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ORIGINAL PAPER

Thermal arc air plasma application for biomass (wood pellets) gasification

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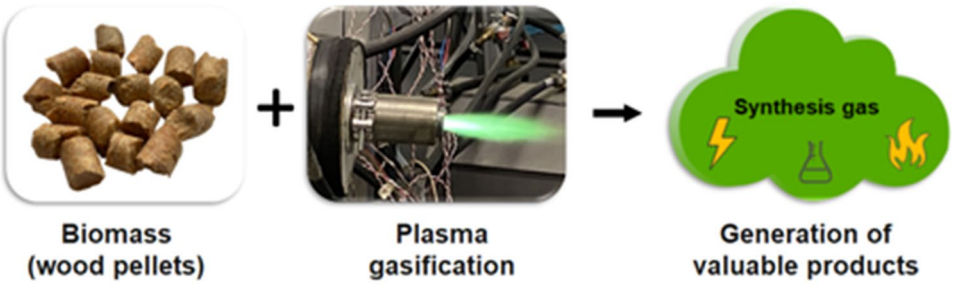
Abstract

Plasma technologies have drawn attention as a possible way for biomass/waste conversion into valuable intermediate products, which could partially satisfy the growing energy demands. Thus, this experimental research aimed to determine the ability to gasify wood pellets to synthesis gas in the thermal air plasma environment. The influence of the plasma torch power, plasma-forming gas flow rate, and the equivalence ratio on biomass gasification was analyzed. The synthesis gas generation varied between 59.95 and 62.51%, while the H_2/CO ratio ranged from 0.68 to 0.8. The producer gas's highest H_2 and CO concentrations were 26.6 and 33.35%, respectively, giving the H_2/CO ratio of 0.8. The lower heating value of the produced synthesis gas ranged from 7.62 to 8.82 MJ/Nm^3. The carbon conversion efficiency and the energy conversion efficiency were equal to 85.3–97.2% and 29.23–30.57%, respectively. The specific energy requirements varied between 165.47 and 195.61 kJ/mol of synthesis gas. Moreover, the energy and mass balance evaluation showed that generated producer gas could produce 15–18 kWh and 111–114 kWh of electrical and thermal energy, respectively, when 20.73 kg/h of wood pellets is gasified. Also, 28 and 33% of the electricity required for the air plasma formation can be received using producer gas in an internal combustion engine and microturbine.

Graphical abstract



Keywords Thermal plasma · Biomass gasification · Wood pellets · Synthesis gas

Introduction

The necessity to fulfill the limitless needs of the growing human population led to the ongoing development of industrialization and growing energy consumption worldwide (Tezer et al. 2022). Indisputable that the well-being of society has become directly dependent on conventional energy sources in the last few decades. However, widely used resources of fossil fuels, including petroleum, natural

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gas, and coal, began to deplete (Kumar et al. 2020). Also, it was acknowledged that these non-renewable fuel sources cause climate change and negatively impact the biosphere (Abdul Malek et al. 2020; Elgarahy et al. 2021). Thus, many policymakers and researchers unanimously seek to find eco-friendly solutions (Ghodake et al. 2021) to fulfill humankind's needs and contribute to environmental protection. Paris Agreement, European Green Deal, and Renewable Energy Directive (REDII) are well-known European initiatives to reach set goals.

Recently, 17 different scenarios have been used to predict how energy consumption will change by 2050 (Raimi et al. 2022). According to evolving policy scenarios, most of these projections (12 scenarios) assumed that global primary energy consumption will increase from ~ 560 QBtu in 2020 to ~ 620–850 QBtu in 2050. Only five scenarios predicted a minor decrease in energy consumption (~ 500–530 Btu in 2050). Moreover, in 2020, 80% (446 QBtu) of the primary energy supply in the world was provided by fossil fuels (coal, oil, natural gas). Nevertheless, 16 scenarios predicted that the share of fossil fuels in the primary energy mix will decrease by 2050 (Raimi et al. 2022). Such a decrease will also probably be stimulated by the global energy crisis, which started in 2022. This crisis led EU policymakers to take even more significant actions. According to the REPowerEU plan, the EU set the target to provide 45% of the primary energy supply from renewables by 2030, seeking to diversify energy supplies (European Commission 2022). Consequently, renewable energy sources, such as solar, wind, geothermal, hydropower, and bioenergy (Faraji and Saidi 2022), received significant attention as a sustainable alternative to fossil fuels. It is assumed that among these sources, biomass-derived energy has the potential to appear as a pivotal source capable of providing relatively consistent energy production and satisfying the present and future needs of humankind (Ubando et al. 2020; Ascher et al. 2022; Ighalo et al. 2022). Thus, biogas, bio-oils, and biochar can be generated from biomass. Since the biomass feedstocks can be forest residues, energy crops, agricultural residues, algae biomass, sewage sludge, and other biodegradable organic fractions of municipal and industrial waste (Siwal et al. 2021; Bolívar Caballero et al. 2022), the biomass is considered carbon–neutral, and it does not contribute to the greenhouse effect induction (Gil 2022). Thermochemical methods, including torrefaction, liquefaction, pyrolysis, gasification, and plasma treatment, are employed for biomass conversion into bioenergy (Siwal et al. 2021; Ascher et al. 2022). Plasma-based gasification lately has drawn widespread attention as an alternative thermochemical method capable of decomposing various organic and inorganic materials (e.g., biomass, waste) into valuable intermediate products, such as synthesis gas and inert vitrified slag. The synthesis gas can be applied in the energy and chemical industries, while vitrified slag can be used as a building material in the construction sector (Mingaleeva et al. 2016; Van Caneghem et al. 2019).

Plasma, also known as the fourth state of matter, is frequently described as either partially or fully ionized gas. Electrons, ions, and neutral species compose the gases in the plasma state. At least part of the plasma species is in electronically excited states. This feature ensures the generation of the highly reactive environment needed for the chemical reactions (Zheng et al. 2010; Wang et al. 2018; Gimžauskaitė et al. 2022). This paper focuses on the thermal plasma characterized by a high energy density and equality between the electrons and heavy particles' temperature. When the temperature of the different plasma species is the same in the localized area, a local thermodynamic equilibrium exists. The temperature of such plasma can vary from $(2–20) \times 10^3$ K (Rahman et al. 2015; Samal 2017). Thermal plasmas have unique characteristics, such as higher temperatures and enthalpy. Also, the environment of the reactive species guarantees efficient chemical reactions, swifts the treatable material conversion process, and ensures high energy conversion efficiency. Moreover, additional chemical reagents or often expensive catalysts are unnecessary to perform the material gasification in the thermal plasma environment (Rahman et al. 2015; Hrabovsky et al. 2018; Gimžauskaitė et al. 2022). Furthermore, air, steam, O_2, N_2, CO_2, Ar, or combinations of these gases can be used as plasma-forming gases and gasifying agents (Samal 2017; Tavares et al. 2019). Summarily, during the material conversion process, such thermal plasma specifications lead to generating higher syngas yield and lower tar content compared with the conventional gasification process (Ma et al. 2020a). Thus, these advantages cause growing attention to the application of thermal plasma technologies for various biomass gasification. A summarization of the several research results of biomass gasification in the plasma environment is given in Table 1. Nevertheless, appropriately comparing the researchers' data is challenging because it is not homogeneous. Thus, a concise discussion of the additional research results received by the researchers will be provided in the text. According to the results presented in Table 1, H_2/CO ratio ranges from 0.58 to 3.76, while the lower heating value (LHV) varies between 4.3 and 12.99 MJ/Nm^{-3}. Moreover, the H_2 and C yields range from 78 to 86% and 81 to 93%, respectively. Meanwhile, cold gas efficiency (CGE) changes from 18 to 41%.

