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Integrated Biomass Gasification and Methanation System for Sustainable Synthetic Natural Gas Production: Experimental and Simulation Study

Jado, A.[1]*; M. M. Abo-habaga[1] and Tatiana Morosuk[2]

[1] Mansoura University, Department of Agricultural Engineering, Mansoura 35516, Egypt.
[2] Institute for Energy Engineering, Technical University of Berlin, Berlin 10587, Germany.

ABSTRACT

This work presents the design and evaluation of an integrated system that combines process simulation and experimental research to produce synthetic natural gas (SNG) from biomass. Using steam and wood waste, a lab-scale, indirectly heated dual fluidized bed gasifier was run at 800°C to produce syngas. A multi-stage gas cleaning system was used to eliminate contaminants like tar, HCl, NH_3, and sulfur compounds in order to facilitate effective catalytic methanation. The methanation process was carried out in a fixed bed reactor using a Ni/Al_2O_3 catalyst, with hydrogen supplied from high temperature electrolysis.A comprehensive Aspen Plus simulation model was created to assess the effects of operational parameters like methanation pressure, steam to biomass ratio, and gasification temperature on syngas composition, SNG yield, and heating value in order to improve the experimental work. The predictive accuracy of the model was confirmed by its strong agreement with experimental results after applying Gibbs free energy minimization.Optimal process conditions were achieved at a gasification temperature of 800 °C, a steam-to-biomass ratio of 0.6, and methanation at 10 bar and 350 °C, leading to a methane yield of 72% using the Ni/Al_2O_3 catalyst and an improved heating value of the produced SNG. This ensured catalyst longevity and stable reactor performance throughout methanation.The integrated strategy demonstrated both technical viability and energy efficiency, providing a viable path toward the production of renewable SNG. A trustworthy tool for system optimization is offered by the validated model.

Keywords: Biomass gasification, synthetic natural gas, methanation, Aspen Plus simulation, nickel catalyst

INTRODUCTION

Renewable resources like biomass and municipal waste can be used to create synthetic natural gas, a clean energy substitute. It provides a renewable alternative to traditional natural gas and lowers carbon emissions by turning organic matter into methane-rich gas (Guilera *et al*., 2021; Sun *et al*., 2024).

Purifying syngas prior to methanation, which turns carbon oxides into methane, is one of the crucial processes in the production of synthetic natural gas from biomass (Chauvy *et al*., 2020). Under the right circumstances, this process is usually simple because methane's better thermodynamic and kinetic characteristics make it easier to handle than hydrogen (Rosales-Asensio *et al*., 2024). The power to synthetic natural gas approach offers an effective way to integrate renewable energy into the natural gas grid, supporting both energy storage and thermal power generation (Predel *et al*., 2024). In this process, biomass is converted into syngas, which is a mixture mainly composed of hydrogen, carbon monoxide, carbon dioxide, and methane. This syngas is then processed to produce synthetic natural gas, which can be stored for long periods and used during times of high energy demand (Lackner *et al*., 2024).

Dual fluidized bed (DFB) steam gasification has shown strong promise for commercial use, as confirmed by both lab and pilot-scale studies (Hanchate *et al*., 2021). DFB permits indirect gasification without adding nitrogen to the syngas, in contrast to fixed bed or entrained flow systems (Karl & Pröll, 2018; Stanger *et al*., 2024). Without requiring an air separation unit, it generates syngas with a heating value and hydrogen content similar to systems that use steam and oxygen (Gabbrielli *et al*., 2022). DFB gasifiers also offer advantages like higher throughput, better heat and mass transfer, fuel flexibility, lower char formation, and a clean gas rich in hydrogen, carbon monoxide, carbon dioxide, and methane (Fuchs *et al*., 2019; Mauerhofer *et al*., 2018).

The process of turning renewable energy into synthetic natural gas, known as syngas methanation, has attracted a lot of attention (Mebrahtu *et al*., 2021). Syngas methanation process optimization relies heavily on Aspen Plus, a potent process simulation tool. Through the use of this software, chemical processes can be thoroughly modeled and simulated, allowing engineers to examine and adjust different parameters to increase productivity and efficiency (Jadoon *et al*., 2024). For example, Mancusi *et al*. (2021) modeled the design and configuration of methanation reactors, including adiabatic fixed-bed systems with inter-cooling and product recycling, to better represent fundamental operations and provide useful guidance for industrial applications. Fuentes *et al*. (2023) reported that a detailed kinetic model for CO_2 methanation in a microreactor offered valuable insights into how operational variables influence methane production, emphasizing the role of process intensification in achieving higher CO_2 conversions.

Even though methanation and biomass gasification have progressed, many studies still treat them independently, concentrating only on simulations or experiments. In order to assess system performance under realistic circumstances,

* **Corresponding author.**
E-mail address: jado@mans.edu.eg
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there is a glaring gap in the integration of thermodynamic modeling and actual experimental data. Additionally, the majority of simulations make ideal assumptions that ignore real-world issues like heat losses and catalyst behavior (Wan *et al*., 2024). By combining experiments with Aspen Plus modeling, this study fills that knowledge gap and enhances the effectiveness of a dual fluidized bed biomass-to-SNG system.

Therefore, the present study aims to investigate the technical feasibility and performance of an integrated biomass-to-SNG system by combining experimental gasification and methanation processes with Aspen Plus simulation. The study seeks to optimize key operating parameters, assess syngas quality and methane yield, and validate simulation results against experimental data to support the development of efficient and sustainable SNG production technologies.

