyrolysis as a result of volatile matter removal from solid biomass. Robust biomass characteristics and types are affecting pyrolysis. Pyrolysis is considered an endothermic reaction type or requires heat addition into the process.

Biomass gasification performance could be characterized and affected by several parameters. Gasification performance could be measured with its efficiency, syngas production, and concentration. Factors that significantly affect the performance are biomass fuel characteristics like particle size and shape, moisture content, organic and inorganic components, ash and char content, volatile matter, and heating value. Gasifier designs such as types, materials, the medium of the gasifier influence the overall gasification process.

Materials and Methods

Vesenjak [7] explained that there are several methods for solving an engineering problem. The first method is the analytical method based on the direct integration of differential equations of mathematical models. The second method is the numerical method based on the approximate solutions to differential equations mathematical model, which is good enough. The third method is based on the experimental measurements of a model or the realistic full-scale object.

Fig 1: Gasification Analytical Model

The gasification process, which is considered in this research, is illustrated in Figure 1 was introduced by Zainal et al., [8] and developed by Htut et al., [9] and Wu & Chein [10]. Input for the gasification model is palm empty fruit bunch as the biomass source entering the gasifier at temperature Tb and air introduced to the gasifier with the composition of 21% oxygen (O_2) and 79% nitrogen (N_2) mass-based. Air temperature and pressure are Ta and Pa, respectively. The gasifier is operating at temperature Tg and pressure Pg. The output of this model is the syngas produced from the chemical reaction inside the gasifier with temperature Ts and pressure Ps.

The gasification process could be modelled with several equations that are developed from the initial global gasification reaction. Based on the previous research, syngas product of biomass gasification consists of hydrogen (H_2), carbon monoxide (CO), methane (CH_4), carbon dioxide (CO_2), and nitrogen (N_2). An experimental study found some remaining residues, such as unconverted carbon (C), tar, and ashes. On the reactant side, biomass could be represented by carbon (C), hydrogen (H), oxygen (O), and nitrogen (N). Based on the known information, global biomass gasification reaction with air as gasification agent could be written as follow.

Numerical analysis in this research is performed by commercial Computational Fluid Dynamics (CFD) solver STAR CCM+ version 9.02.007. CFD will be explained as a numerical approach for solving and describing the fluid dynamic problem in a computational fluid domain. The fluid dynamic domain is discretized into small volumes of computational cells in general. The governing equation will be solved in each computational cell. Discretization fluid domain or meshing technique is one of the most critical steps in CFD and can be seen in Figure 2.

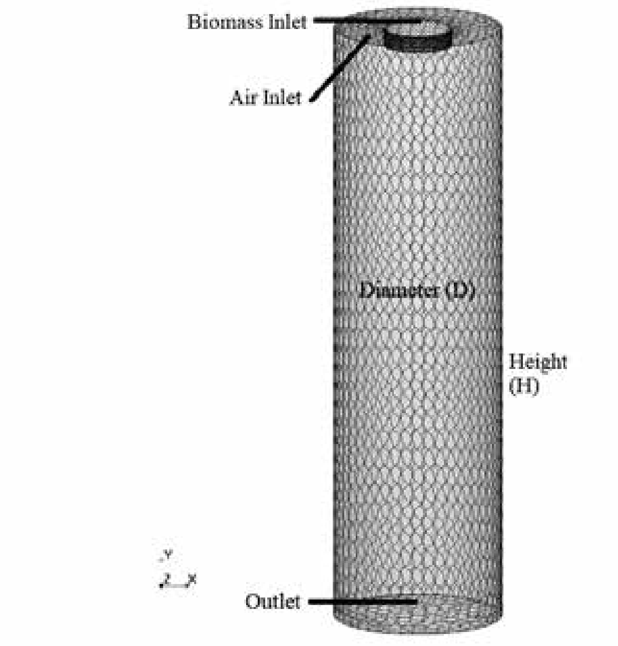

Fig 2: Meshed Geometry

The Eulerian and Lagrangian approach was performed in this research. The Eulerian approach was employed to model the continuous phase of the gasifier, which is air as the gaseous phase. In comparison, the Lagrangian approach was proposed to model the discrete phase of biomass gasifier, which is solid biomass in the solid phase. Continuous phase use conservation of mass (the Continuity equation), conservation of momentum (Second Law of Newton's equation), and conservation of energy (Thermodynamics First Law of the equation). In contrast, the dispersed discrete phase uses particle motion, the trajectory of particles, and the temperature of particles. Particle behaviour in the solid phase was calculated with Lagrangian particle modelling. Transport equations were solved by implementing the segregated flow model as Nikrityuk et al., [11] suggested.