Further, Rutberg et al. used alternating current (AC) air plasma to gasify wood residues. The energy conversion ratio was ~ 64.2% (Rutberg et al. 2011).

Muvhiiwa et al. used DC non-transfer arc thermal plasma torch to gasify the wood pellets in the nitrogen plasma environment. It was determined that the synthesis gas yield increased from 33 to 66%, the carbon efficiency rose from

Table 1 Summary results of biomass gasification using different plasma technologies

Discharge type and power, kW	Gasifying agent type	Feedstock type	H_2, vol%	CO, vol%	H_2/CO ratio	H_2 yield, %	C yield, %	CGE, %	LHV, MJ/Nm^{-3}	References
AC plasma, 2.2–3.3[a]	Air	Wood residues	28.7–32.2	23.6–27	1.06–1.23	n.d.	n.d.	n.d.	13.9[a]	Rutberg et al. (2011)
DC plasma, 11–13	N_2	Wood pellets	n.d.	n.d.	~1	n.d	n.d.	22–39[g]	2.3–4.3[b]	Muvhiiwa et al. (2018)
DC plasma, 11.3–12.05	N_2+O_2	Wood	n.d.	n.d.	~0.8	78–86	81–88	34–37[g]	3.89–4.26[c]	Muvhiiwa et al. (2021)
DC plasma, 11.3–12.05	N_2+O_2	Wood	n.d.	n.d.	~0.8	80–85	82–93	22–23[g]	3.96–4.22[c]	Muvhiiwa et al. (2021)
Microwave plasma, 2.1–2.4	N_2+O_2	Raw lignin	~30–35	~52–55	0.58–0.64	n.d.	n.d.	~18–41	n.d.	Delikonstantis et al. (2019)
DC plasma, 16–24	N_2 + Steam	Wood sawdust	~43	~18.6	2.31	38[c]	n.d.	n.d.	8.72	Ma et al. (2020b)
DC plasma, 16–24	N_2 + Steam	Wood sawdust (20%) & HDPE[d] (80%)	52.4	~13.94	3.76	68[c]	n.d.	n.d.	12.99	Ma et al. (2020b)
DC plasma, 7850	Air	Pine wood chips[e]	17–29	20–35	0.83–0.85	n.d.	n.d.	n.d.	4.3–7.4	Kuo et al. (2020)
DC plasma, 7850	Air	Forest residue[f]	15–27	22–37	0.68–0.73	n.d.	n.d.	n.d.	4.4–7.7	Kuo et al. (2020)
DC plasma, 70	Air	Wood waste	25.1	42	~0.60	n.d.	n.d.	n.d.	n.d.	Messerle et al. (2020)
AC plasma, 79.95	Air	Wood	28.20	26.97	1.05	n.d.	n.d.	n.d.	5.91	Surov et al. (2017)

[a]MJ/kg^{-1}, [b]kWh/kg, [c]mol/kg^{-1}, [d]HDPE—high-density polyethylene, [e,f]as raw materials, n.d.—no data. [g]plasma power was excluded from the CGE calculation

27 to 34%, and hydrogen efficiency increased from 54 to 62% for temperatures 400–1000 °C, respectively. The process efficiency was evaluated regarding the carbon conversion to all product gases, which ranged between 47 and 77% when the temperatures varied between 400 and 1000 °C (Muvhiiwa et al. 2018).

Muvhiiwa et al. applied a DC plasma torch for the gasification of wood. Researchers used nitrogen as a plasma-forming gas and oxygen as the gasification agent. It was observed that the product gas yield was equal to 85% and 81% when the gasification process temperatures were equal to 700 and 900 °C, respectively (Muvhiiwa et al. 2021).

Delikonstantis et al. carried out raw lignin gasification in microwave plasma. Researchers used nitrogen as a carrier gas and air as a gasifying agent. The temperature ranged from ~ 700 to ~ 1900 °C. Five different cases of raw lignin gasification were performed with an air/N_2 mixture at different tested swirl gas flows and direct (feed) flow rates. It was observed that synthesis gas composition was relatively stable in all five cases. Also, it was found that the carbon conversion efficiency ranged from ~ 55 to ~ 89% (Delikonstantis et al. 2019).

Ma et al. used DC thermal plasma to gasify the wood sawdust and high-density polyethylene (HDPE). Nitrogen was used as a plasma-forming gas, and steam was used as a gasification agent. It was observed that in the total produced gas composition, the content of the syngas varied between 60 and 80% (Ma et al. 2020b).

Kuo et al. carried out thermodynamic modeling of various raw and torrefied biomass gasification with thermal plasma. Air, steam, and CO_2 were used as gasifying agents. This paper will discuss the impact of air as a gasifying agent on pine wood chips and forest residue (as raw materials) gasification. It was determined that the increase of the equivalence ratio (ER) from 0.2 to 0.4 caused the reduction of H_2 and CO concentrations and the LHV of produced synthesis gas in both cases. Moreover, the plasma gasification efficiency (PGE) decreased with the increase of ER (0.2–0.4). The PGE decreased from 31 to 9% and 30 to 8% during the gasification of pine wood chips and forest residue in the air plasma environment. Also, the researchers observed that the plasma energy-to-syngas production ratio (PSR) increased with the ER increase. The PSR grew from 4.2 to 11.8 kWh/kg and from 4.1 to 11.4 kWh/kg via the pine wood chips and forest residue gasification process (Kuo et al. 2020).

