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# The Effect of Steam-Oxygen Gasifying Medium on Syngas Upgrading for Nitrogen Reduction

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**Abstract.** In this work, a promising strategy to achieve nitrogen reduction in syngas produced in small-scale gasification systems is explored. It consists in the substitution of air with steam and oxygen as the gasification medium. The impact of gasifying medium composition on syngas quality was evaluated through both modeling and experimental approaches. A steady-state model of a biomass gasification plant, developed by DTU in Engineering Equation Solver (EES) was adapted to simulate different gasifying media with varying oxygen fractions. The model predictions were then validated against experimental results obtained with steam and oxygen as gasifying agents in an APL Char Pallet, a downdraft gasifier capable of processing 10–25 kg/h of various residual biomasses. The results demonstrated a significant reduction in nitrogen content alongside a concurrent increase in hydrogen concentration in the syngas. Upgrading syngas with low nitrogen content can be a promising carbon-negative alternative pathway for producing green hydrogen, compared to water electrolysis. The experimental findings closely aligned with the model predictions, confirming the effectiveness of switching the gasification medium in enhancing syngas quality for subsequent upgrading.

## 1. Introduction

Green hydrogen, generated through renewable energy, has emerged as a promising solution for decarbonization, especially for hard-to-abate industries like steel, cement, and chemicals [1]. Producing hydrogen from residual biomass offers a sustainable approach to complement renewable hydrogen generation in the years ahead [2].

A possible route for hydrogen production from biomass is gasification, a high-temperature process that transforms carbon-rich feedstock into a gaseous fuel consisting of hydrogen, carbon monoxide, nitrogen, carbon dioxide, water vapor, and various hydrocarbons [3]. In this work explores how the composition of the gasifying agent influences syngas quality, using both modeling and experimental methods. A steady-state model of a biomass gasification plant, originally developed by DTU in Engineering Equation Solver (EES), was adapted to simulate various gasifying agents with different oxygen concentrations [4]. Model predictions were

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validated through experiments, using different proportion of air, steam and oxygen as gasifying agents in the APL CharPallet, a gasifier capable of processing up to 25 kg/h of diverse residual biomasses [5]. The results revealed a notable decrease in nitrogen content and a corresponding increase in hydrogen concentration within the syngas. Experimental outcomes closely matched the model forecasts, confirming that altering the gasification medium can effectively enhance syngas, maximizing hydrogen production for downstream hydrogen upgrading [6]. Notably, lowering the nitrogen content in syngas can lead to substantial energy savings during the purification stage. For example, a 2% reduction in nitrogen concentration can decrease the energy consumption of the pressure vacuum swing adsorption process by more than 50% [7].

## 2. Materials and Methods

### *2.1 Nitrogen reduction modelling*

To model the gasification process and calculating the syngas composition with different gasification agent it was used the DTU stationary equilibrium model built in the equation solver program ”Engineering Equation Solver” (EES). It is a 0D mass and energy balance model based on chemical equilibrium, which accounts for key thermochemical conversion processes. The energy demand for pyrolysis is calculated as the difference between the energy content of the incoming and outgoing flows. The pyrolysis gas composition is determined based on experimental data. Gas composition from the gasification reactions is derived from elemental balance equations and the water-gas shift reaction. The water-gas shift equation is temperature-dependent and represents the chemical equilibrium between $H_2$, CO, $CO_2$, and steam. This model does not refers to a specific gasification system, for this reason it can be used with flexibility for multiple downdraft system by tuning the input parameters [4]. The primary goal is to analyze which parameters most significantly influence key output variables, such as producer gas composition and the overall heat and power conversion efficiencies of the system. For instance, it has been observed that increasing the temperature of the input mass flows to the gasification chamber leads to a higher calorific value of the producer gas and improved power conversion efficiency [4]. In this study, the input parameters were adjusted to replicate the APL Char Pallet for those values that were known. For the fixed parameters used in each simulation, informed guesses were made based on years of experience operating similar systems. A summary of the selected input parameters is provided in Table 1.