MATERIALS AND METHODS

Experimental study

Experimental gasification setup

A lab-scale, indirectly heated dual-fluidized bed gasifier intended to generate nitrogen-free synthesis gas with a high methane content was used for the experimental gasification procedure, as illustrated in Figure 1. Because of its advantageous thermal and catalytic qualities, olivine was used as the bed material and steam as the fluidizing medium in this system, which ran at about 800°C. The primary processes for producing synthetic natural gas and gasifying biomass are depicted in Figure 2.

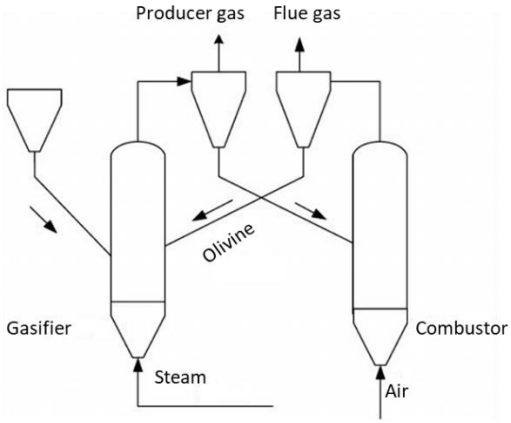

Fig. 1. Indirectly heated dual fluidized bed system. (Srinivasakannan & Balasubramanian, 2010)

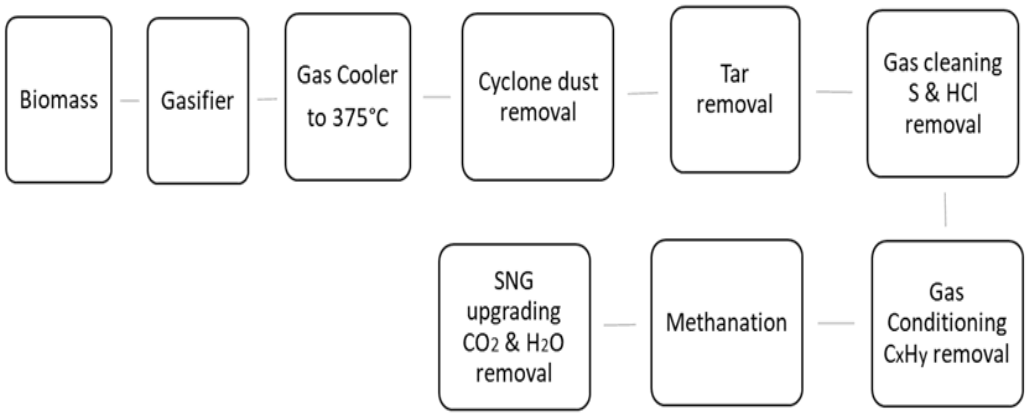

Fig. 2. Schematic representation of biomass gasification and SNG synthesis process

Table 1 shows the characteristics of the biomass feedstock, which was wood residue, as determined by proximate and ultimate analysis. Prior to feeding, the biomass was pre-dried to the necessary moisture content. The product gas left the reactor at about 800°C, and the gasification system ran at atmospheric pressure. In order to make room for the cyclone separator's operating range, which eliminated coarse particles from the gas stream, the hot raw syngas was first cooled to 400°C using a product gas cooler. To keep the system's energy balance, the carbon-rich ash that was recovered from the cyclone was recycled back into the combustor.

Following the removal of the particles, the tar removal unit was used to remove the tar from the gas. This system used a three-step scrubbing procedure that included an absorber for light tars, a demister for heavy tars, and a collector for heavy tars. The system made sure that the product gas was suitable for downstream processing by lowering the tar concentrations from about 30 g/m³ to 0.2 g/m³ and ensuring that the tar dew point was below -5 °C. The gas was sent to a gas cleaning stage after the tar was removed in order to get rid of trace pollutants like sulfur species (H_2S, COS) and hydrogen chloride (HCl). In order to meet the requirements for methanation catalyst protection, these impurities were adsorbed using commercial solid sorbents in dry conditions, making sure that the concentrations were lowered to less than 100 ppbV.

Table 1. Proximate and ultimate analysis of wood residue

Proximate analysis (wt % dry basis)	
Volatile matter	79.20
Fixed carbon	15.83
Moisture	4.63
Ash	0.34
Ultimate analysis (wt % dry basis)	
C	49.64
H	7.32
O	42.63
N	0.18
S	0.23
HHV (MJ/kg)	20.13

Gas conditioning, the last stage prior to methanation, involved the catalytic conversion of aromatic compounds (benzene, toluene, naphthalene) and unsaturated hydrocarbons (ethylene, acetylene) into

methane, hydrogen, and carbon monoxide. Additionally, this conversion preserved the nickel-based catalysts utilized in the methanation reactor and reduced the amount of soot that formed. Clean, tar-free syngas with improved calorific value and chemical composition that is appropriate for high-efficiency methanation and upgrading synthetic natural gas was produced thanks to this experimental setup.

Methanation catalyst and reactor design

A fixed-bed reactor built into the downstream portion of the gasification system was used to carry out the methanation process. Figure 3 illustrates how the reactor was built to catalytically transform the cleaned and conditioned synthesis gas—which mostly contained CO, CO_2, and H_2—into CH_4 via the Sabatier reaction. Because of its high activity and stability under the operating conditions, a nickel-based catalyst (Ni/AlO_3) was used. To achieve methane concentrations that met synthetic natural gas requirements and to guarantee maximum CO and CO_2 conversion, the catalyst was loaded in a double-pass reactor configuration. High-temperature solid oxide electrolysis cells, which electrochemically split steam into hydrogen and oxygen, were used to produce the hydrogen used in the methanation process. The generated hydrogen is directly fed into the methanation reactor, where it combines with carbon dioxide to create high-purity methane in an environmentally friendly and low-carbon manner.