Messerle et al. gasified the wood waste (WW) in the air plasma environment. The propane–butane mixture was used to reduce copper electrode erosion. Also, researchers compared the obtained experimental results with the thermodynamic computations. Thermodynamic calculations revealed that the highest synthesis gas yield, equal to 71.6% (H_2 = 29.7% and CO = 41.9%), was obtained at the temperature of ~ 1327 °C. Meanwhile, the specific power

consumption for wood waste gasification and WW gasification efficiency was equal to 2.49 kWh/kg and 82%, respectively. Furthermore, the temperature in the reactor varied between ~ 1287 and ~ 1327 °C during the WW gasification experiment. The obtained synthesis gas concentration was equal to 67.1% (H_2 = 25.1% and CO = 42%). The specific power consumption corresponded to 3.05 kWh/kg. Thus, the experimental results agreed with the thermodynamic calculations. Also, generated gasification products did not contain tars or harmful substances (Messerle et al. 2020).

Surov et al. used an AC plasma torch to gasify wood in the air plasma environment. The average temperature in the reduction zone varied between 1038 (on the wall) and 1450 °C (on the axis). It was determined that 55.17 vol% of synthesis gas was generated during gasification. The specific output on gas and lower heating value was equal to 2.46 m^3/kg (or 2.36 kg/kg) and 5.91 MJ/m^3 (or 6.16 MJ/kg), respectively (Surov et al. 2017).

Mourão et al. conducted a thermochemical assessment of the sugarcane bagasse gasification using different plasma oxidants. Air, steam, CO_2, and O_2 were used as gasifying agents. This paper will present only the results obtained using air as a gasifying agent. The researchers estimated the effect of the equivalence ratio (ER varied between 0 and 0.5) and temperature (~ 727 and ~ 1227 °C) on gasification process performance by evaluating the energy efficiency (EnE), exergy efficiency (ExE), and energy yield (EY).

When the ER was changing in the interval of 0–0.5 at the constant temperature equal to ~ 727 °C, the calculated EnE and ExE varied from ~ 0.84 to 0.71 and from ~ 0.78 to 0.67, respectively. Furthermore, the EY content increased from ~ 4 to ~ 18%, when ER ranged from 0 to 0.3, respectively. The EY acquired negative values as ER grew from 0.4 to 0.5. When the temperature was equal to ~ 1227 °C, while ER ranged from 0 to 0.5, the EnE and ExE values decreased from ~ 0.83 and ~ 0.77% to ~ 0.59 and ~ 0.57%, respectively. Meanwhile, the EY increased from ~ 3 to ~ 16 (Mourão et al. 2015).

Although plasma technologies are considered promising methods for various biomass and waste gasification, these technologies are not yet fully developed and commercialized. Therefore, further research at the laboratory-scale level is needed. Thus, this experimental research aimed to determine the ability to gasify biomass (wood pellets) to synthesis gas in the thermal air plasma environment. The influence of different material conversion parameters, including the power of the plasma torch and the plasma-forming gas flow rate on the biomass gasification process, was analyzed. Also, the evaluation of the plasma system performance was carried out. Moreover, to the authors' knowledge, there is a lack of articles (e.g., (Messerle et al. 2018)) evaluating the energy balance of the plasma technologies used for biomass or waste gasification. Thus, the novelty of the present article lies within the fact that a comprehensive evaluation of the energy balance of the newly constructed plasma-based technology applied for biomass (wood pellets) gasification is presented in this work.

Materials

The experimentations were performed using the 6-mm-diameter wood pellets as the reference biomass feedstock. The ultimate and proximate analysis of the wood pellets was completed before the feedstock gasification with thermal air plasma, as summarized in Table 2.

The ultimate analysis showed that wood pellets mainly consisted of carbon, oxygen, and hydrogen, lower values of nitrogen and sulfur, as well as chlorine traces.

Proximate analysis revealed that the volatile matter of the wood pellets was equal to 78.2 wt%, while the moisture content comprised 7.88 wt%. Moreover, the feedstock's ash and fixed carbon contents were equal to 0.30 and 13.62 wt%, respectively. The wood pellets' lower heating value was identified as equal to 18.28 MJ/kg.

The experimental plasma gasification system of the biomass

The experimental plasma-based gasification system of the biomass was designed at the Plasma Processing Laboratory of the Lithuanian Energy Institute and is presented in Fig. 1.

The system is composed of an atmospheric pressure DC arc plasma torch (1), a feedstock feeder (2), a cyclone (3), a gas cooling (heat exchanger) (4), a gas burner (5), a rotameter (6), a gas and tar sampling point (7), a condenser (8), a plasma-chemical reactor (9), an ash–char container

Table 2 The ultimate and proximate analysis of the wood pellets

Ultimate analysis, wt%	
Carbon (C)	51.69
Hydrogen (H)	6.17
Nitrogen (N)	< 0.01
Sulfur (S)	0.011
Chlorine (Cl)	0.005
Oxygen (O)[a]	42.11
Proximate analysis, wt%	
Moisture	7.88
Ash	0.30
Fixed carbon	13.62
Volatile matter	78.2
LHV, MJ/kg	18.28

[a]By difference

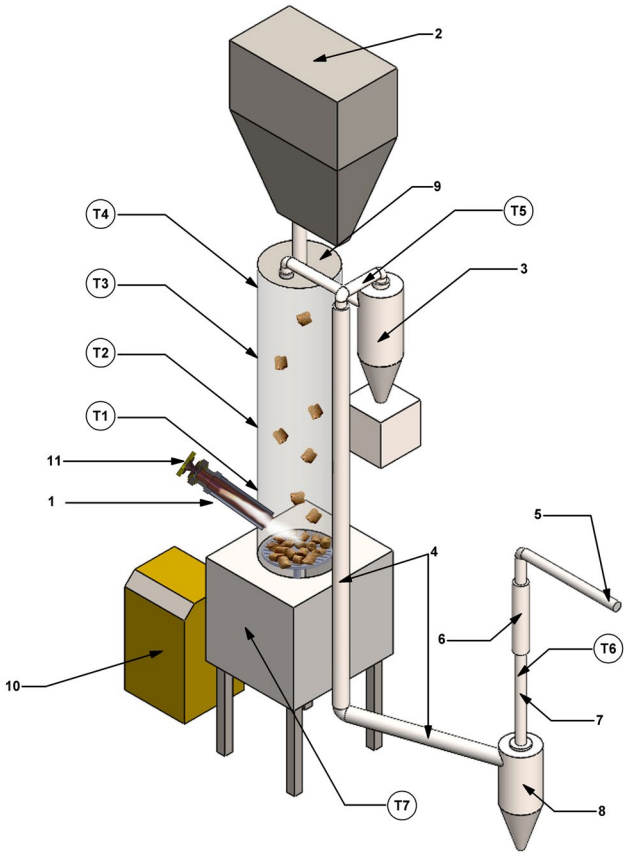

Fig. 1 The plasma-based gasification system of the biomass: 1—an atmospheric pressure DC arc plasma torch, 2—a feedstock feeder, 3—a cyclone, 4—a gas cooling (heat exchanger), 5—a gas burner, 6—a rotameter, 7—a gas and tar sampling point, 8—a condenser, 9—a plasma-chemical reactor, 10—an ash–char container, 11—plasma-forming gas supply, T1, T2, T3, T4, T5, T6, T7—thermocouples

(10), plasma-forming gas supply (11), and thermocouples (T1, T2, T3, T4, T5, T6, T7).