Data provided from the analytical and numerical model were validated with the experimental study. The biomass gasifier experimental model is available in Figure 3 based on Jaojaruek et al., [12]. The test gasifier was a fixed bed type, open-top downdraft model. The gasifier was designed and assembled on a laboratory scale to keep the simplicity for operation and reproduce quickly. Refractory cement was used to manufacture the gasifier and surrounded with a stainless-steel tube to hold the heat provided from the gasification process.

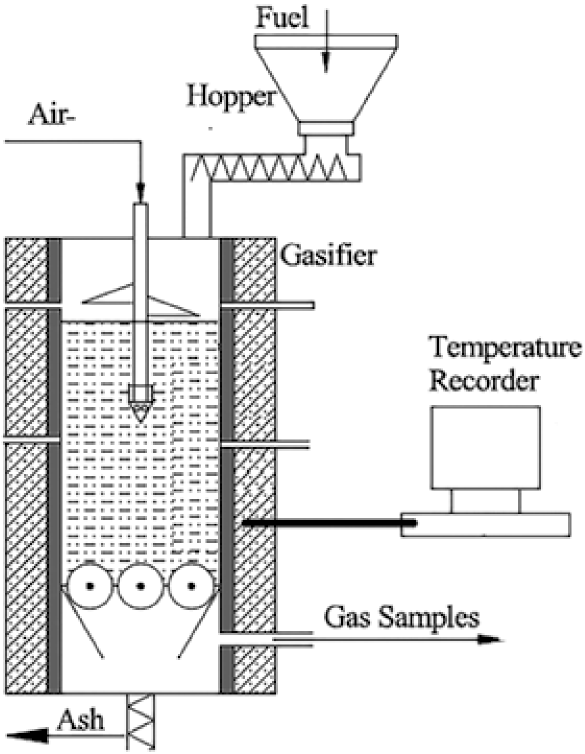

Fig 3: Experimental Setup

Results and Discussion

Temperature distribution and temperature profile inside the gasifier could be illustrated in Figures 4 and 5, respectively. In Figure 4, the temperature reported in previous numerical research published by Jayathilake and Rudra [13], denoted as Temp Ref, is compared with the numerical method and displayed as a function of distance along the central axis of the gasifier. Distance in the y-axis refers to the height from the base of the gasifier. Consequently, distance 0 meter means the bottom of the gasifier, and distance 0.35 meter means the top of the gasifier. The temperature profile in Figure 5 aims to figure out the thermocouple installation for a later experiment method.

Air as a gasifying agent initially at 25°C (298.15 K) is introduced into the gasifier. As the chemical reactions occur within the gasifier, hot air reacts with biomass particles, and the gasification process starts. The initial gasification step is biomass drying and occurs at around 300°C (573.15 K), as seen at 0.35 m distance (top of the gasifier), and continued pyrolysis or thermal decomposition takes place at a higher temperature. The third gasification step is oxidation or partial combustion of gases, vapour, and char. As an exothermic chemical reaction, the third step happened at the highest temperature, more than 1000°C (1273.15 K). At the bottom of the gasifier, the last step is the reduction or gasification of decomposed products. The endothermic reaction occurred at a lower temperature compared to the previous step. Gasification steps theory reported by Basu [6] and past research by Jayathilake and Rudra [13] are well explained with the numerical results.