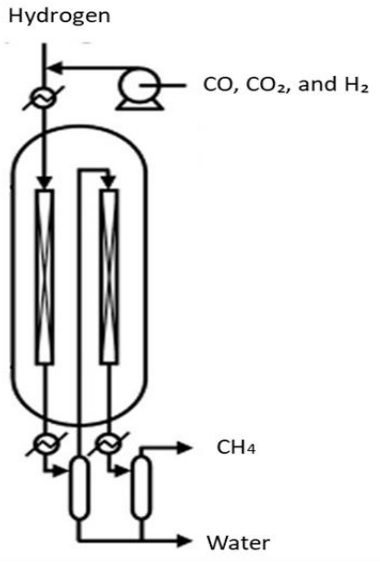

Fig. 3. Double-pass packed bed methanation reactor. (Dannesboe *et al*., 2020)

Around 350 °C was the operating temperature of the reactor. To guarantee steady flow and ideal reaction kinetics, a pressure control valve was used to maintain a constant reactor outlet pressure of. Methane yield was maximized while preventing catalyst deactivation from hotspot formation by optimizing the gas hourly space velocity (GHSV) and linear gas velocity. To track the axial temperature profile while the reactor was operating, ten thermocouples were positioned along its length, three centimeters apart. This configuration made it possible to track thermal behavior in detail across the catalyst bed, yielding important insights into the stability and performance of the catalyst.

The process gas, which was now abundant in methane and water vapor, underwent condensation and water removal following its initial passage through the reactor. To guarantee full conversion, the dehydrated gas was subsequently run through the second reactor section. The final product gas was able to meet the required Wobbe Index for SNG injection into natural gas grids thanks to this double-pass design, which also increased methane yield. A Micro GC 490 (Agilent Technologies) fitted with a thermal conductivity detector (TCD) and MS5A and PPQ columns was used to track the final gas composition. The apparatus made it possible to analyze hydrogen, methane, carbon monoxide, carbon dioxide, and nitrogen automatically and online. This analytical configuration allowed for performance monitoring of the methanation reactor during continuous operation and guaranteed real-time quality control of the generated SNG.

Simulation framework and model development

Process description

This system turns biomass into syngas through thermochemical reactions after dried wood residues are fed into a steam-blown gasifier. Using its catalytic properties to improve gasification reactions and drastically lower tar formation in the product gas stream, olivine is employed as a bed material and heat carrier (Han *et al*., 2022). After gasification, steam, hydrogen sulfide (H_2S), and other dangerous impurities are eliminated from the syngas by passing it through a cooling and purification train. Following the purification of the syngas, it is fed into the methanation reactor, where catalysts based on Ni/AlO_3 facilitate the conversion of hydrogen and carbon oxides (CO and CO_2) into methane at temperatures between 300°C and 500°C and high pressure (Ren *et al*., 2020).

A high-temperature electrolysis unit driven by excess renewable energy is used to guarantee a clean hydrogen source for methanation. Hydrogen and oxygen are produced by electrolyzing water in this unit and are kept in buffer tanks. The methanation reactor is then pressurized and continuously supplied with hydrogen, allowing for stable operation and the best possible CO/CO_2 conversion. By recovering condensed water and residual heat for use in the gasification process, the system also integrates thermal integration, increasing the integrated cycle's overall energy efficiency.

Process simulation with Aspen Plus

As shown in Figure 4, Aspen Plus was used to simulate the integrated system. Based on the idea of minimizing Gibbs free energy, the study forecasts the product composition. It also examines how the temperature during gasification and the ratio of steam to biomass (S/B) affect the composition of syngas and how the temperature and pressure during methanation affect the yield of CH_4. The equilibrium conditions are defined using Gibbs free energy minimization, which offers theoretical insight into system performance in idealized situations.RGibbs reactor blocks, which use Gibbs free energy minimization to calculate the equilibrium composition of the product gases, were used to model the gasification and methanation units. Before entering the gasifier reactor (GR), where it reacts with steam produced upstream, biomass is broken down into elemental species in a DEC block. Before being combined with hydrogen from the electrolysis unit, the resultant syngas is purified by passing through a heat exchanger (COL1) and separation block (SEP2). After that, this mixture is sent to the methanation reactor (MET), which produces methane. To separate SNG, the product stream is then subjected to dehydration (SEP7). Meanwhile, the heat needed for the gasification process is produced in the COM combustor by

burning biochar and some of the product gas. The bed material is continuously circulated between the gasifier reactor and combustor, facilitating the energy transfer.

It is crucial to remember that the RGibbs-based equilibrium approach makes the assumption that reaction conditions are perfect, even though the process model offers valuable insights into system integration and performance trends. The dynamics and constraints of a real-world methanation plant are thus not adequately captured by it, especially in relation to catalyst kinetics, pressure drop, and thermal gradients. Table 2 provides a summary of the features and setup of every model block utilized in the Aspen Plus simulation.

