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*Article*

# Gasification of Lenga (Nothofagus pumilio) chips in a fixed bed system for rural area implementation: Magallanes case study

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**Abstract:** This research explores the gasification of Lenga wood chips (*Nothofagus pumilio*) sourced from forest remnants within a fixed-bed gasification system with a 10 kWe capacity. The primary focus is on its potential application in remote rural regions. Utilizing a factorial analysis approach, we examine the influence of particle size (ranging from 3-8 mm to 8-20 mm) and the frequency of bed agitation (occurring every 2, 4, and 6 minutes) on critical performance indicators. Throughout the experimentation, the equivalence ratio (ER) remains constant within the range of 0.17-0.20. Cold efficiency demonstrates variability, spanning from 44.8% to 58.8%. Meanwhile, the High Heating Value (HHV) varies between 6.07 and 7.18 MJ/Nm$^3$, with gasification temperatures fluctuating between 850 and 900 °C. The introduction of bed agitation, whether at high or low frequencies, has a notable impact on gas flow, leading to substantial deviations. Larger particle sizes tend to enhance gas flow and process stability but simultaneously have adverse effects on HHV, ER, and overall process efficiency. During transient analysis, it becomes evident that gas flow requires a prolonged duration to achieve stabilization. Frequent agitation cycles (at a rate of 1/140 s$^-$1) result in fewer deviations but a slower stabilization process, whereas less frequent agitation (1/380 s$^-$1) induces greater variations but accelerates the stabilization phase. This comprehensive investigation offers valuable insights into the optimization of Lenga wood chip gasification, particularly for addressing energy needs in rural areas by harnessing forest residues.



## Nomenclature

| Symbols | Meaning | Units |
|---|---|---|
| $\bar{Y}$ | Average HHV of the gas in each test | MJ/Nm$^3$ |
| $\eta$ | Cold efficiency of the process | % |

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| | | |
|---|---|---|
| $x$ | Concentration (v/v) | - |
| $ER$ | Equivalence ratio | - |
| $Y$ | HHV for a sample | MJ/Nm$^3$ |
| $HHV$ | High heating value | MJ/Nm$^3$ |
| $m$ | Mass | kg |
| $\dot{m}$ | Mass flow | kg/s |
| $T$ | Temperature | °C |
| $t$ | Time | s |
| $\Delta t$ | Time elapsed | s |

**Subscripts**

| | |
|---|---|
| air | Air |
| bms | Biomass |
| j | Each sample of the experiment |
| e | Final |
| f | Gas filter |
| i | Initial |
| in | Inlet |
| out | Output |
| real | Real |
| r | Reduction zone |
| stq | Stoichiometric |
| sg | Syn-gas |
| g | Throat gasification reactor |

## 1. Introduction

Globally, biomass is recognized as a renewable energy source with significant potential, owing to its abundance, adaptability, and ease of management—attributes that distinguish it from other unconventional energy sources. Moreover, the prospect of harnessing both household and industrial waste underscores the pivotal role of biomass-based generation systems in advancing the circular economy concept, helping to mitigate the environmental impact associated with electricity generation processes and agricultural practices [1]. The Magallanes Region in Chile stands out for its attributes concerning Lenga biomass. The region boasts an abundance of this resource due to the presence of forest clusters, generating readily available by-products such as leaves, trimmings, and thinnings. Additionally, the Magallanes Region, along with the Chilean Antarctic, has a population density of 1.1 inhabitants/km$^2$, with 11,157 rural residents constituting 7.4% of the region's total population [1]. Due to its geographical location, the region heavily relies on imported fuels to meet its energy demands [2], highlighting the potential for emerging technologies, such as gasification, to address the void in electricity generation. It's essential to note that the circumstances in the Magallanes Region are not unique; several Latin American regions face similar challenges characterized by limited access to interconnected power grids. In these areas, domestic generation systems with capacities exceeding 50 kWe necessitate the deployment of electrification networks covering areas greater than 2 km$^2$, posing economic viability concerns for the system [3–5]. The Magallanes Region's geographic and socio-economic attributes, such as its remote location and reliance on imported fuels, necessitate the adoption of self-sustaining energy solutions like biomass gasification. These factors not only influence the choice of technology but also underscore the potential benefits for local communities in terms of energy independence and economic sustainability.

Gasification is a thermochemical process that generates a combustible gas from carbonaceous materials, suitable for use in internal combustion engines. This alternative energy source shows significant promise in supplying low-power electricity needs, as demonstrated in the rural electrification case study conducted by

Pujoldevall et al. [6]. Their work underscores the feasibility of this system using gopher residues to generate 20 kWe. Similarly, Depoorter [7] conducted simulations of the generation process, achieving gasifier efficiencies approaching 80%, with the gas subsequently utilized in a 30% efficient engine. Previous studies on biomass gasification have primarily focused on common wood species and agricultural residues [6, 9, 11]. However, limited research has been conducted on the specific conditions and biomass types prevalent in the Magallanes Region. In the context of this study, the motor-gasifier assembly is projected to attain an overall efficiency of 24%. Considering the Low Heating Value (LHV) of the biomass, approximately 15 MJ/kg, this translates to a specific fuel consumption of roughly 1 kg/kWh. This value is marginally lower than the 1.1 kg/kWh reported previously by Raman et al. [8] for high-performance equipment. While other studies have demonstrated a correlation between specific consumption and motor-generator performance, reaching values near 2 kg/kWh for engine efficiencies around 11% [9], the typical range for this metric falls between 1-1.5 kg/kWh [10]. It's evident that the cost-effectiveness of the system heavily relies on the procurement and transportation costs associated with residual biomass, due to its affordability [11].

This underscores the necessity for local-level studies to facilitate equipment development, as emphasized by Pujoldevall et al. [6]. Despite industrial-level equipment availability, technology-related challenges, primarily related to fuel properties and process stability, persist and serve as primary impediments to widespread technology adoption. Consequently, comprehensive research that explores the influence of each process variable on gas quality, system performance, and equipment dynamic response becomes imperative. In this context, Susastriawan et al. [11] conducted a review highlighting the effect of major process variables on gas quality and equipment performance. They also emphasized the significant impact of reactor design on gas quality and efficiency, particularly in the context of low bulk density biomass. Additionally, Palmer et al. [12] evaluated the performance of a 20 kWe downdraft gasifier-based generator set, addressing variable electrical demands and utilizing typical biomass from remote areas in various regions of the United States. Their experiments encompassed three species of lignocellulosic biomass with moisture levels of 15% and 25%, analyzing equipment performance regarding electrical parameters and gasification efficiency. Although energy quality parameters remained consistent despite changing conditions and biomass types, thermal efficiency (biomass-electricity) remained below 11%, contrasting with other works reporting values near 17%. Importantly, these systems align with emission regulations for diesel-powered generators, apart from carbon monoxide emissions, which can be mitigated through catalysts [11]. Furthermore, in the United States, Li et al. [13] conducted a theoretical-experimental study analyzing the feasibility of a Combined Cooling, Heating, and Power (CCHP) system based on gasification to meet the energy demands of small offices. Their findings demonstrated optimal system performance when equipment operated under electrical and non-thermal demand, with the latter exerting a significant influence on system performance. Lastly, De Oliveira et al. [14] explored the gasification of Eucalyptus chips and residues from their processing industry, achieving gas energy densities ranging from 5.5 to 7.76 MJ/Nm$^3$. The highest density was associated with coffee husk gasification, albeit accompanied by challenges linked to variable composition and biomass feeding. Noteworthy, the authors observed stable equipment performance over a period close to 5 hours.