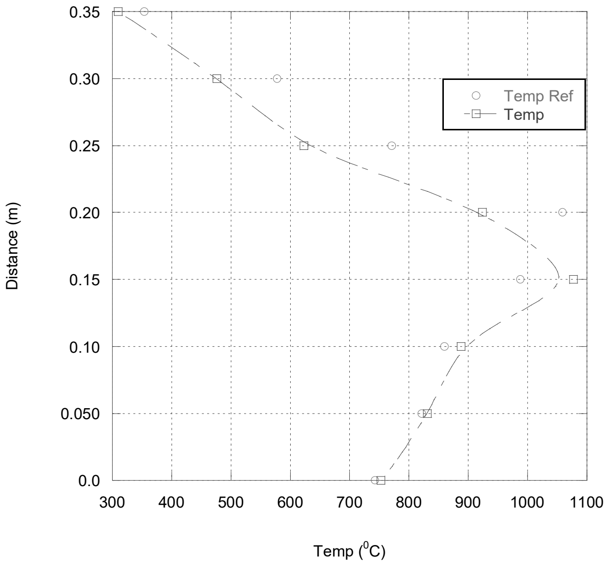

Fig 4: Temperature Distribution

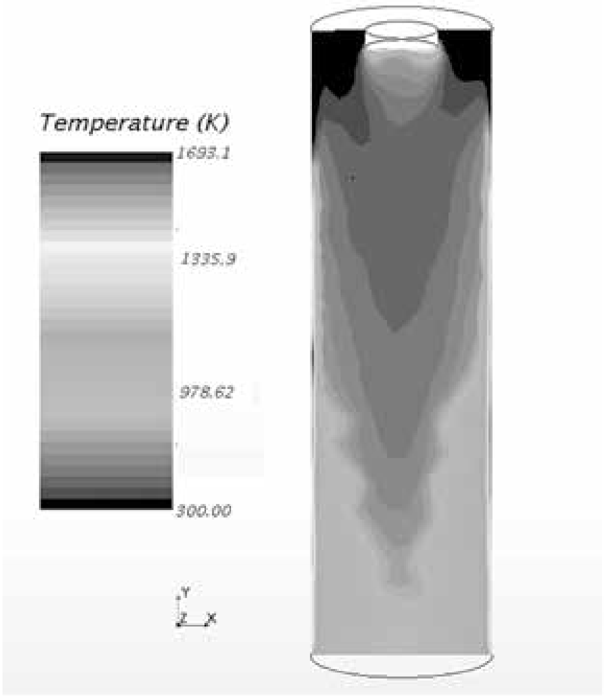

Fig 5: Temperature Profile

Figure 6 shows the syngas mass fraction as a function of the gasification reaction temperature. Complete combustion could be achieved by increasing temperature within the gasifier. Complete combustion leads to the reduction of combustible species amounts like hydrogen (H_2), carbon dioxide (CO), and methane (CH_4), while carbon dioxide (CO_2) also shows a declining trend, although not as much as other syngas species. The maximum value of H_2 occurred within an optimum temperature range of 700–800°C. The analytical method (A) satisfies with reference (Ref) published by Htut et al., [9] and Wu & Chein [10]. However, a numerical method (N) shows slightly lower combustible species than analytical results (A).