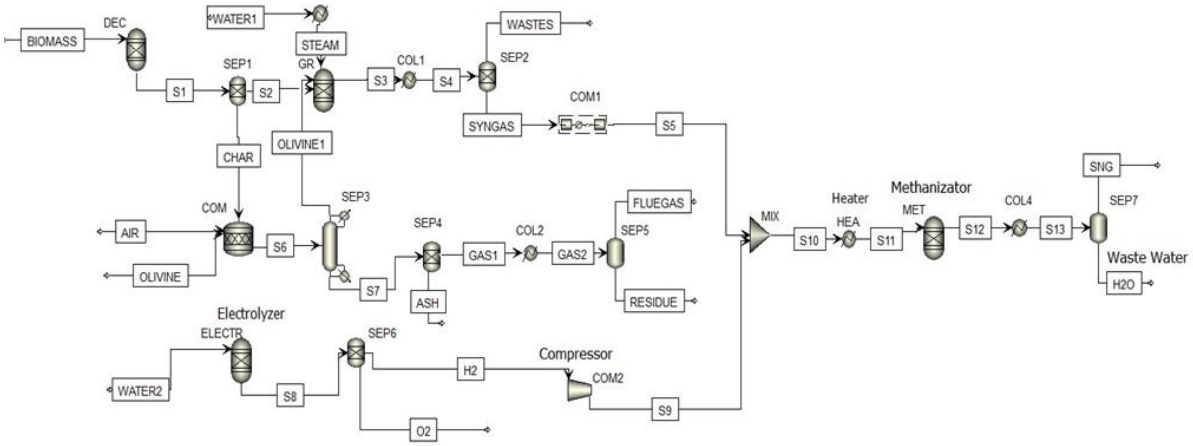

Fig. 4. Aspen Plus simulation flowsheet of the integrated biomass gasification, electrolysis, and methanation process for SNG production

Table 2. Summary of Unit Blocks with Associated Temperature and Pressure Conditions

Name	Type	Scheme	Description
DEC	RYIELD		Conversion of raw materials from unconventional components to conventional components at 550 °C and 0.1 MPa.
GR	RGibbs		The gasification reactions are simulated using the Gibbs free energy minimization principle at 0.1 MPa and a temperature range of 600–1000 °C.
Methanizator	RGibbs		The methanation process of biomass-derived syngas was simulated using the Gibbs free energy minimization principle at temperatures ranging from 300 to 500 °C and pressures between 0.1 and 4.0 MPa.
COM	RStoic		The combustion chamber was simulated at 90 °C and 0.1 MPa.
Electrolyzer	RYIELD		The water electrolysis unit for hydrogen production was simulated at 80 °C and 2.0 MPa.

Model methodology and assumptions

The process simulation was conducted using Aspen Plus, employing the "General with metric units" template. In order to integrate both conventional and non-conventional components, the model was constructed using the MIXCINC process category. Because of their unclear molecular structure, biomass and ash were regarded as non-conventional components in this framework, while gaseous streams were represented by conventional chemical species. The model used Gibbs free energy minimization, a thermodynamically sound method that estimates product distributions under ideal equilibrium conditions, to predict the system's chemical equilibrium. Even though kinetics and transport constraints may cause actual gasification processes to deviate from equilibrium, equilibrium models are useful for estimating baseline performance and directing the creation of more intricate, kinetically driven simulations. The fundamental equations governing Gibbs free energy minimization were derived from prior literature (Ajorloo *et al*., 2022; Ibrahim *et al*., 2022).

The thermophysical properties of biomass, including density and enthalpy, were calculated using the built-in DCOALIGT and HCOALGEN property models, respectively. The Peng–Robinson equation of state with Boston–Mathias modification (PR-BM) was applied across the simulation. This equation is widely used in gasification, petrochemical, and natural gas processing due to its suitability for complex vapor–liquid equilibrium systems (Pala *et al*., 2017; Hasnain *et al*., 2024). The decomposition of biomass in the gasifier was modeled using RYield blocks, with component yield fractions defined via custom FORTRAN subroutines. In these models, ash was assumed to behave as an inert material and did not participate in any chemical reactions. All syngas and SNG yield calculations were performed on a dry basis, ensuring consistency with experimental and literature-reported values. Table 3 presents the key assumptions made to simplify the gasification and methanation model in Aspen Plus.

Table 3. Assumptions used in the model

Model Assumptions	
• Hydrocarbons other than CH_4 are not considered in the modeling process.	• Catalyst deactivation is not considered in the simulation.
• The gas–solid separation efficiency was specified as 99 %.	• Carbon deposition is not considered in the simulation.
• Ash is recognized as an inert component that does not participate in the reaction.	

RESULTS AND DISCUSSION

Experimental Results

The experimental findings from the combined biomass gasification and methanation system are shown and examined in this section. The purpose of the controlled experimental campaign was to examine how important process parameters affected methanation performance, gas quality, and the effectiveness of impurity removal.

Effect of temperature on tar formation

The results of the experiment show that the temperature at which gasification occurs and the concentration of total tar are strongly inversely related. Figure 5 illustrates the enhanced thermal cracking of tar precursors at elevated temperatures, as the overall tar content dropped dramatically from 57,281 mg/Nm³ to 23,015 mg/Nm³ as the temperature rose from 600°C to 1000°C. Heterocyclic substances like phenol, pyridine, and cresol are examples of class 2 tars. They showed a steady decrease over the temperature range, going from 6197 mg/Nm³ at 600 °C to 462 mg/Nm³ at 1000 °C. The inherent thermal instability of light tar compounds, which easily break down in high-temperature environments like fluidized bed gasifiers, is reflected in this behavior.

Class 5 tars, on the other hand, which are mostly made up of heavy poly-aromatic hydrocarbons (PAHs) with four to five aromatic rings, increased gradually with temperature, going from 2568 mg/Nm³ to 9144 mg/Nm³. Secondary polymerization reactions of lighter tar species, especially at temperatures between 750°C and 1000°C, are probably the source of these heavier tars.