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**Table 1.** Model Fixed Input Parameters

| Parameter | Value |
|---|---|
| Dry wood chips mass flow | 25 kg/h |
| Biomass moisture content | 10% |
| Biomass element composition | $CH_{1.44}O_{0.66}$ |
| Methane content in the gas | 3% v/v |
| Air pre-heated temperature | 450 °C |
| Gasification temperature | 900 °C |
| Gas outlet temperature | 300 °C |
| Heat loss | 3% |

Concerning the methane concentration, a higher value than usual was chosen to account for the possible reduction of other components in the gas. To assess the impact of varying the gasification agent, the model had already been set up with different steam mass flows. However, no predefined option for adding oxygen was available. To overcome this constraint, the approach involved modifying the composition of the input air by decreasing its nitrogen content and increasing the oxygen concentration. Specifically, four different air compositions were tested.
For each composition, five different steam input levels were analyzed, resulting in twenty distinct simulation scenarios. These simulations were repeated across four different biochar yield values, leading to a total of one hundred simulations. The input parameters for these variables are summarized in Table 2.

**Table 2.** Model Variable Input Parameters

| Parameter | Values |
|---|---|
| Steam [kg/h] | 0 – 3 – 5 – 8 – 10 |
| Oxygen content in the agent v/v [%] | 21 – 30 – 50 – 75 |
| Nitrogen content in the agent v/v [%] | 79 – 70 – 50 – 25 |
| Biochar yield w/w [%] | 0 – 5 – 10 – 20 |

*2.2 Experimental Test*
For the experimental tests, the ALL Power Labs CharPallet 25 was used. it is a combined heat and biochar gasifier system designed to convert 25 kg/h woody biomass into high-quality biochar (Figure 1).

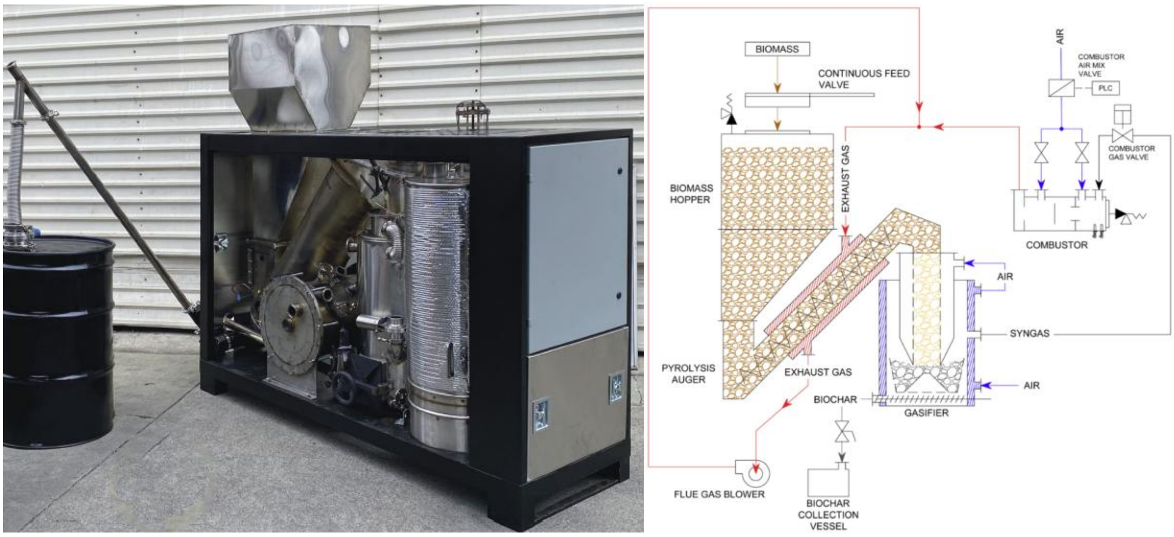


**Figure 1.** ALL Power Labs CharPallet 25 and its process flow diagram [5]

This system, has a multi-stage and process-separated architecture and a swirl hearth that allows feedstock flexibility. It encompasses a forced convection pyrolysis reactor designed to ensure a controlled heating rate and efficient heat transfer for high-throughput operation.