Despite the well-established understanding of how most biomass properties and process variables influence gas quality and gas efficiency, industrial-level equipment supply is typically geared towards utilizing fuels within a predefined range and under standardized environmental conditions. Unfortunately, the reality often involves the availability and location of biomass resources being more unpredictable than desired. This unpredictability leads to the use of fuels that fall outside the manufacturer's specified parameters, resulting in diminished equipment performance and reduced process stability. Moreover, there remains a limited comprehension of equipment performance during the crucial phases of heating and dynamic stability, which can significantly impact overall performance indicators. Given these considerations, this study explores the gasification of residual Lenga biomass within a 10 kWe downdraft fixed-bed system, with a focus on its applicability in rural areas. The selection of this system aligns with the fact that in Latin America, 10-20% of the population resides in regions with population densities below 20 inhabitants/km$^2$ [2]. In such contexts, it is evident that the technology under consideration must start with low-power equipment that is cost-effective for small communities. The primary objective of this study is to evaluate the gasification performance of Lenga wood chips in a fixed-bed system, particularly focusing on its applicability in rural areas. The hypothesis is that variations in particle size and bed agitation frequency significantly impact the gasification efficiency and output quality. The findings could have significant implications for local communities and policymakers. Implementing efficient gasification technologies can provide a sustainable energy source, reduce reliance on imported fuels, and promote local economic development. The analysis of gasification encompasses both the initial transient period and the steady-state gas generation phase. Through factorial analysis, we determine the impact of particle size and bed agitation on key process performance indicators. These parameters have been chosen since, when maintaining the factory-set configuration, they are the sole variables in the process that are contingent upon the end user of the technology. It is worth noting that while this study is region-specific, the procedures employed, and the ensuing results can serve as a blueprint for optimization in any gasification process that allows for adjustments in biomass size and bed shaking frequency. Furthermore, the insights gained from transient operation findings can contribute to future studies and model validation efforts aimed at enhancing our understanding of this critical yet relatively understudied operational condition. Future research could explore the scalability of this technology for larger communities and the integration of gasification systems with other renewable energy sources to further enhance energy security and sustainability.

## 2. Methodology

The processing of Lenga biomass occurs in a 10 kWe fixed-bed gasification system. An experimental factorial design was used to evaluate the effects of two variables: biomass particle size and bed agitation. It is inferred that these factors affect the gasification performance metrics; therefore, by examining their influence, the aim is to enhance the performance of Lenga biomass gasification.

### *2.1. Biomass characteristics*

Lenga (Nothofagus pumilio) is a distinctive South American species originating from the Andean Patagonian woodlands in the southern regions of Argentina and Chile [15]. While precise records regarding Lenga utilization are somewhat limited, it is notable that the timber industry in the Magallanes Region yielded approximately 29,735 m$^3$ of sawn wood in 2019. The native forest area encompasses a vast expanse of 2,779,700 hectares, with Lenga accounting for 51.77% of this total area, as reported by INFOR data [16]. Table 1 presents the physico-chemical characteristics of Lenga biomass, while Figure 1 provides photographs of the chips used in this research.

The material, donated by a local sawmill to the Center for the Study of Energy Resources (for its name in Spanish CERE) of the University of Magallanes, consisted of approximately 300 kg of Lenga wood chips with a maximum length of 80 mm and a moisture content of 16%. To align with the objectives of the study, a resizing process was conducted, reducing them into chips ranging from 3 to 30 mm in size. Additionally, the chips were further categorized into two groups: 3.0-8.0 mm and 8.0-20.0 mm, using sieves for this purpose [15, 16]. The experimental design encompasses the manipulation of variables within the gasification equipment, influencing parameters such as the HHV of the generated gas, cold efficiency, ER, biomass consumption rate, and gas flow. A two-factor factorial design was proposed, tailored to equipment limitations, involving three levels for factor A and two for factor B. The specific levels of particle size (3-8 mm and 8-20 mm) and shaking frequency (every 2, 4, and 6 minutes) were chosen based on preliminary

(a) (b)

**Figure 1.** Sifted Lenga chip, a) 3.0-8.0 and b) 8.0-20.0 mm.

tests that indicated significant impacts on gasification efficiency and stability. These levels align with the study's objectives to optimize performance under practical conditions. For an overview of the experimental conditions, please refer to Table 2. Due to some restrictions of the experimental facility and biomass availability, replicates were not considered; instead, each experimental condition was maintained until the steady state was reached, which, in some cases, meant more than three hours of operation. Certain factors, such as air flow and biomass humidity, were monitored but not controlled.

**Table 1.** Biomass physico-chemical properties.

| Thermo-chemical properties | | |
|---|---|---|
| **Proximate Analysis** | | |
| **Parameter** | **Value (wt.%)** | **Standard** |
| Humidity | 13.61 | |
| Volatiles | 72.72 | ASTM D 7282-15 |
| Fixed carbon | 13.24 | |
| Ashes | 0.44 | |
| HHV (MJ/kg) | 16.89 | ASTM D 7282-13 |
| **Ultimate Analysis** | | |
| **Element** | **Value (wt.%)** | **Standard** |
| Carbon | 42.54 | ASTM D 5373 |
| Hydrogen | 6.59 | |
| Oxygen | 50.13 | |
| Nitrogen | 0.08 | ASTM D 4239-14 Method A |
| Sulfur | <0.01 | By difference |
| **Physical properties — as supplied** | | |
| Chip size | 20–30 mm, 10–15 mm, 3–5 mm | |
| Bulk density | 193.25 kg/m$^3$ | |
| **Physical properties — after processing** | | |
| **Granulometry (mm)** | **Bulk density (kg/m$^3$)** | |
| 3.0–8.0 | 174.15 | |
| 8.0–20.0 | 193.25 | |