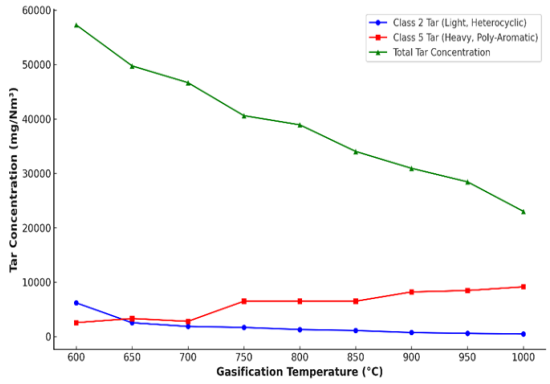

Fig. 5. Effect of gasification temperature on tar formation

Effect of gas cleaning and conditioning on impurity reduction

The implemented gas cleaning and conditioning system significantly reduced the concentration of harmful and undesired components in the raw product gas, as shown in Table 4. The most notable change was the sharp drop in tar content from 28 g/Nm³ to 0.4 g/Nm³, which demonstrated how well the multistage tar removal unit removed both heavy and light tar fractions. In a similar vein, H_2O was decreased from 41.13% to 12.21%, which improved the cleaned syngas's calorific value and methanation suitability.

Ammonia (NH_3) and hydrogen chloride (HCl), two corrosive and acidic gases, were also significantly reduced by the system. By lowering NH_3 from 1415 ppmV to 617 ppmV and HCl from 31 ppmV to less than 0.1 ppmV, the risks of equipment corrosion and catalyst degradation were reduced. Furthermore, the downstream Ni-based methanation catalyst was protected from sulfur poisoning by reducing sulfur-containing compounds like hydrogen sulfide (H_2S) and carbonyl sulfide (COS) from 105 ppmV and 14 ppmV, respectively, to levels below 0.1 ppmV.

All of these reductions show how important the gas conditioning and cleaning processes are in converting raw syngas into a stream that is cleaner and more chemically stable, ready for effective catalytic conversion to synthetic natural gas.

Table 4. Comparison of Gas Impurities Before and After Cleaning

Component	Unit	Raw Gas	Cleaned Gas
H_2O	vol%	41.13	12.21
Tar	g/Nm³	28.0	0.4
H_2S	ppmV	105.0	<0.1
COS	ppmV	14.0	<0.1
NH_3	ppmV	1415.0	617.0
HCl	ppmV	31.0	<0.1

Catalyst support influence on methanation performance

Figure 6 illustrates the CH_4 yield (%) as a function of reaction temperature for Ni-based catalysts supported on different oxide materials (Al_2O_3, SiO_2, ZrO_2, and CeO_2). All catalysts exhibit a distinct temperature-dependent trend, with notable variations in peak performance. The highest CH_4 yield was shown by the Ni/AlO_3 catalyst, which peaked at about 72% at 400°C. This catalyst also continued to perform exceptionally well at lower temperatures (300–350 °C), reaching a yield of over 50% at 350 °C, while all other catalysts stayed below 20% in the same temperature range.

Throughout the tested temperature range, Ni/CeO_2 and Ni/ZrO_2 demonstrated moderate methane yields, peaking at about 30–35% between 450 and 500 °C. Ni/SiO_2, on the other hand, continuously showed the lowest CH_4 yield, never rising above 20% at any temperature. These results suggest that during bio-syngas methanation, the catalyst support is essential for increasing methane yield. Ni/Al_2O_3 outperforms the other systems, particularly in the intermediate temperature range (350–400 °C), making it a promising candidate for practical SNG production processes.

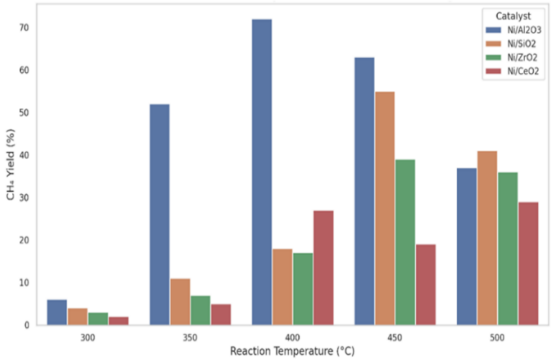

Fig. 6. Effect of reaction temperature on CH_4 yield using different Ni-based catalysts

Aspen Plus simulation of biomass gasification performance

Simulated impact of temperature on syngas composition and energy content

The effect of gasification temperature on syngas composition and energy performance was investigated using Aspen Plus simulation, with the steam-to-biomass ratio (S/B) fixed at 0.6 and pressure at 0.1 MPa. The molar fractions of the main syngas components (H_2, CO, CO_2, and CH_4) show clear trends over the 600–1000 °C temperature range, as seen in Figure 7. Driven by enhanced endothermic reforming reactions, hydrogen continuously showed the highest concentration, peaking at 51.26% at 800°C. While carbon dioxide and methane gradually decreased as a result of their consumption in the water-gas shift and steam reforming pathways, carbon monoxide also rose with temperature. The best temperature for optimizing the production of H_2 and CO, which are essential for effective downstream methanation, is 800 °C, according to these compositional shifts.

The corresponding impact of gasification temperature on the syngas yield and lower heating value is depicted in Figure 8. The increasing proportion of flammable species in the syngas was reflected in the LHV's consistent rise with temperature. Syngas yield, on the other hand, showed a non-linear trend, reaching a maximum of 1.61 Nm³/kg at 800 °C and then slightly decreasing at higher temperatures. The thermodynamic limits of biomass conversion and the start of reverse water-gas shift reactions at high temperatures are responsible for this behavior. In general, 800°C was found to be the ideal gasification temperature, providing the best balance between syngas volume and energy quality for the production of SNG later on.