The air was used as a plasma-forming gas and the main gasifying agent during the biomass gasification process. The feedstock feeder was fitted in the upper part of the plasma-chemical reactor so that wood pellets could fall through the reactor gradually to its bottom, where the plasma torch was installed. Such construction ensures preferable conditions for the interaction of biomass with active species in the plasma environment. The gasification of the wood pellets was carried out at the plasma torch power of 40.5–54.9 kW, the air flow rate of 10.18–18.18 kg/h, and the feedstock flow rate of 20.73 kg/h (equivalence ratio of 0.11–0.16).

The gas analysis was performed three times to ensure the reliability of the data using the SWG 300^{-1} and an Agilent 7890A gas chromatograph. This paper provides the data as the mean value of three replicates. The relative error of the measurements carried out with a gas chromatograph is ± 5%.

The tar content in the formed producer gas also was measured three times to guarantee data reliability using the Varian GC-3800 gas chromatograph equipped with a flame ionization detector (FID). The measurements were taken according to the standard method of tar condensation in a solvent (isopropanol, 99.5%), also known as cold trapping.

Evaluation of the biomass gasification system

The quantification of the biomass (wood pellets) gasification system in terms of the producer gas composition, the H_2/CO ratio, the lower heating value (LHV), the carbon conversion efficiency (CCE), the energy conversion efficiency (ECE), and the specific energy requirement (SER) was performed. The equations expressing these parameters are provided as follows (Tamošiūnas et al. 2019; Gimžauskaitė et al. 2022):

$$\begin{aligned}\mathrm{LHV}_{\mathrm{syngas}} &= 10.78\mathrm{H}_2(\%) + 12.63\mathrm{CO}(\%) \\ &\quad + 35.88\mathrm{CH}_4(\%) + \cdots + X\mathrm{C}_x\mathrm{H}_y(\%)\end{aligned} \tag{1}$$

where $\mathrm{LHV}_{\mathrm{syngas}}$ is a lower heating value of synthesis gas (MJ/Nm^3) and H_2, CO, CH_4, and C_xH_y are the content of gaseous products in the producer gas (vol%).

Carbon conversion efficiency is described as the ratio between the carbon in the produced gaseous products and carbon in the solid wood pellets fed to the gasification system:

$$\begin{aligned}\mathrm{CCE} &= 12 \times Y_{\mathrm{dry\ gas}} \\ &\times \left(\frac{[\mathrm{CO} + \mathrm{CO}_2 + \mathrm{CH}_4] + 2 \times [\mathrm{C}_2\mathrm{H}_2 + \mathrm{C}_2\mathrm{H}_4 + \mathrm{C}_2\mathrm{H}_6]}{22.4 \times \mathrm{C}} \right) \\ &\times 100\%\end{aligned} \tag{2}$$

where CCE is the carbon conversion efficiency (%), $Y_{\mathrm{dry\ gas}}$ is a dry gas yield in Nm^3 per kg of dry feedstock (Nm^3/kg), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4), and ethane (C_2H_6) are in % (v/v), and C is in % of carbon in the dry feedstock.

The cold gas efficiency (CGE) can be expressed as the ratio between the chemical energy of the produced synthesis gas and the chemical energy of the solid wood pellets fed to the gasification system:

$$\mathrm{CGE} = \frac{\mathrm{LHV}_{\mathrm{synthesis\ gas}} \times m_{\mathrm{synthesis\ gas}}}{\mathrm{LHV}_{M,\mathrm{IN}} \times X_{M,\mathrm{IN}}} \tag{3}$$

where CGE is a cold gas efficiency (%), $\mathrm{LHV}_{\mathrm{synthesis\ gas}}$ is a lower heating value of produced synthesis gas (MJ/nm^3), $m_{\mathrm{synthesis\ gas}}$ is a flow rate of synthesis gas (m^3/h), $\mathrm{LHV}_{M,\mathrm{IN}}$

is a lower heating value of injected feedstock (MJ/kg), and $X_{M,\mathrm{IN}}$ is a mass flow rate of injected feedstock (kg/s).

The energy conversion efficiency (ECE) can be defined as a ratio of generated synthesis gas chemical energy to wood pellets chemical energy with the addition of plasma energy:

$$\mathrm{ECE} = \frac{(\mathrm{H_2} + \mathrm{CO})_{\text{synthesis gas}} \times \mathrm{LHV}_{\text{synthesis gas}}}{P_{\text{plasma}} + X_{M,\mathrm{IN}} \times LHV_{M,\mathrm{IN}}} \times 100\% \quad (4)$$

where ECE is the energy conversion efficiency (%), $(\mathrm{H_2} + \mathrm{CO})_{\text{synthesisgas}}$ is a mass flow rate of synthesis gas (kg/s), $\mathrm{LHV}_{\text{synthesis gas}}$ is a lower heating value of synthesis gas (MJ/Nm^3), P_{plasma} is a plasma torch power (W), $X_{M,\mathrm{IN}}$ is a mass flow rate of injected wood pellets (kg/s), and $\mathrm{LHV}_{M,\mathrm{IN}}$ is a lower heating value of injected wood pellets (MJ/kg).

Specific energy requirement (SER), also known as specific energy consumption, defines the amount of energy used to produce a product unit. The SER can be expressed by the ratio between the used energy and the amount of generated products:

$$\mathrm{SER} = \frac{P_{\text{plasma}}}{m_{\text{synthesisgas}} \times M_{\text{synthesis gas}}} \quad (5)$$

where SER is a specific energy requirement (kJ/mol or kWh/kg), P_{plasma} is a plasma torch power (kJ/s), $m_{\text{synthesisgas}}$ is a mass flow rate of synthesis gas (mol/s), and $M_{\text{synthesis gas}}$ is a molar mass of synthesis gas (kg/mol).

The estimation of the possible ways to use producer gas generated during the biomass (wood pellets) gasification process was also carried out according to thermal efficiency (Eq. 6) and electrical efficiency (Eq. 7), respectively (Striūgas et al. 2017):

$$\eta_{\text{heat}} = \left(\frac{Q_{\text{hw}}}{Q_{\text{biomass}} + P_{\text{PT}}}\right) \times 100\% \quad (6)$$

where η_{heat} is the thermal efficiency of the producer gas usage process (%), $\mathrm{Q_{hw}}$ is the energy content accumulated in hot water (kWh), $\mathrm{Q_{biomass}}$ is the energy content in the biomass (wood pellets) (kWh), and P_{PT} is the power of the plasma torch (kWh).

$$\eta_{\text{el}} = \left(\frac{P_{\text{el}}^{\text{out}}}{\mathrm{Q_{biomass}} + P_{\text{PT}}}\right) \times 100\% \quad (7)$$

where η_{el} is the electrical efficiency of the producer gas usage process (%) and $P_{\text{el}}^{\text{out}}$ is the electrical energy content in the internal combustion engine or microturbine gained from producer gas (kWh).