**Table 2.** Experimental considerations.

| **Design factors** | **Low level (-1)** | **High level (1)** |
|---|---|---|
| (A) Shaking frequency | 1/380 $s^{-1}$ | 1/140 $s^{-1}$ |
| (B) Biomass granulometry | 3,0–8,0 mm | 8,0–20,0 mm |
| **Constant factors** | | |
| Biomass feeding to the hoper | Automatic | |
| Engine load | Idle | |
| Shaker time kept ON | 20 s | |
| **Non controlled factors** | | |
| Air flow | 4.0–6.0 $Nm^3/h$ (measured) | |
| Biomass humidity | < 15% (measured) | |
| Biomass chemical composition | Ultimate analysis (Carbon 49.25%, Hydrogen 5.87%, Oxygen 44.04%, Nitrogen 0.1%, Sulfur < 0.01) | |
| Real | 1.515 $kg/m^3$ | |
| Bulk density | Measured for 3,0–8,0 mm: 174 $kg/m^3$; Measured for 8,0–20,0 mm: 193 $kg/m^3$ | |
| Environment relative humidity | 40–60% (measured) | |
| Environment temperature | 5–10 °C (measured) | |
| Air chemical composition | 79.03% $N_2$, 20.93% $O_2$, 0.04% $CO_2$ (measured) | |

*Note: The shaking system is based on ON/OFF control. The low and high levels refer to 20 seconds ON/6 minutes OFF and 20 seconds ON/2 minutes OFF, respectively.*

### *2.2. Instrumentation and experimental design*

To characterize the gasification process, a downdraft gasification system was employed—specifically, the All Power Labs® model PP10, with a capacity of 10 kWe (as visually depicted in Figure 2). This system enabled an examination of the dynamics involved in the conversion of Lenga biomass into synthesis gas (syn-gas). For the analysis of gas species—encompassing $H_2$, $CH_4$, $C_nH_m$, CO, $CO_2$, and $O_2$—a GASBOARD 3100P analyzer was utilized. Measurements were taken on a dry basis, with the nitrogen content meticulously determined through a rigorous difference method. The analyzer has a precision of 3% for $H_2$ and $O_2$, and 2% for CO, $CO_2$, $CH_4$, and $C_nH_m$, with accuracy similarly within these ranges. Instruments were calibrated according to the manufacturer's specifications. Calibration procedures included regular checks using standard reference materials and adjustments to ensure accuracy and precision. Temperature was monitored at key locations using four K-type OMEGA temperature sensors connected to a DAQ HotMux DCC (±1.1°C or ±0.4% for Grade 1). These sensors were positioned to capture temperatures at ambient temperature, the reaction reduction zone, the throat reactor, and the gas filter. Beyond temperature, tracking extended to air flow into the reactor and syn-gas production, facilitated by two orifice plate sensors equipped with differential pressure sensors ranging from 0 to 1000 Pa, a sampling frequency of 0.5 kHz, and an accuracy of 0.5% over the measured value, for calibration details of the curve for air flow and syn-gas measurement, refer to Figure 3, where regression data was conducted with around 1200 observations and ANOVA results show R2 = 0.99. These sensors were integrated into the experimental setup, feeding data directly to the Process Control Unit (PCU) of the gasification plant. The PCU continuously monitored pressure drop across the reactor and filter, offering real-time insights into the operational conditions. To augment the instruments suite, a TESTO 435-4 device was deployed to record local barometric pressure (accuracy of ±0.1% of full scale) and air relative humidity (accuracy ±2%).

In each experimental run, the gasification process begins with the loading of 3 kg of charcoal into the reactor bed, accompanied by 12~18 kg of Lenga chips deposited in the hopper. The controlled factors outlined in Table 2 are then adjusted, and measurement instruments and data systems are activated in real-time to ensure accurate data acquisition. Following this setup, the air supply and gas entrainment systems are engaged, and a flammable liquid is introduced through the air inlet, kickstarting the ignition process, which typically lasts for 2–3 minutes. The establishment of a stable state usually occurs within a timeframe of 130 to 150 minutes post-reactor ignition. Potential sources of bias, such as operator error and environmental variability, were mitigated by standardizing experimental procedures. Measurement errors were minimized through regular instrument calibration. Data collection begins from the startup of the equipment, with a focus on information obtained during the stationary state of the process. On average, each individual run spans approximately 160 minutes. Upon the conclusion of each run, an assessment is conducted, including weighing the remaining biomass in the hopper, the carbon content within the reactor bed, and the ashes. Environmental and safety protocols included regular monitoring of gas emissions, maintaining proper ventilation, using protective equipment, and adhering to standard operating procedures for handling combustible gases and high-temperature equipment.

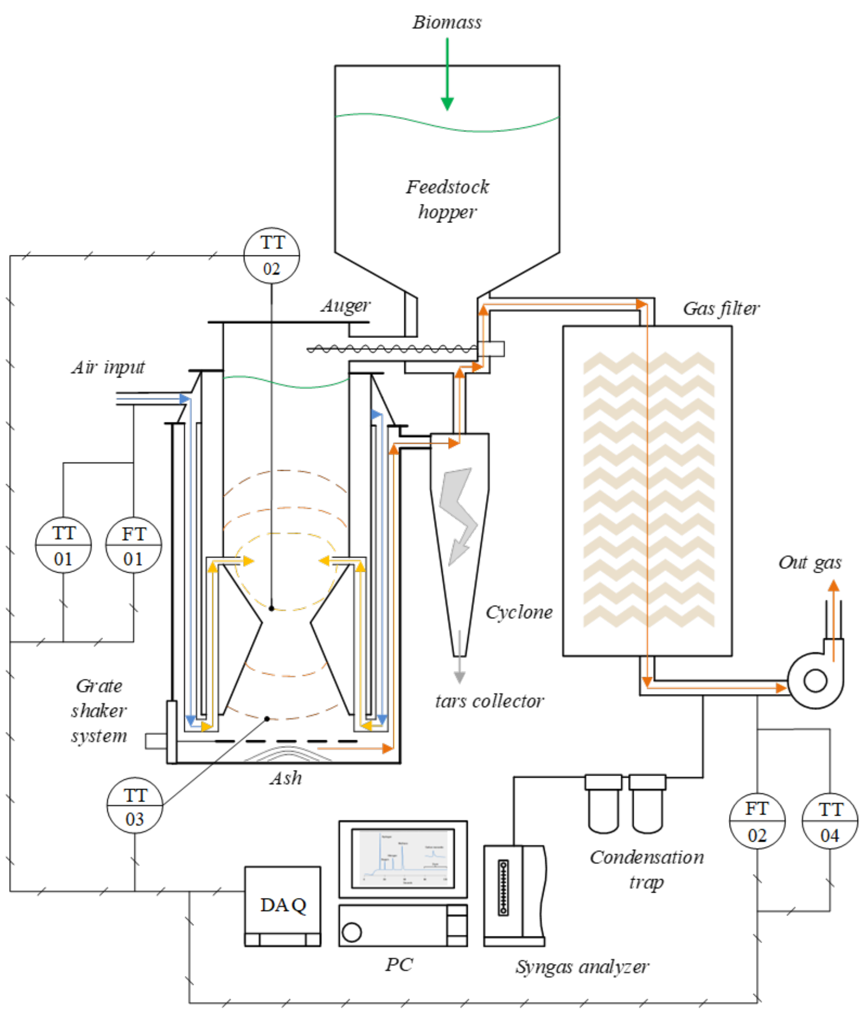


**Figure 2.** Experimental setup scheme.

In summary, the experimental procedure involved the following steps: loading the reactor with 3 kg of charcoal, followed by 12~18 kg of Lenga chips; adjusting the controlled factors; activating measurement instruments; initiating air supply and ignition process; and maintaining steady-state conditions for data collection. Throughout each experiment, several parameters were evaluated:

- Air flow entering the reactor: Quantified using Bernoulli's principle by calibrating an orifice plate.
- Syn-gas flow obtained: Calculated by applying Bernoulli's principle in conjunction with an orifice plate.
- Higher Heating Value (HHV) of the gas: To determine the average HHV of the gas during each test (denoted as $\bar{Y}$), the arithmetic mean of the calorific value of gas samples acquired during steady-state conditions was computed. Each individual sample (represented as $Y_j$) is indirectly determined using the syn-gas composition, which is ascertained via the gas analyzer, according to Equation 1. Gas samples are collected every second, adhering to the predefined equipment configuration.

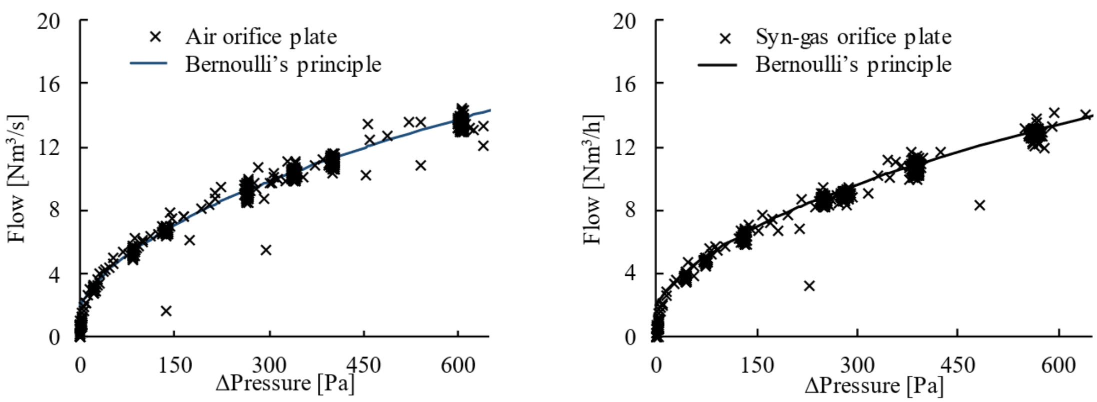


**Figure 3.** Orifice plate calibration curve for air flow and syn-gas measurement.

Examining these variables offers a perspective on the gasification procedure and the effectiveness of Lenga chips. The computations of HHV provide information regarding the energy content of the gas, a pivotal factor for assessing the system's efficiency and possible uses. The assessment of these parameters across different scenarios enables researchers to identify the most favorable configurations and operating conditions, thereby improving gasification for application in rural regions [15].

$$Y_j = x_{H_2,j}\,Y_{H_2} \;+\; x_{CO,j}\,Y_{CO} \;+\; x_{CH_4,j}\,Y_{CH_4} \tag{1}$$

The process efficiency ($\eta$) is determined by establishing the ratio between the energy exiting the process, considering the HHV of the syn-gas (sg), and the energy supplied by the biomass (refer to Equation 2). It's important to note that the sensible energy of the gas is not factored in due to its elevated temperature. The equivalence ratio (ER) is estimated using Equation 3. The calculation of the air mass ($m_{\text{air}}$) involves the integration of the flow curve over the duration of the equipment's operation in each test. Meanwhile, the biomass consumption rate (denoted as $\dot{m}_{bms}$) is ascertained by measuring the initial mass ($\dot{m}_{bms,i}$) and the final mass ($\dot{m}_{bms,e}$) and dividing this by the elapsed time of the test ($\Delta t$), following Equation 4.

$$\eta \;=\; \frac{E_{\text{out}}}{E_{\text{in}}} \;=\; \frac{\dot{m}_{sg}\,\cdot\,HHV_{sg}}{\dot{m}_{bms}\,\cdot\,HHV_{bms}} \tag{2}$$

$$ER \;=\; \frac{(m_{\text{air}}/m_{\text{bms}})_{\text{real}}}{(m_{\text{air}}/m_{\text{bms}})_{\text{stq}}} \tag{3}$$

$$\dot{m}_{bms} = \frac{m_{bms,i} - m_{bms,e}}{\Delta t} \tag{4}$$

## 3. Results

Throughout the experimental process, a set of variables was monitored on a per-second basis, including air flow, HHV, temperatures at different locations within the equipment, syn-gas flow, and its composition [15]. Furthermore, for each test run, reactor cold efficiency, ER, and the rate of biomass consumption were calculated. The steady-state averages for air flow, HHV, gas flow, process temperatures, and gas concentrations are presented in Table 3. The analysis of the results is conducted following two approaches. Initially, it is determined which factors are statistically significant for the air flow entering the reactor, HHV, cold efficiency, ER, biomass consumption rate, and gas flow. Additionally, an analysis of the behavior of the mentioned factors was performed. Secondly, some observations regarding the transitory condition were considered.

**Table 3.** Experimental results.

| **Experimental matrix** | | | **Averaged Variables** | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Run** | **A** | **B** | **Air Flow**[$Nm^3$/h] | $\dot{m}_{bms}$ [kg/h] | **ER** | **HHV**[MJ/$Nm^3$] | $\eta$ [%] | **Syn-gas Flow**[$Nm^3$/h] |
| 1 | 1 | 1 | 3.64 | 6 | 0.185 | 6.07 | 44.8 | 7.02 |
| 2 | -1 | -1 | 3.05 | 4.2 | 0.185 | 6.68 | 50.6 | 6.48 |
| 3 | 0 | 1 | 4.40 | 6.67 | 0.188 | 6.38 | 53.2 | 9.73 |
| 4 | 0 | -1 | 3.50 | 4.64 | 0.205 | 7.12 | 58.8 | 7.13 |
| 5 | 1 | -1 | 2.91 | 4.31 | 0.205 | 6.79 | 56.4 | 5.37 |
| 6 | -1 | 1 | 3.91 | 5.90 | 0.173 | 7.18 | 55.3 | 8.87 |