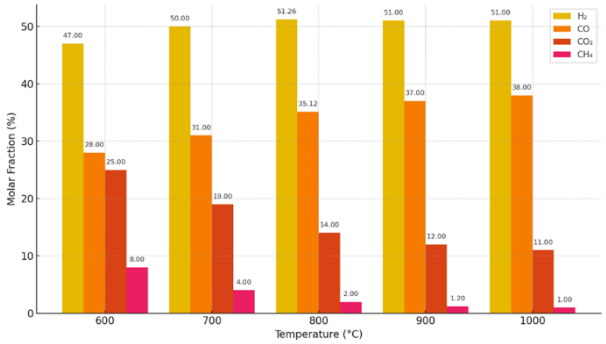

Fig. 7. Simulated syngas composition at different gasification temperatures

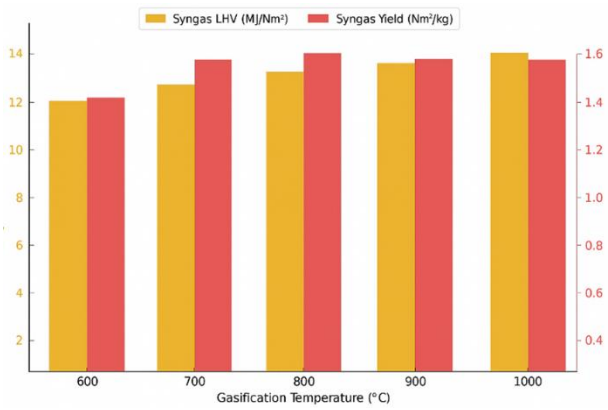

Fig. 8. Effect of gasification temperature on syngas LHV and yield

Simulated impact of steam-to-biomass ratio on syngas composition and heating Value

The influence of the steam-to-biomass ratio (S/B) on syngas composition and performance was investigated through equilibrium-based simulation at a fixed gasification temperature of 800 °C and pressure of 0.1 MPa. All other parameters were held constant to isolate the effect of S/B variation. The results are presented in Figures 9 and 10.

Figure 9 illustrates how raising the S/B ratio caused the molar fraction of carbon dioxide and hydrogen to continuously increase while the concentrations of carbon monoxide and methane sharply declined. The increased partial pressure of steam, which encourages steam reforming and water-gas shift reactions, is responsible for this compositional change. Notably, CO decreased from over 50% to about 14%, while H_2 content rose from about 45% to almost 60% as S/B increased from 0.2 to 2.0. Throughout the S/B range, methane continuously decreased, falling below 2%.

The corresponding changes in syngas lower heating value and volumetric yield are depicted in Figure 10. The LHV decreased from 16.0 to 10.4 MJ/Nm³, whereas the syngas yield increased steadily from 1.35 to 2.05 Nm³/kg biomass with higher S/B. Because of the increased share of CO_2 and steam dilution, a higher steam input increases gas volume but decreases the calorific content per unit volume. Consequently, a high S/B has a negative impact on the syngas's energy density even though it increases H_2 generation and overall gas volume. Taking both energy efficiency and gas composition into account, an S/B ratio of 0.6 was identified as the optimal operating point for further simulation and process design.

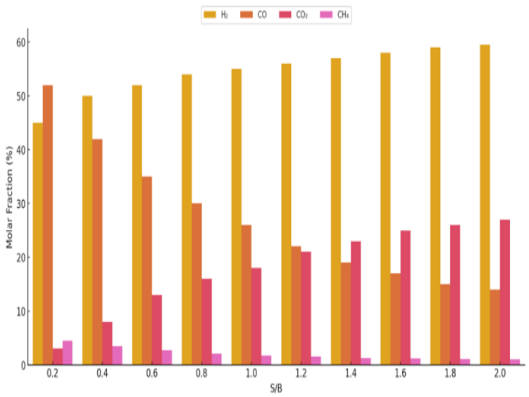

Fig. 9. Effect of S/B on syngas components

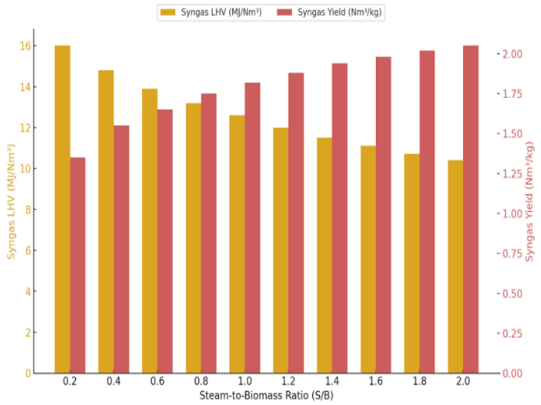

Fig. 10. Effect of S/B ratio on syngas yield and LHV

Aspen Plus simulation of syngas methanation behavior

Effect of methanation temperature and pressure on CH_4 and CO_2 Concentrations in SNG

The effects of methanation temperature and pressure on the composition of synthetic natural gas SNG were thoroughly examined, with particular attention to CH_4 and CO_2 concentrations. As shown in Figures 11 and 12, increasing the methanation pressure from 1 to 30 bar led to a noticeable rise in CH_4 content at all tested temperatures. The highest CH_4 levels, exceeding 87 vol.%, were obtained at a temperature of 300 °C, and 30 bar, highlighting the favorable kinetics and equilibrium conditions for methane formation at lower temperatures under elevated pressures.

Conversely, higher methanation temperatures (e.g., 400 °C) resulted in a marked reduction in CH_4 concentration, particularly at lower pressures, indicating thermodynamic limitations and the promotion of side reactions. CO_2 content showed a slight upward trend with increasing pressure but remained relatively stable across the temperature range. While elevated temperatures slightly reduced CO_2 levels, this came at the expense of CH_4 yield.