Also, the plasma gasification system's electrical efficiency was evaluated according to Eq. 8:

$$\eta_{\text{el}} = \left(\frac{P_{\text{el}}^{\text{out}}}{P_{\text{el}}^{\text{in}}}\right) \times 100\% \quad (8)$$

where η_{el} is the plasma gasification system's electrical efficiency (%) and $P_{\text{el}}^{\text{in}}$ is the total power input (kWh).

Results and discussion

The experimental studies on biomass conversion began with the gasification of wood pellets using thermal air plasma. The effect of the air (as plasma-forming gas and gasifying agent) flow rate, the equivalence ratio, and the plasma torch power on the gasification of wood pellets to synthesis gas is discussed in the following. Moreover, quantification of the biomass gasification system performance in terms of the producer gas composition, the $\mathrm{H_2/CO}$ ratio, the lower heating value, the carbon conversion efficiency, the energy conversion efficiency, and the specific energy requirement is provided in the following.

The concentrations of produced gases measured during the gasification of wood pellets by thermal air plasma are shown in Fig. 2. As the ER increased from 0.09 to 0.16, the concentration of $\mathrm{H_2}$ remained, in essence, stable (25.17–26.60 vol%), while the concentration of CO slightly decreased from 36.75 to 33.35 vol%.

Synthesis gas accounted for 59.95–62.51 vol% in the obtained producer gas. The concentrations of $\mathrm{CO_2}$ slightly increased from 6.86 vol% to 7.38%, with the increase of ER from 0.09 to 0.11. However, it started to decrease with the further growth of the ER and was equal to 5.60 vol% when ER was equal to 0.16.

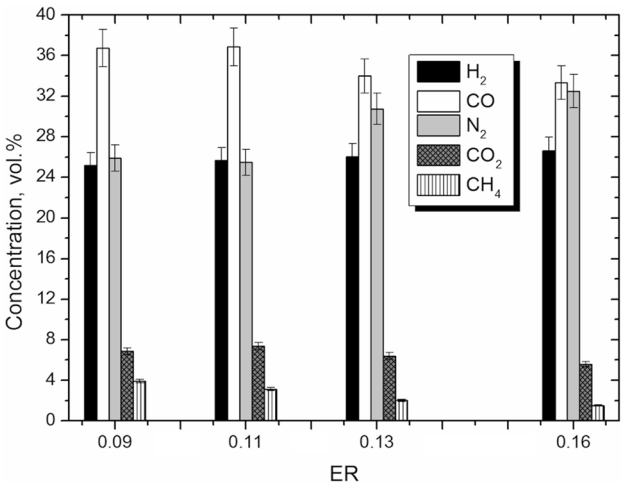

Fig. 2 Effect of the equivalence ratio (ER) on the produced gas composition

Moreover, as the ER increased from 0.09 to 0.16, the concentration of CH_4 tendentiously decreased from 3.92 to 1.5 vol%, respectively. The remaining gas in the mix of the producer gas was nitrogen (25.47–32.50 vol%). Also, a small amount of the C_2H_2 (0.43–1.45 vol%) and the traces of the C_2H_6 (0.01–0.08 vol%) and C_3H_8 (0.01 vol%) were recorded.

Furthermore, the effect of the equivalence ratio on the H_2/CO ratio was evaluated and is shown in Fig. 3.

As the ER increased from 0.09 to 0.16, the H_2/CO ratio changed from 0.68 to 0.80. Thus, the change in the ER caused a slight increase in the H_2/CO ratio. Such a tendency was mainly attributed to the generation of the slightly higher content of H_2 and lower content of CO. Moreover, the effect of the equivalence ratio on the lower heating value of the generated synthesis gas was assessed (Fig. 3). As the ER increased from 0.09 to 0.16, the LHV of the synthesis gas decreased from 8.82 to 7.62 MJ/Nm^3. This trend was observed due to reduced CH_4 and CO concentrations and increased N_2 content in the generated gases.

The effect of the equivalence ratio on the carbon conversion efficiency is presented in Fig. 4. The carbon conversion efficiency increased from 85.27 to 97.21% when the ER increased from 0.09 to 0.16. The observed tendency shows that the increased airflow rate and ER, with the wood pellets feeding rate being constant (5.76 g/s), induced growth of the produced gas flow rate. Consequently, this directly affected the CCE increase.

Also, the increase in the airflow rate (and ER), while the arc current remained constant (180 A), led to a plasma torch power increase from 40.5 to 54.9 kW. This trend could be explained by the rise of voltage from 225 to 305 V, induced by the increased airflow rate (and ER).

The effect of the equivalence ratio on the energy conversion efficiency is given in Fig. 4. As the ER increased from 0.09 to 0.13, the ECE slightly decreased from 30.56 to 27.62% due to the increased plasma torch power. However, when the ER reached the value of 0.16, the ECE slightly increased to 29.24%. Such trend was influenced by an increase in generated producer gas content, compared with the measurement point at ER = 0.13, which partly compensated for the influence of the plasma torch power increase.

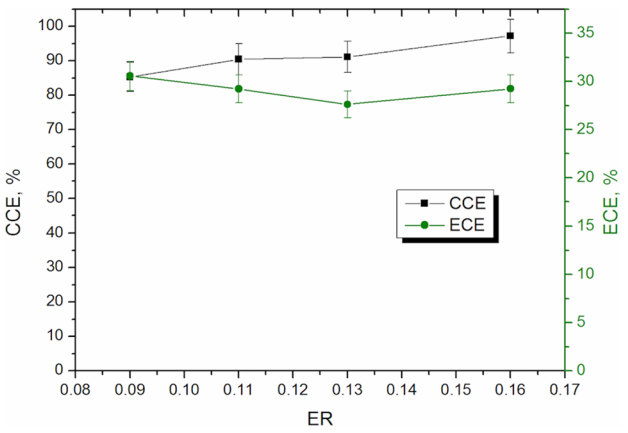

Fig. 4 Effect of the equivalence ratio (ER) on the change of the carbon conversion efficiency and the energy conversion efficiency

The effect of the equivalence ratio on the specific energy requirements is shown in Fig. 5.