| | **Process Averaged Temperatures [°C]** | | | **Averaged Syn-gas Concentrations (n/n)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Run** | $T_g$ | $T_r$ | $T_f$ | **CO** | $CO_2$ | $CH_4$ | $C_nH_m$ | $H_2$ | $N_2$ |
| 1 | 853.5 | 828.2 | 43.1 | 18.9 | 8.5 | 3.6 | 0.06 | 16 | 52.8 |
| 2 | 869.6 | 827.7 | 36.3 | 24.4 | 11.7 | 2.7 | 0.05 | 18 | 42.9 |
| 3 | 889.9 | 852.5 | 40.7 | 21.9 | 7.3 | 2.9 | 0.02 | 17.8 | 49.9 |
| 4 | 851.6 | 847.3 | 38.1 | 24.9 | 12.7 | 3.6 | 0.06 | 18.3 | 40.3 |
| 5 | 852.5 | 831.9 | 36.3 | 22.7 | 13.1 | 3.4 | 0.03 | 18.7 | 42.0 |
| 6 | 899.0 | 852.6 | 39.9 | 26.0 | 11.8 | 3.4 | 0.06 | 18.2 | 40.3 |

### *3.1. Factors effect analysis*

The results were subjected to statistical tests, including t-tests and ANOVA, to validate the observed differences. Standard deviations, confidence intervals, and p-values were calculated to support the significance of the findings. The results directly address the research questions by demonstrating the impact of particle size and shaking frequency on gasification efficiency and stability. Table 4 presents the analysis of variance for all the factors. It was found that only the biomass consumption rate was significantly affected by the variation in particle size, although this factor approached a significant p-value for air flow, ER, and gas flow. Nevertheless, modifying the operational parameters results in noticeable shifts in both biomass consumption rate and air flow, as visually represented in Figure 4. These two variables showcase analogous patterns, a consequence of the relationship among biomass consumption, ER, and process temperature [17]. Typically, the highest air flows are linked with the largest particle size, primarily because of decreased pressure losses within the bed. Despite the manufacturer's recommendation against using biomass containing a substantial proportion of particles smaller than 12 mm, the range of 3–8 mm was considered due to the prevalence of such particles in sawmill waste. The research findings reveal that the highest air flows and levels of biomass consumption are observed when the shaking system is inactive for a duration of 4 minutes. This behavior can be linked to the design of the reactor and the thermodynamic processes involved in gasification. A controlled, intermittent shaking system benefits by improving the settling of particles, which, in turn, reduces the flow due to lower pressure losses. On the contrary, a low shaking frequency (1/380 $s^{-1}$) leads to the accumulation of ash in the reduction zone, causing an increase in pressure losses and subsequently reducing both air and biomass flows. Both the rate of biomass consumption and air flow play pivotal roles in the reactor's capacity to maintain the thermodynamic state of the gasification process. Nevertheless, discontinuities in the agitation process have an impact on process stability, favoring continuous shaking despite the reduction in biomass processing rates. Anomalies, such as unexpected fluctuations in gas flow, were attributed to specific experimental conditions, such as variations in shaking frequency or particle size distribution. Further investigation into these anomalies could enhance the understanding of the gasification process.

In terms of the ER, Figure 4c demonstrates limited variations, remaining within the range of 0.17 to 0.20, even as airflow varies from 4.0 to 4.5 $Nm^3/h$ [17]. Typically, higher airflow would lead to an increase in ER, but this effect is mitigated by the proportional rise in biomass consumption, further compounded by a measurement uncertainty of approximately 15% [17]. Conversely, temperature behaves as expected, exhibiting a slight rise with increased availability of oxidants, indicating a shift towards the combustion

**Table 4.** ANOVA for the main performance indicators of the gasification reactor.

| Variable | Source | SS | df | MS | F-Ratio | P-Value |
|---|---|---|---|---|---|---|
| Air flow | A Shaking frequency | 0,0025 | 1 | 0,0025 | 0,02 | 0,8959 |
| | B Biomass granulometry | 0,98415 | 1 | 0,98415 | 7,96 | 0,0667 |
| | Total Error | 0,3709 | 3 | 0,123633 | | |
| | Total (corr.) | 1,35755 | 5 | | | |
| HHV | A Shaking frequency | 0,2401 | 1 | 0,2401 | 1,24 | 0,3473 |
| | B Biomass granulometry | 0,220417 | 1 | 0,220417 | 1,13 | 0,3649 |
| | Total Error | 0,582833 | 3 | 0,194278 | | |
| | Total (corr.) | 1,04335 | 5 | | | |
| Cold efficiency $(\eta_1)$ | A Shaking frequency | 5,3824 | 1 | 5,3824 | 0,18 | 0,7028 |
| | B Biomass granulometry | 25,8337 | 1 | 25,8337 | 0,85 | 0,4254 |
| | Total Error | 91,5405 | 3 | 30,5135 | | |
| | Total (corr.) | 122,757 | 5 | | | |
| ER | A Shaking frequency | 0,000256 | 1 | 0,000256 | 0,62 | 0,0985 |
| | B Biomass granulometry | 0,00040167 | 1 | 0,00040167 | 8,78 | 0,0594 |
| | Total Error | 0,000136667 | 3 | 0,000045556 | | |
| | Total (corr.) | 0,000792833 | 5 | | | |
| Biomass consumption rate $(\dot{m}_{bms})$ | A Shaking frequency | 0,011025 | 1 | 0,011025 | 0,07 | 0,8027 |
| | B Biomass granulometry | 4,89607 | 1 | 4,89607 | 33,05 | 0,0105 |
| | Total Error | 0,444442 | 3 | 0,148147 | | |
| | Total (corr.) | 5,35153 | 5 | | | |
| Syn-gas Flow | A Shaking frequency | 0,099225 | 1 | 0,099225 | 0,09 | 0,7816 |
| | B Biomass granulometry | 9,42507 | 1 | 9,42507 | 8,73 | 0,0598 |
| | Total Error | 3,23984 | 3 | 1,07995 | | |
| | Total (corr.) | 12,7641 | 5 | | | |

zone (as illustrated in Figure 4c and 4d). HHV and cold efficiency follow similar trends, both increasing with higher process temperatures, except for small particles subjected to 6 minutes of shaking cessation, which can be attributed to increased instability in this particle size [17]. The analysis of the syn-gas unveils that the most favorable fuel species outcomes were observed with particle sizes falling within the 3–8 mm range, notwithstanding the increased process variations associated with this choice. On average, the fuel volume concentrations were approximately 25% CO, 18% for H2, and 4% for CH4, which align closely with values previously reported by Rollinson et al. [18] for similar equipment.