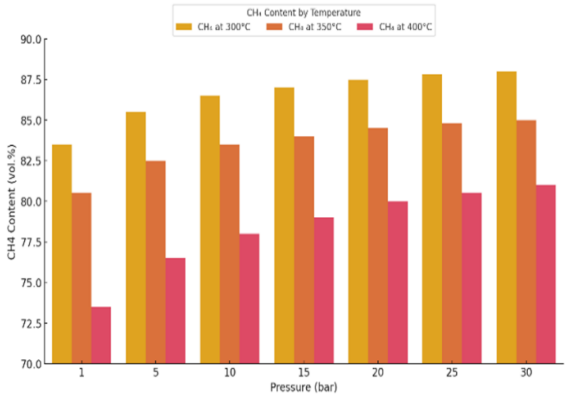

Fig. 11. Effect of methanation pressure on CH_4 content at different temperatures

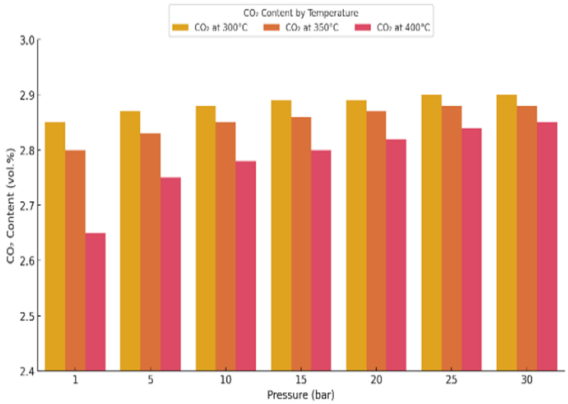

Fig. 12. Effect of methanation pressure on CO_2 content at different temperatures

Effect of methanation temperature and pressure on HHV and SNG yield

The influence of methanation temperature and pressure on the performance of the SNG production process was investigated through variations in both the higher heating value and SNG yield, as illustrated in Figures 13 and 14.

As shown in Figure 13, the HHV of the produced SNG ranged from 31.37 to 34.74 MJ/Nm³ under different operating conditions. At any fixed temperature, increasing the methanation pressure led to a higher HHV, with the maximum value recorded at 300 °C and 30 bar. These results suggest that higher pressures enhance the energy content of the gas, making it more suitable for injection into gas grids or for high-efficiency combustion applications.

Conversely, Figure 14 reveals that the SNG yield exhibited a negative correlation with pressure. At constant temperatures, increasing preasure caused a gradual decline in product yield. The highest yield of approximately 19.0 kmol/hr was achieved at 400 °C and 5 bar, whereas pressures beyond 10 bar had minimal additional effect. Additionally, higher temperatures consistently improved SNG yield, confirming that thermal energy strongly enhances methanation kinetics, especially at lower pressures.

Considering the trade-off between energy content and production volume, it was determined that the operating point of 350 °C and 10 bar provides a balanced solution. At these conditions, the process achieves a high HHV (34.0 MJ/Nm³) along with a stable and acceptable SNG yield, avoiding the drawbacks of excessive pressure or thermal stress. This operating point thus represents an effective compromise for applications that require both high fuel quality and cost-effective throughput.

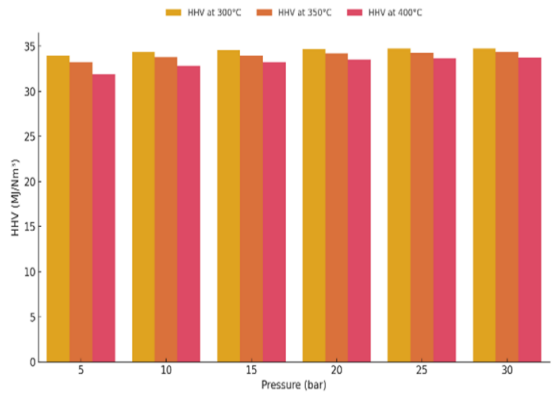

Fig. 13. Effect of methanation Pressure on HHV at different temperatures

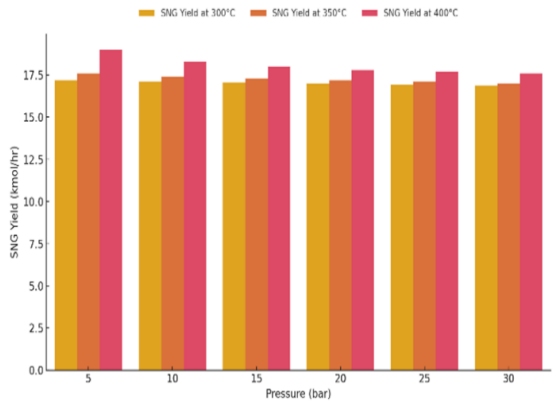

Fig. 14. Effect of methanation pressure on SNG yield at different temperatures

Comparative analysis between experimental and simulation results

To evaluate the accuracy and predictive capability of the simulation model, a comparative analysis was conducted between the experimentally measured and simulated compositions of syngas and synthetic natural gas. The results are illustrated in Figures 15 and 16.

As shown in Figure 15, the molar fractions of the major syngas components (H_2, CO, CO_2, and CH_4) obtained experimentally are in close agreement with the simulated values. The largest deviation was observed for CH_4, where the experimental measurement slightly exceeded the simulation result by 0.63 vol.%. For H_2 and CO, the differences remained within 2 vol.%, indicating strong alignment. The minor discrepancies can be attributed to idealized equilibrium assumptions within the simulation, while the experimental setup reflects realistic operational limitations, such as kinetic resistance and heat losses.

Figure 16 further supports the model validation by comparing CH_4 concentrations at various methanation temperatures (300°C, 350°C, and 400°C) under a constant pressure of 10 bar. The experimental data consistently show slightly higher CH_4 concentrations across all temperatures, with deviations ranging from 0.8 to 1.4 vol.% compared to the simulation. The highest deviation occurred at 350°C, likely due to catalyst kinetics and temperature sensitivity that are not fully captured by the equilibrium-based simulation.