The SER grew from 165.47 kJ/mol (1.53 kWh/kg) to 193.29 kJ/mol (1.79 kWh/kg) when the ER increased from 0.09 to 0.11. Such trend was observed due to the increased power of the plasma torch from 40.5 to 50.4 kW, while the synthesis gas concentration remained relatively stable (61.92–62.51 vol%). As ER continued to rise, the SER remained essentially stable and ranged between 193.29 and 195.61 kJ/mol (1.79–181 kWh/kg). A minor change was observed due to the slight change in the synthesis

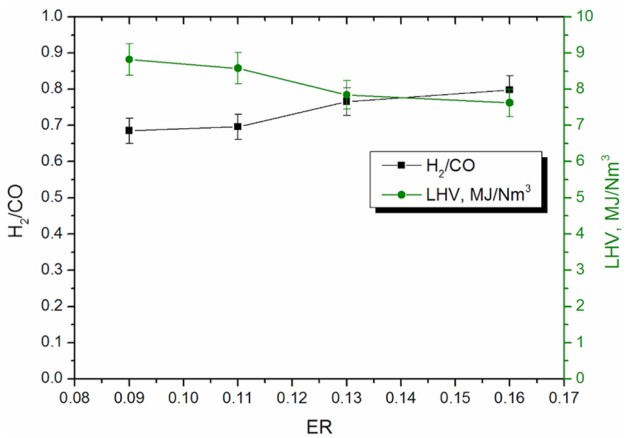

Fig. 3 Effect of the equivalence ratio (ER) on the change of the H_2/CO ratio and the lower heating value

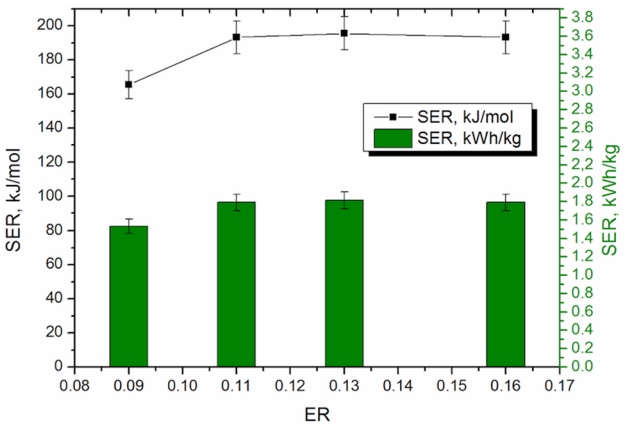

Fig. 5 Effect of the equivalence ratio (ER) on the change of the specific energy requirements

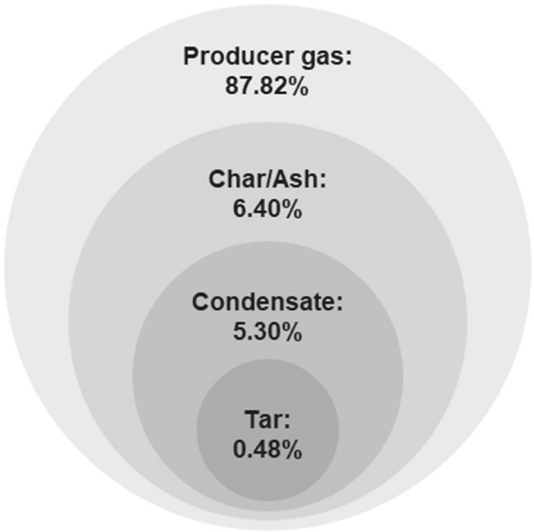

Fig. 6 The composition of reaction products after the biomass (wood pellets) gasification in the air plasma environment

Table 3 The ultimate and proximate analysis of the char/ash

Ultimate analysis, wt%	
Carbon (C)	89.48
Hydrogen (H)	1.39
Nitrogen (N)	< 0.01
Sulfur (S)	0.028
Chlorine (Cl)	0.016
Oxygen (O)[a]	9.08
Proximate analysis, wt%	
Moisture	3.58
Ash	3.08
Fixed carbon	87.21
Volatile matter	6.13
LHV, MJ/kg	32.52

[a]By difference

gas content (59.95–62.51 vol%) and plasma torch power (50.4–54.9 kW).

Moreover, the evaluation of the biomass (wood pellets) gasification system showed that the best performance conditions were achieved when the ER was equal to 0.16, the airflow rate corresponded to 4.56 g/s, and the plasma torch's power was 54.9 kW. Thus, the further focus was directed on additional analysis of this particular experimental point by evaluating the distribution of gasification products quantity and their composition. It was revealed that wood pellets in the air plasma environment were mainly converted into producer gas (87.82%) (Fig. 6). Also, 6.40% of the char/ash, 5.30% of condensate, and 0.48% of the tar were recorded.

The tar content was equal to 4.196 g/Nm^3, mainly consisting of benzene and toluene (62%). Also, the ultimate and proximate analysis of the char/ash revealed that it mainly consisted of fixed carbon (87.21%) and ash (3.08%) (Table 3). Moreover, small contents of volatile organic compounds (6.13%) and moisture (3.58%) were recorded. Furthermore, the lower heating value of the char/ash corresponded to 32.52 MJ/kg and was almost two times higher than the initial wood pellets LHV (18.28 MJ/kg, Table 2). The generated char/ash can be returned to the gasification process to create a closed material reuse cycle and convert this feedstock into useful gaseous products, such as synthesis gas.

Additionally, the energy efficiency determination of the wood pellets gasification system was carried out by evaluating the mass and energy balance in separate parts of the thermal air plasma technological system (Fig. 7) when ER was equal to 0.16. Primarily, 54.9 kWh of electrical energy and 18.18 kg/h of air were provided to the plasma torch seeking to generate thermal air plasma, which was further used for wood pellets gasification. The electrical energy transformation into thermal energy occurred during the air plasma formation. The water was used for the plasma torch cooling. Therefore, part of the thermal energy was transmitted to the water, which cools down the cathode (10.15 kWh) and anode (18.29 kWh) in the plasma torch. Thus, the cathode cooling water and anode cooling water were warmed to 40.2 and 51.20 °C, respectively, from the primary 20 °C cooling water temperature. Accordingly, the energy provided to the plasma-chemical reactor accounted for 26.46 kWh. Additionally, 20.73 kg/h of wood pellets was supplied to the plasma-chemical reactor to perform its gasification process. The share of energy stored in the wood pellets accounted for 105.26 kWh. Hence, the total energy supplied to the plasma-chemical reactor was equal to 131.72 kWh.

However, during the wood pellets gasification process, part of the energy was lost in the form of condensate (0.05 kWh), tar (2.20 kWh), char (27.76 kWh), and heat losses (2.04 kWh). Thus, 35.93 kg/h of producer gas, which contains within itself the remaining energy content (103.67 kWh), was generated via the wood pellets gasification process. The formed producer gas was diverted to the heat exchanger, where 12.28 kWh of producer gas energy was lost into the cooling water. Thus, the temperature of the producer gas decreased from 492 to 72 °C. Hence, the remained total producer gas energy accounted for 91.39 kWh. Generalizing, a noticeable amount of the energy was lost into the plasma torch cooling water. Thus, optimizing the plasma torch construction should be considered to reduce energy losses in the cathode and anode cooling sections.