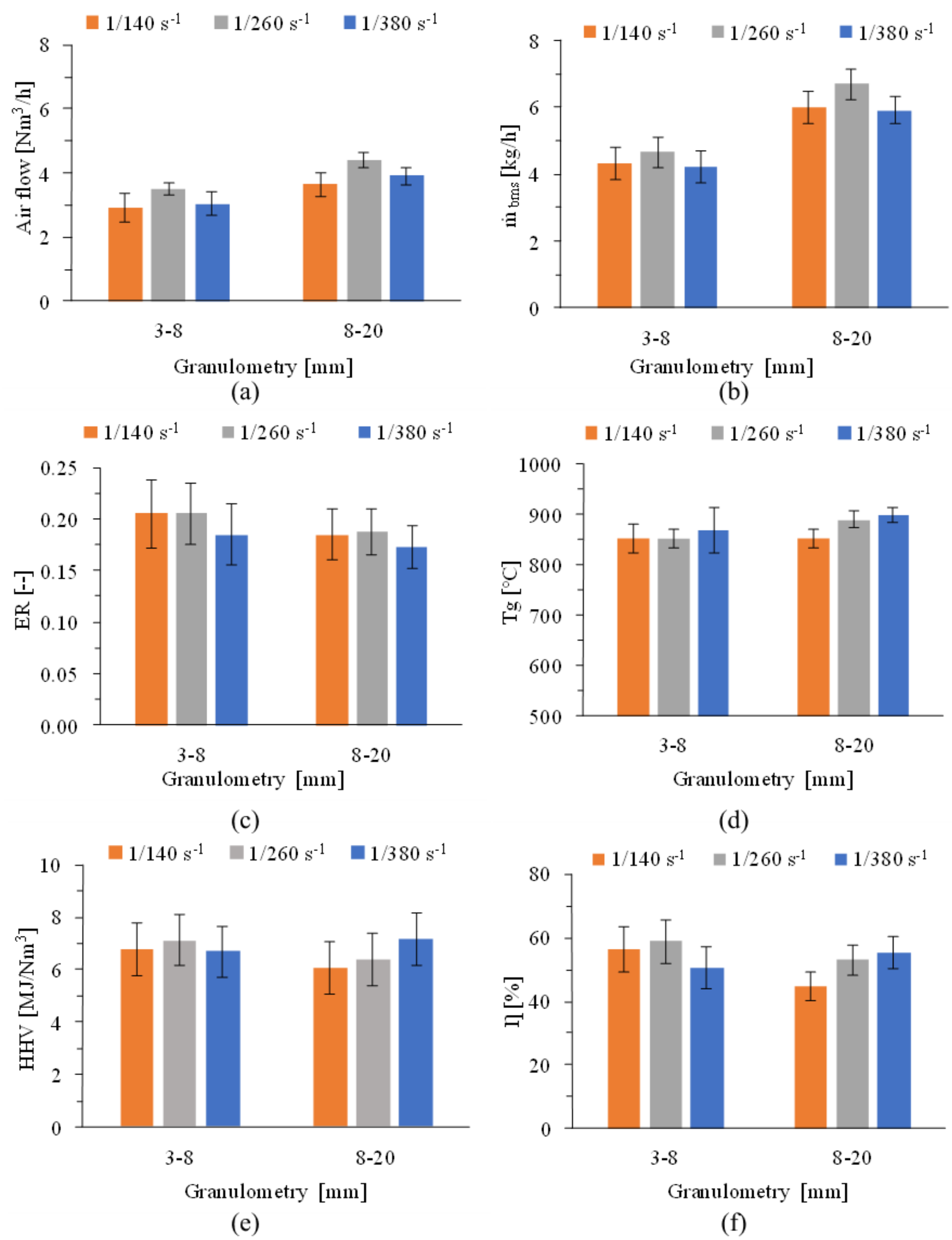


**Figure 4.** Effect of particle size and shaking frequency on a) air flow, b) biomass consumption rate, c) ER, d) gasification temperature, e) HHV and f) process efficiency.

Additionally, there exists a minor tendency for the concentrations of $H_2$ and CO to increase as the shutdown times extend, mirroring a trend similar to the maximum process temperature. In contrast, $CH_4$ exhibits a subtle decline with escalating gasification temperature, denoted as $T_g$ (as illustrated in Figures 5(a) and 5(b)). This phenomenon can be attributed to the prevalence of thermal decomposition reactions involving charring, tar reforming, and methane reforming. Notably, thermal efficiency, although higher with smaller particles, undergoes significant impacts when the shaking durations surpass 4 minutes, primarily due to the reduced generation of $CH_4$ [18].

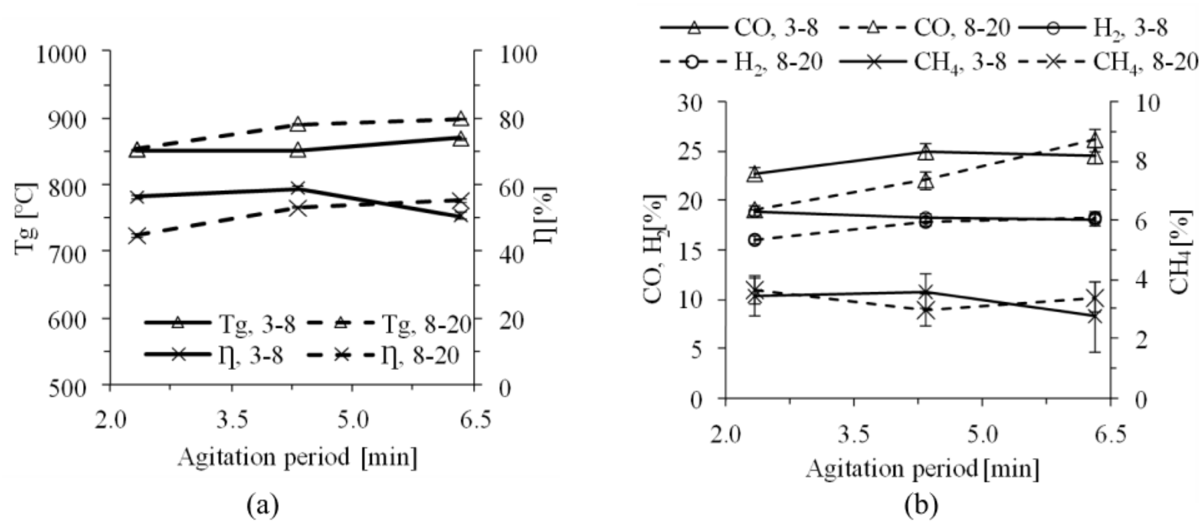


**Figure 5.** Effect of particle size and agitation period on a) gasification temperature and process efficiency, b) combustible gases concentrations.