In conclusion, the strong correlation between simulation and experimental results confirms the model's validity and reliability in predicting system behavior under similar operating conditions. This validated model can serve as a dependable tool for further parametric studies, sensitivity analysis, and process optimization.

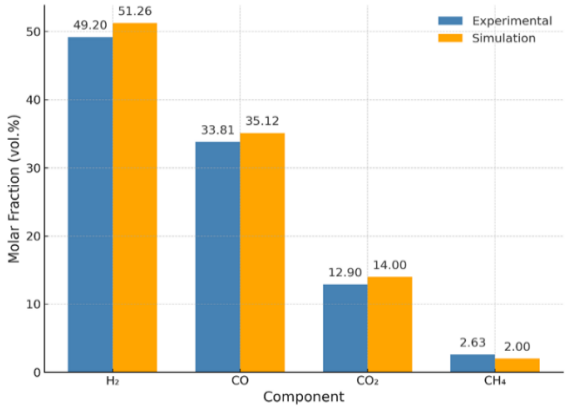

Fig. 15. Experimental and Simulated Syngas Composition at 800°C

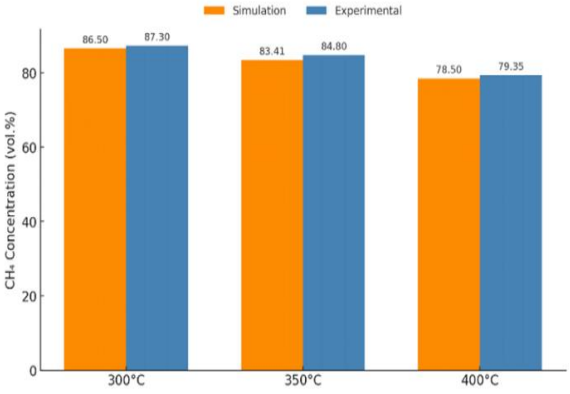

Fig. 16. Comparison of Simulated and Experimental CH_4 Concentration at 10 bar

CONCLUSION

This study successfully demonstrated the technical feasibility and performance of an integrated biomass gasification and methanation system for renewable synthetic natural gas production. By combining experimental trials with Aspen Plus simulation, the research bridged the gap between theoretical modeling and practical implementation.

Experimentally, the dual fluidized bed gasifier operating at 800 °C with wood residue and steam produced high-quality syngas, while the multi-stage cleaning and conditioning system effectively removed contaminants to meet methanation standards. The Ni/Al_2O_3 catalyst in the double-pass methanation reactor showed superior methane yields, particularly at moderate temperatures around 350 °C.

The simulation model, based on Gibbs free energy minimization, provided valuable insight into how operating conditions influence gas composition, SNG yield, and energy content. Despite the idealized nature of equilibrium assumptions, the model predictions closely matched the experimental data, with minor deviations attributed to real-world limitations such as kinetic constraints and heat losses.

Importantly, the results identified optimal process conditions namely a gasification temperature of 800 °C, a steam-to-biomass ratio of 0.6, and methanation at 10 bar and 350 °C which collectively ensured a high methane yield and elevated heating value. This balance between energy quality and process efficiency supports the viability of this system for sustainable SNG production. Overall, this work provides a validated framework for optimizing biomass-to-SNG conversion processes.

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نظام متكامل لتغويز الكتلة الحيوية وميثنتها لإنتاج الغاز الطبيعي الاصطناعي المستدام: دراسة تجريبية ومحاكاة

أحمد جادو[١]، محمد مصطفى أبوحباجة[١] و تتيانا موروزوق[٢]

[١]قسم الهندسة الزراعية والنظم الحيوية – كلية الزراعة – جامعة المنصورة – مصر
[٢]معهد هندسة الطاقة - جامعة برلين للتقنية - برلين - ألمانيا

الملخص

في ظل التوجه العالمي نحو مصادر الطاقة النظيفة، يهدف هذا البحث إلى تطوير وتقييم نظام متكامل لإنتاج الغاز الطبيعي الاصطناعي (SNG) من الكتلة الحيوية، من خلال الجمع بين التجارب المعملية والمحاكاة الحرارية باستخدام Aspen Plus . شملت الدراسة تحليل تأثير عدة عوامل تشغيلية، من بينها: درجة حرارة التغويز (600–1000°C) ، نسبة البخار إلى الكتلة الحيوية (S/B) ، نوع مادة الحفاز، وضغط ودرجة حرارة الميثنة .تم استخدام وحدة تغويز مزدوجة السرير غير مباشرة التسخين، تعمل عند 800°C باستخدام بقايا الخشب كبادرة تغويز، وبخار الماء كوسيط. تم تطبيق منظومة تنظيف غازية متعددة المراحل لإزالة القطران والمركبات الضارة مثل HCl و NH_3 و H_2S . بعد التنظيف، أُجريت عملية الميثنة في مفاعل ثابت مزدوج المرور باستخدام محفز Ni/Al_2O_3 ، مع تزويد الهيدروجين عبر تحليل كهربائي عالي الحرارة.أظهرت النتائج أن الظروف المثلى تحققت عند 800°C للتغويز، ونسبة بخار/كتلة 0.6 ، وضغط ميثنة 10 بار ودرجة حرارة 350°C ، مما أدى إلى مردود ميثان بلغ 72%. كما أظهرت المحاكاة توافقًا كبيرًا مع النتائج التجريبية، مما يعزز موثوقية النموذج . يوضح هذا البحث أهمية تكامل التجربة والنمذجة في تطوير تقنيات مستدامة لإنتاج وقود نظيف، ويمثل خطوة واعدة نحو الاعتماد على الغاز الاصطناعي كخيار استراتيجي للطاقة المتجددة.