Furthermore, the formed producer gas can be used for thermal energy generation in the boiler or electrical and

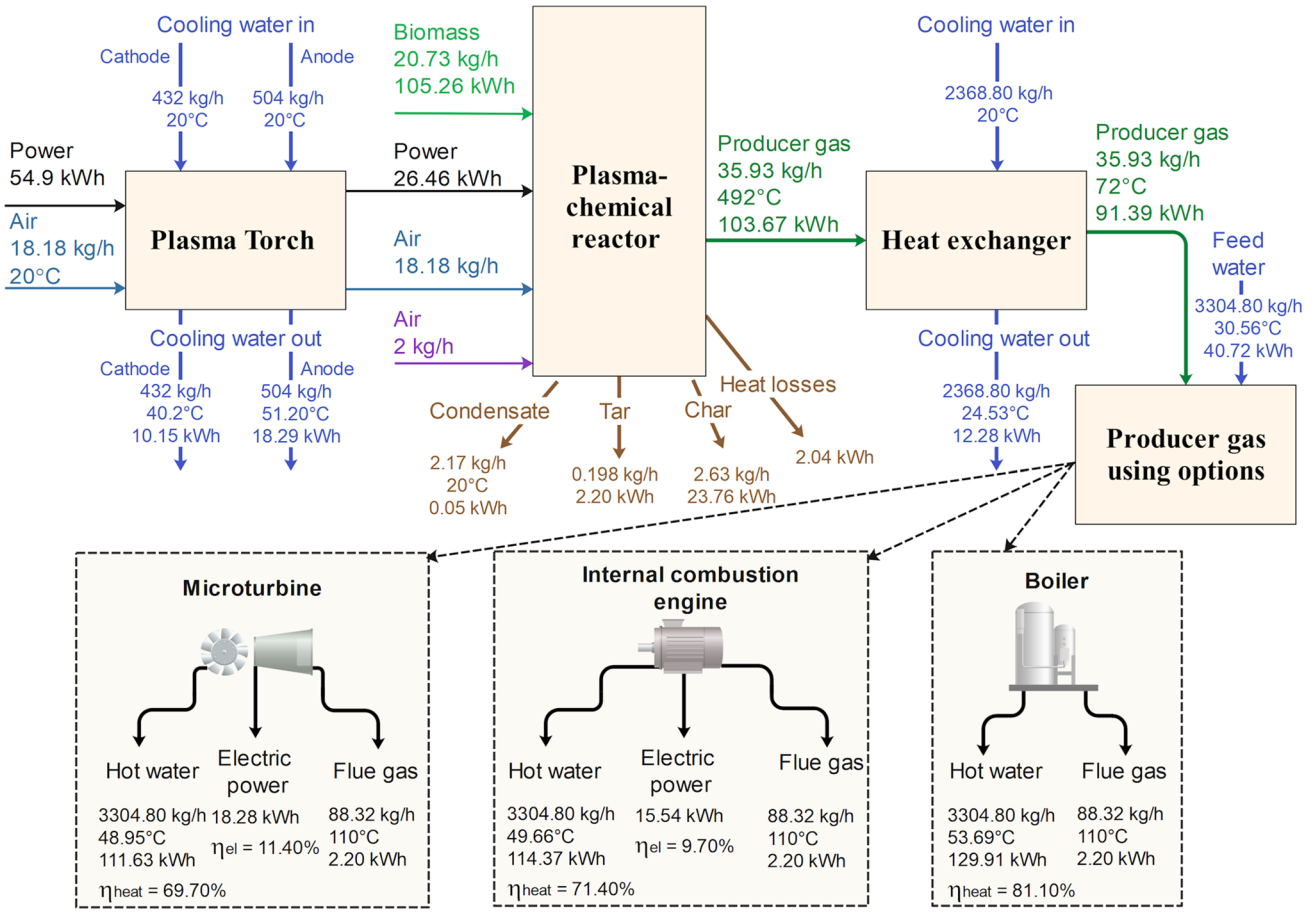

Fig. 7 Energy balance of the thermal air plasma technology applied for biomass (wood pellets) gasification at ER equal to 0.16

thermal energy generation in the internal combustion engine (ICE) or microturbine. The efficiency of these feasible usage ways was established by Eqs. 6 and 7, respectively. The producer gas conversion efficiency into electricity can reach up to 17 and 20% in an internal combustion engine and microturbine, respectively (Chaves et al. 2016; Striūgas et al. 2017). In this present case, the total process efficiency may be equivalent to 81.10% (or 129.91 kWh) if the generated producer gas would be utilized in the boiler. When producer gas would be used in the internal combustion engine, the process thermal energy may be equal to 71.40% (or 114.37 kWh) and the process electrical energy could be equivalent to 9.70% (or 15.54 kWh). Meanwhile, the thermal efficiency of the process may correspond to 69.70% (or 111.63 kWh), and the electrical energy could be 11.40% (or 18.28 kWh) if the producer gas would be used in the microturbine.

Moreover, the summary of the parameters obtained via calculation of the producer gas utilization options in the boiler, internal combustion engine (ICE), and microturbine is presented in Table 4. The electrical efficiency calculations (Eq. 8) revealed that 28.30 and 33.30% of the energy needed for the plasma formation could be recovered after generated producer gas utilization in the ICE and microturbine, respectively.

Consequently, the calculations showed that a higher part of the energy is received in the thermal energy form. In contrast, a small amount could be recovered in the electrical energy form. Furthermore, the evaluation of possible ways to utilize producer gas was carried out, presuming that the hot water generated via cooling of the wood pellets gasification system could be applied as feed water provided, for instance, to the boiler.

Although the calculations of the electrical efficiency showed that only about one-third of the required energy could be received for plasma formation, it is a starting point for further optimization of the newly constructed plasma torch and all plasma gasification system and future experimental research.