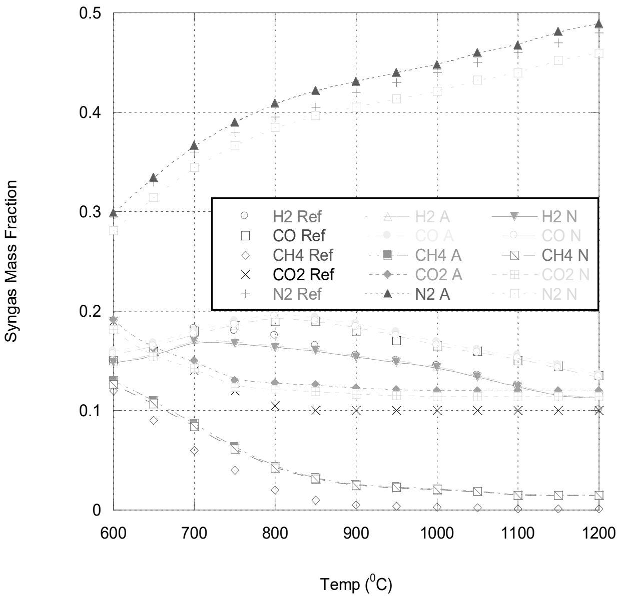

Fig 6: Effect of Gasification Temperature on Syngas Mass Fraction

The gasification temperature effect on the efficiency is shown in Figure 7 by keeping the moisture content constant below 20%, ER 0.35, and no preheated air temperature. The gasification temperature increase will make the efficiency decrease almost linearly from 89.174% to 61.023% because a higher gasification temperature leads to combustible species amount. According to the thermodynamic law, as the temperature of the system increase, there will be more irreversibility generated within the system, as explained by Htut et al., [9] denoted as (Ref). Lower combustible species in the numerical method (N) will make efficiency slightly about 5% lower compared to analytical results (A).

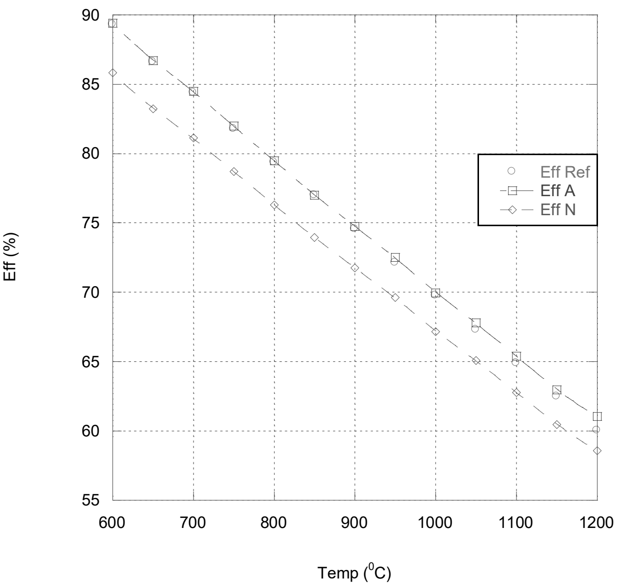

Fig 7: Effect of Gasification Temperature on Efficiency

Calorific value was greatly affected by gasification temperature from range 600 to 1200°C. As shown in Figure 8, with increasing temperature, combustible species amount available will be decreased, and calorific value also shows declining phenomena. This result shows a good agreement with analytical methods (Ref) reported by Htut et al., (2015) and Wu & Chein (2015) by maintaining moisture content value below 20% without preheated air temperature. The calorific value for the numerical method (N) tends to be lower than the analytical method (A) due to the lower combustible species produced in the syngas.

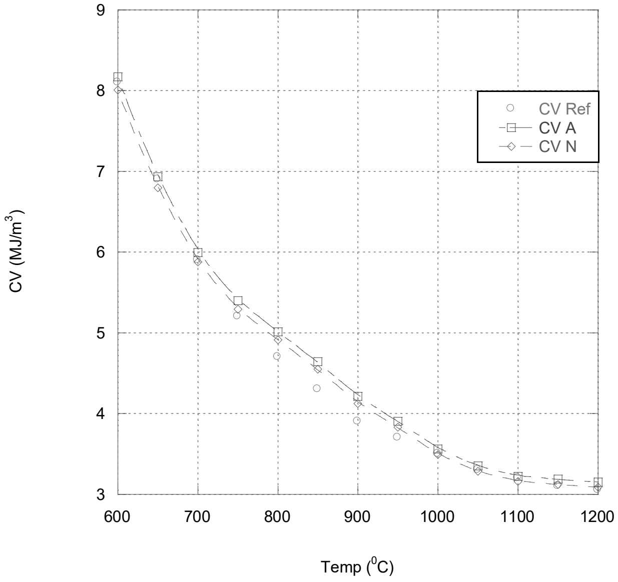

Fig 8: Effect of Gasification Temperature on Calorific Value

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Syngas and Calorific Value (CV) derived and acquired from the model were validated with the available experimental results using Root Mean Square Error (RMSE) analysis. The experimental method (E) was used to validate the analytical and numerical model performed previously (model). Gasification characteristics for experimental are based on the optimum analytical and numerical model presented. Gasification temperature was set to 800°C; moisture content was lower than 20%, equivalence ratio 0.35, and no preheated air as a gasifying agent. Based on the comparison from Figure 9, it was concluded that the model suggested in this research is mainly consistent with the result from the experimental model. Suggested models are considered better as a result of lower RMSE compared with another previous model.