### *3.2. Transitory condition observations*

Figures 6 and 7 unravel details from transient runs 1 and 4 of our experiment, shedding light on the effects of particle sizes and shaking intervals on gasification dynamics. In the case of particle sizes ranging from 8–20 mm, with shaking occurring every 140 seconds (1/140 $s^{-1}$), the experimental setup yielded the lowest cold efficiency, registering at 44.8%. Conversely, in run 4, utilizing particle sizes within the 3–8 mm range and implementing shaking intervals of 260 seconds (1/260 $s^{-1}$), the highest cold efficiency was achieved, reaching 58.8%. These findings underscore the critical role of particle size and shaking frequency in optimizing gasification performance.

The act of shaking the bed, as evident in the extended durations between shaking episodes, has impact on various aspects of the gasification process. These aspects include process temperatures, concentrations of combustible gases, and HHV. Extended durations exacerbate variations, a phenomenon notable in Run 4. The fluctuations arise from the slippage of the flame front due to the ash removal system, exposing fresh material to the heat of combustion. Lower shaking frequencies lead to ash accumulation, obstructing air passage and causing fluctuations in the gasification front, influencing fuel gas composition and biomass consumption rates. Conversely, higher shaking frequencies contribute to a reduction in process variability by ensuring consistent bed renewal, potentially enhancing particle settling, bed compaction, and unobstructed gas flow [18].

An additional noteworthy phenomenon observed is the reduction in gas flows at both the inlet and outlet during the same experimental run, with a more pronounced reduction in combustible gases at the outlet. This phenomenon can be attributed to the dynamic stabilization of the process. As the system attains its typical operating temperatures, fuel gases become less dense. Operating under suction, with fans extracting the fuel gases maintaining a consistent volumetric flow, this results in a decrease in the mass flow of the fuel gas due to heating, subsequently reducing air flow into the reactor. The stabilization process is prolonged due to specific environmental conditions, with ambient temperatures at approximately 9.4 ± 0.9 °C and relative humidity at 49.8 ± 1.2%. Hypotheses regarding these observations find support in the behavior observed in pressure graphs at various points, including the throat, reduction zone, and reactor filter.

It's noteworthy that, at lower shaking frequencies, the pressure curves exhibit greater fluctuations, and the stabilization of both inlet and outlet gas flows occurs at a slower pace. Temperature stabilizes within a timeframe of 25–34 minutes, accompanied by occasional oscillations. The stabilization of species concentrations and HHV follows a similar trajectory. On the other hand, pressure, air flow, and syn-gas flows take approximately 70–85 minutes to reach a state of stability, highlighting their interconnected nature. Variability in flow measurements, stemming from instrument precision, contributes to obscuring pressure fluctuations. Overall, the analysis of transient conditions provides insights into the dynamics of gasification, emphasizing the role of particle sizes and shaking intervals in shaping process efficiency and stability. Additionally, these findings contribute to optimizing gasification technologies for enhanced sustainability and efficacy.