Steam used as the gasifying agent was generated using a monotube propane boiler, while pure oxygen was supplied from a cylinder. Various proportions of air, pure oxygen, and steam were employed as gasifying agents. The resulting gas compositions at the outlet were measured with a gas analyzer and compared to the composition predicted by simulation.

## 3. Results

### *3.1 Modelling results*

The DTU model was run with a revised air composition to account for the oxygen addition. Table 3 reports the syngas compositions of the most representative tests, which are similar to the experimental results. In these cases, char yield was fixed to 20%.

**Table 3.** Model results

| Gasifying agent | | | Syngas composition [v/v] | | | | |
|---|---|---|---|---|---|---|---|
| Air [kg/kg] | Pure $O_2$ [kg/kg] | Steam [kg/kg] | $H_2$ [%] | CO [%] | $CH_4$ [ %] | $CO_2$ [%] | $N_2$ [%] |
| 100%[a] | 0%[a] | 0%[a] | 21.3 | 17.6 | 3 | 14.7 | 43.4 |
| 63%[b] | 9%[b] | 28%[b] | 28.8 | 15.8 | 3 | 21 | 31.4 |
| 13.6%[c] | 32.6%[c] | 53.8%[c] | 42 | 21 | 3 | 28.3 | 5.7 |

[a] Incondensable agent volume composition 21% $O_2$, 79% $N_2$, steam 0 kg/h

[b] Incondensable agent volume composition 30% $O_2$, 70% $N_2$, steam 8 kg/h

[c] Incondensable agent volume composition 75% $O_2$, 25% $N_2$, steam 10 kg/h

As shown in Table 3, substituting air with pure oxygen and steam proves to be highly effective in significantly reducing the nitrogen content while concurrently increasing the hydrogen content in the syngas stream. In this case, the impact on methane concentration cannot be directly evaluated, as it is explicit input parameter in the model. However, the model outcomes could be refined by comparison with experimental data. In any case, the methane content is generally low in biomass gasification, and therefore, a slightly inaccurate estimation is not expected to significantly affect the calculated quantities of the other gas components in the syngas [8].

*3.2 Experimental tests results*

In Table 4, four gas compositions measured with a gas analyzer are reported, corresponding to three different gasification agents.

As observed from the experimental results, the syngas compositions predicted by the modified DTU model are consistent with the compositions measured during the various test runs, showing a consistent increase in hydrogen content and a reduction in nitrogen content with decreasing air in the gasifying medium.

**Table 4.** Experimental results

| Gasifying agent | | | Syngas composition [v/v] | | | | |
|---|---|---|---|---|---|---|---|
| Air [kg/kg] | Pure $O_2$ [kg/kg] | Steam [kg/kg] | $H_2$ [%][a] | CO [%] | $CH_4$ [ %] | $CO_2$ [%] | $N_2$ [%][a] |
| 100% | 0% | 0% | 20 | 18 | 2 | 15 | 45 |
| 68% | 8% | 24% | 25-33 | 15-20 | 1-3 | 18-23 | 25-35 |
| 0% | 20% | 80% | >35 | 19 | 6 | 30 | <10 |
| 0% | 25% | 75% | >35 | 20 | 2 | 30 | <8 |

[a] The $H_2$ detection limit of the instrument is 35%. The $N_2$ content is calculated by subtracting the measured concentrations of other gas species from 100%

## 4. Conclusions

The modifications applied to the DTU stationary equilibrium model were successful, yielding syngas compositions that aligned well with the experimental results. As expected, the switch to oxygen and steam as gasifying agents led to a reduction in nitrogen content and an increase in hydrogen concentration [9], confirming the effectiveness of the revised model. Producing green hydrogen from residual biomass represents a highly promising pathway, and the ability to reliably and easily predict syngas composition under varying process conditions may be decisive for the optimization and scalability of the technology.

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