Conclusions

Biomass gasification behaviour could be well understood by performing either analytical or numerical modelling. Optimizing design and operational parameters could be studied by keep saving time and economic aspects. As an illustration, gasifier commissioning is performed at a particular area where recommended biomass stock is not ready to use. Then the gasifier should be operated on the very different available biomass sources and very distinct operational parameters. The actual process could be time-consuming and pricey to be performed. In different circumstances, with the available biomass gasification model, it is very convenient to switch the biomass source and set the optimum working parameters to provide the desired output. Analytical and numerical modelling could be specified to provide an acceptable description of chemical and physical phenomena that occurred within the gasifier.

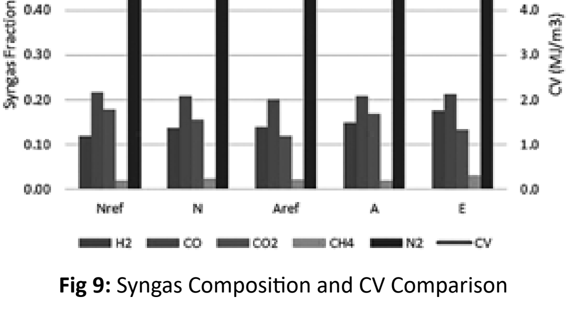

Fig 9: Syngas Composition and CV Comparison

The analytical method, widely known as equilibrium thermodynamic zero-dimensional models, has been proven convenient in forecasting the behaviour of biomass gasification. The reality is that the equilibrium state could be achieved even in a brief period within the gasifier. The pyrolysis and gasification process products were forced to enter the highest temperature zone in the gasifier, which is the oxidation section. The maximum performance of the gasifier could be easily visualized and require effortless operation compared to another modelling. However, the absence of complication comes with limitations because some assumptions taken with the analytical method could differ from the actual condition. It is suggested that some adjustment with the equilibrium model by considering experimental parameters or interrelationship with the experiment method would help develop the precision or correctness of the models.

The numerical method offered as a powerful instrument to learn the biomass gasifier design and operational behaviour could be achieved by consolidating the benefit of distinct models. The numerical method could precisely predict the performance of the gasifier, and the details provided are also satisfactory. However, this model is quite computationally intensive, and practice is needed to ensure that the initial condition, assumption, and models selected are appropriate with the actual condition. The numerical method shows to be a powerful instrument to analyse the biomass gasification system. It could recognize that application of details and accurate chemical reactions, biomass ultimate and proximate analysis, and biomass gasifier dimension joined with comprehensive numerical methods, especially for multiphase flow, are fundamental to build an accurate CFD simulation of the biomass gasification system.

The experiment method is the most suitable technique for performing the actual biomass gasification system. Laboratory scale experiments could be upscaled into original size without losing important vital parameters. The experiment method could be reiterated, and the result could be used as validation data for the analytical or numerical method performed previously. Controlled experimental operation conditions within a laboratory environment could lead to better results than the actual gasification process. On the contrary, the experimental method could establish artificial illustration and thus not always depict real-life circumstances. The unrealistic case could happen due to fully controlled working parameters and may not accurately reflect actual biomass gasification systems.

The present study has performed a comparative study of three well-known engineering solving methods: analytical, numerical, and experimental. Information derived from this research could benefit the researcher or designer by providing a complete guideline for endorsing an appropriate biomass gasification parameter, and possible performance could be achieved.

The optimal operation parameter for biomass gasification using palm empty fruit bunch was gasification temperature 800–900°C, moisture content less than 20%, and equivalence ratio of 0.35. Optimum biomass gasification performance is syngas calorific value 5.69 MJ/m^3, efficiency 73.71% while syngas mass fraction is 17.5% H_2, 21.3% CO, 13.3% CH_4, 3.1% CO_2, and 44.2% N_2. Maximum biomass gasification performance was reached with established operation parameters from the analytical and numerical methods.

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