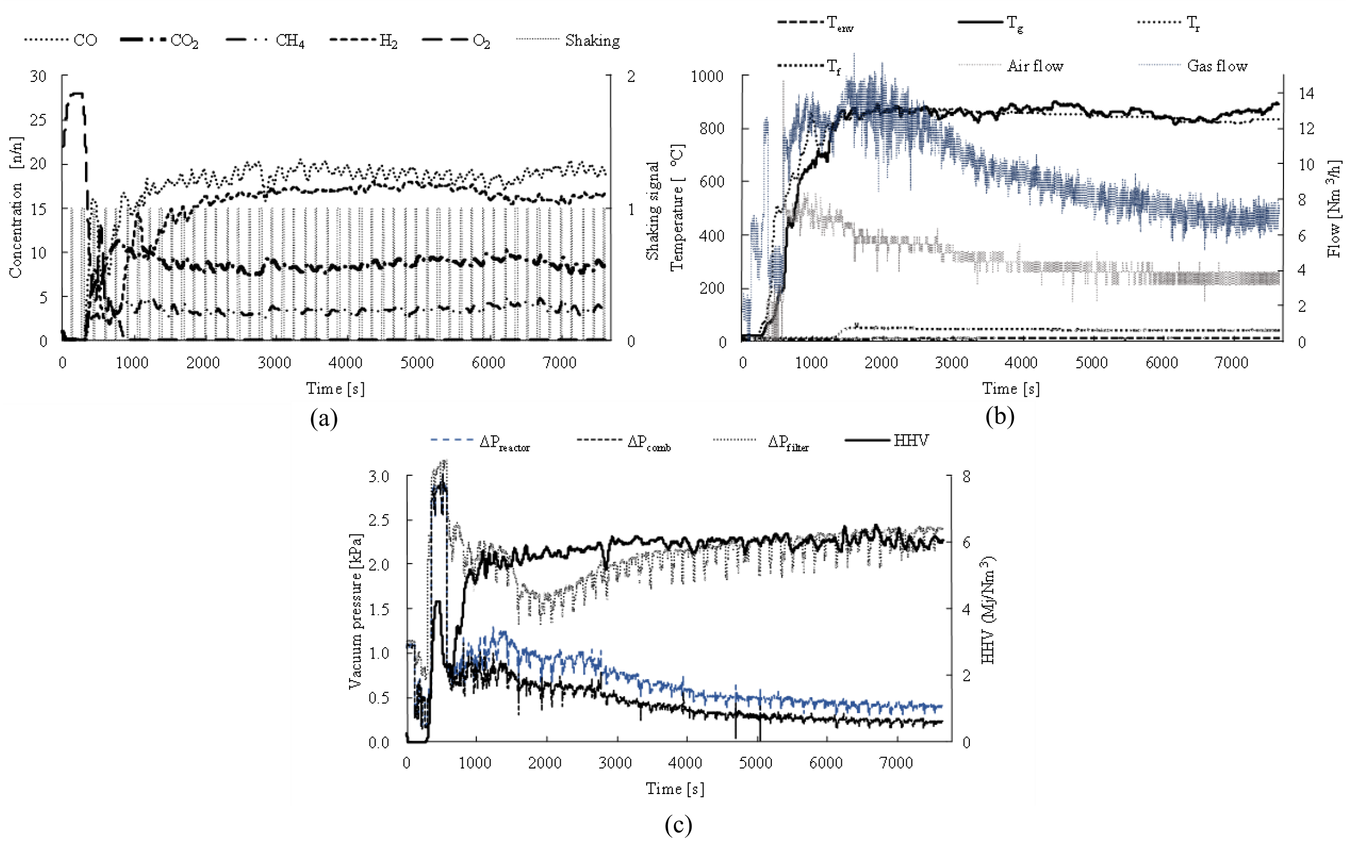


**Figure 6.** Run 1:, 8-20 mm, 120 s, a) Concentrations, b) temperatures and c) pressure drops and HHV.

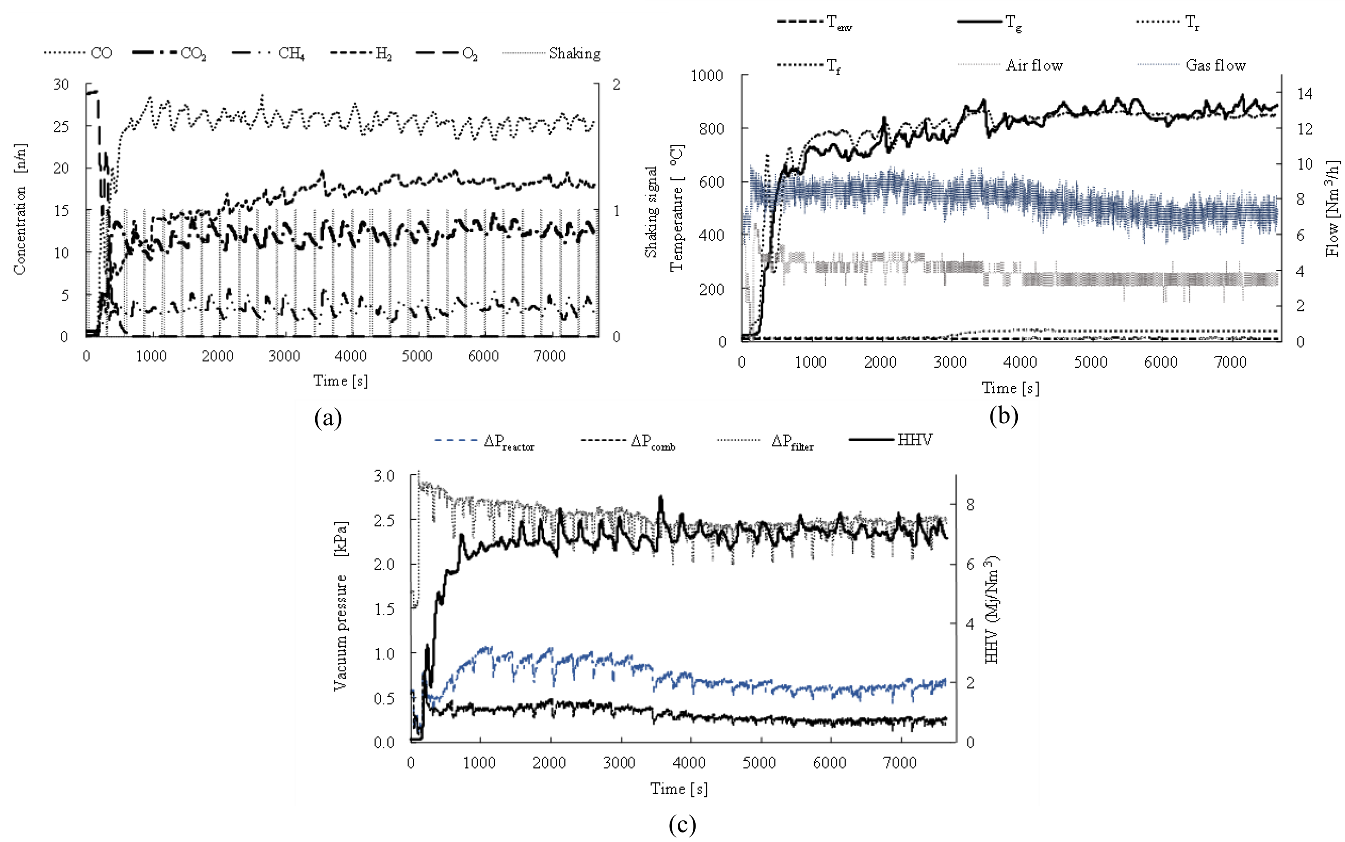


**Figure 7.** Run 4: 8-20 mm, 120 s, a) Concentrations, b) temperatures and c) pressure drops and HHV.

## 4. Conclusions

The findings clearly support the study's objectives by demonstrating the impact of particle size and shaking frequency on gasification efficiency and stability. After conducting comprehensive experiments involving a commercial gasifier and employing diverse agitation methods and Lenga biomass particle sizes, several key findings have emerged:

- Cold efficiency reaching approximately 55% and syn-gas HHV of 6.9 MJ/Nm$^3$ can be achieved with particle sizes falling within the 3–8 mm range, although this falls outside the specified recommendations. Process stability is influenced by factors such as pressure losses and particle settlement. These results have broader implications for the field of renewable energy, highlighting the potential of biomass gasification as a sustainable energy solution for remote areas.
- Particles within the recommended 8–20 mm range result in higher thermal power ranging from 12 to 17.7 kWth, efficiency at 55.3%, and enhanced calorific power measuring 7.18 MJ/Nm$^3$. However, lower agitation frequencies introduce variations in gas quality, potentially impacting the performance of the equipment.
- Regardless of the particle size, maintaining a low shaking frequency ensures the stability of process temperature within the range of 850–900 °C, as well as the ER within the range of 0.17–0.20. This highlights the thermochemical stability of the fixed-bed reactor.

- Throat and reduction zone temperatures stabilize within a timeframe of 25–34 minutes, while inlet and outlet gas flows reach a state of stability in 70–85 minutes, primarily due to the suction within the reactor. The introduction of forced flow could potentially expedite the stabilization process.
- Agitation frequency plays a significant role in influencing process variability and stability. Shaking every 140 seconds reduces variations but extends the time required for stabilization, whereas shaking every 380 seconds accelerates the stabilization process but introduces fluctuations. Optimizing particle size and shaking frequency can enhance gasification efficiency and process stability. Implementing continuous shaking mechanisms may offer additional benefits over ON-OFF control systems.
- Continuous shaking with variable intensity surpasses ON-OFF control in terms of enhancing stability and reducing variations in gas composition, taking into account the gas pressure drops in the control loop.

The study contributes to the existing body of knowledge by providing new insights into the gasification of Lenga wood chips, offering a comparative perspective with similar studies on other biomass types. Economically, the optimized gasification process can reduce fuel costs and improve energy security for rural communities. Environmentally, it offers a sustainable solution to biomass waste management, reducing carbon emissions and promoting a circular economy. In summary, these experiments provide compelling evidence supporting the optimization of gasification efficiency, thermal power, and stability through the application of specific agitation techniques and particle sizes. This opens possibilities for enhanced performance and potential applications in various thermal systems. Future research should explore the scalability of these findings, the integration of gasification systems with other renewable technologies, and the long-term performance under varied environmental conditions.

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**Author contributions:** Conceptualization, A.B.; Methodology, A.V. and H.V.; Formal Analysis, A.V and Y.L. Investigation, A.B. H.V.; Resources, H.V.; Writing – Original Draft Preparation, A.V.; Writing – Review & Editing, A.B and H.V.

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