A brief comparison of experimental results obtained with several biomass gasification methods is presented in Table 5. The focus was on analyzing the experimental studies in which similar gases were used as gasifying agents. Also, the concentration was on studies in which the

Table 4 The energy received from produced gas generated during wood pellets gasification in the air plasma environment

	The gasification of 20.73 kg/h of biomass (wood pellets) in the air plasma environment	The gasification of 1 kg/h of biomass (wood pellets) in the air plasma environment
Producer gas, kWh	103.67	5.00
Boiler, thermal energy, kWh	129.91	6.27
ICE, thermal energy, kWh	114.37	5.52
ICE, electrical energy, kWh	15.54	0.75
Microturbine, thermal energy, kWh	111.63	5.38
Microturbine, electrical energy, kWh	18.28	0.88
The energy needed for plasma formation, recovered from the producer gas using ICE, %	28.30	1.37
The energy needed for plasma formation, recovered from producer gas using microturbine, %	33.30	1.61

feedstock type was kindred to the feedstock investigated in this experimental research study. Accordingly, the woody biomass gasification with traditional or plasma-based methods revealed that the H_2/CO ratio varied between 0.35 and 1.05, while the LHV ranged from 3.7 to 8.82 MJ/Nm^{-3}. Also, the CCE and the CGE were equal to 52.00–97.21% and 22.00–76.9%, respectively. The highest values of the LHV and CCE were obtained using thermal plasma technologies to gasify the biomass. The slightly highest H_2/CO ratio values were obtained with thermal plasma gasification, except in one study with traditional gasification in which H_2/CO ratio reached 1 (Ong et al. 2015). Also, the cold gas efficiency showed that the highest values of this parameter were achieved using traditional gasification methods.

It should be noted that part of woody biomass conversion experiments applying traditional gasification was performed using pilot-scale reactors. Meanwhile, woody biomass gasification experiments in the plasma environment were performed by applying laboratory-scale reactors. Differences in technology readiness levels also affected the results of experimental studies. Traditional gasification has its strong points in materials conversion and is better studied. However, plasma-based technologies are also promising for biomass gasification to valuable products, such as synthesis gas ($H_2 + CO$).

Life cycle assessment (LCA) must also be considered while comparing the different materials conversion methods.

Sanjaya et al. (2023) performed state-of-the-art LCA comparison of the thermochemical conversion methods. The evaluation was carried out under several impact categories, including global warming potential (GWP), acidification potential (AP), abiotic depletion potential (AD), eutrophication potential (EP), photochemical ozone creation potential (POCP), ozone depletion potential (ODP), and human toxicity potential (HTP). During the comparison of plasma gasification and traditional gasification, the authors revealed that 75% of the reviewed LCA showed that plasma gasification has a lower GWP than conventional gasification. Regarding the AP and AD categories, 67% and 100% of LCAs reported that plasma gasification has lower AP and AD than traditional gasification. Moreover, for the rest of the categories, 50% of reviewed LCAs showed that plasma gasification has a lower EP, POCP, OD, and HTP, compared to traditional gasification. However, researchers stated that there is a need to perform broader research to specify plasma gasification impact on parameters such as OD, POCP, and HTP. Hence, plasma gasification can be a suitable technology for the circular economy. However, further development of the related policy regulations and decisions is still needed.

As for the experimental study presented in this paper, further research is required to optimize the biomass/waste conversion process conditions in various plasma environments. For instance, applying water vapor as a plasma-forming gas and gasifying agent could increase the overall biomass conversion parameters. Nevertheless, it was important first to perform the well-known wood biomass gasification in a newly constructed plasma-chemical reactor with a widely used and easily accessible gasifying agent—air. Since the plasma-chemical reactor and plasma torch showed good working performance, the technology could be applied to convert more complex feedstocks using different gasifying agents.

Conclusions

Plasma-based gasification of biomass (wood pellets) was presented in this experimental study.

The wood pellets gasification in the thermal air plasma environment was carried out when the airflow rate varied

Table 5 Summary results of biomass gasification using traditional and plasma gasification methods

Method	Gasifying agent type	Feedstock type	H_2, vol%	CO, vol%	H_2/CO ratio	LHV, MJ/Nm^{-3}	CCE, %	CGE, %	Ref
Fluidized bed gasification	Air	Pine sawdust	9	16.7	0.54	n.d.	n.d.	~35	Cao et al. (2019)
Bubbling fluidized-bed gasification	Air	Pine waste pellets	10.3–11.1	14.7	0.70–0.75	5.4	60.4–81.8	46.9–65.8	Nobre et al. (2020)
Bubbling fluidized-bed gasification	Air	Pine pellets	5–7	11–15	0.46–0.47	3.7–5.4	58–60	33–40	Pio et al. (2020)
Bubbling fluidized-bed gasification	Air	Pine chips	5.8–6.5	13.5–18.5	0.35–0.43	4.6–6.2	77–78	48–52	Pio et al. (2020)
Circulating fluidized-bed gasification	Air	Sawdust	8.6–9.5	14.6–17.8	0.53–0.59	3.73–4.42	52–82	39–56	Mallick et al. (2020)
Fixed-bed downdraft gasification	Air	Wood chips	17.3	17.1	1.01	4.7	n.d.[a]	66.9	Ong et al. (2015)
Fixed-bed downdraft gasification	Air	Wood chips	15.1	23.8	0.63	5.86	n.d.	76.9	Barontini et al. (2021)
DC plasma gasification	N_2+O_2	Wood	n.d.	n.d.	~0.8	3.89–4.26 [b]	n.d.	34–37	Muvhiiwa et al. (2021)
DC plasma gasification	N_2+O_2	Wood	n.d.	n.d.	~0.8	3.96–4.22[b]	n.d.	22–23	Muvhiiwa et al. (2021)
DC plasma gasification	Air	Pine wood chips[c]	17–29	20–35	0.83–0.85	4.3–7.4	n.d.	n.d.	Kuo et al. (2020)
DC plasma gasification	Air	Forest residue[d]	15–27	22–37	0.68–0.73	4.4–7.7	n.d.	n.d.	Kuo et al. (2020)
DC plasma gasification	Air	Wood waste	25.1	42	~0.60	n.d.	n.d.	n.d.	Messerle et al. (2020)
AC plasma gasification	Air	Wood	28.20	26.97	1.05	5.91	n.d.	n.d.	Surov et al. (2017)
DC plasma gasification	Air	Wood pellets	25.17–26.60	33.35 –36.75	0.68–0.80	7.62–8.82	5.27–97.21	27.62–30.56 [e]	This work

[a]n.d.—No data; [b]mol/kg^{-1}; [c,d]as raw materials; [e]in the case of plasma gasification, the values of the ECE are provided. ECE in plasma gasification is equivalent to CGE in traditional gasification

between 10.18 and 18.18 kg/h and the feedstock flow rate was equal to 20.73 kg/h. Thus, the equivalence ratio ranged between 0.11 and 0.16. Moreover, the gasification was performed at 40.5–54.9 kW plasma torch power. The quantification of the biomass gasification system in terms of several parameters defining the system's performance was implemented. Thus, the increase of the equivalence ratio from 0.09 to 0.16 caused a rise in the H_2/CO ratio, the carbon conversion efficiency, and a decrease in the lower heating value as well as the energy conversion efficiency. Meanwhile, the specific energy requirements increased with the increase of ER from 0.09 to 0.11 while remaining stable as the ER continued to grow. Moreover, the experimental results revealed that the optimal performing conditions for the gasification of wood pellets in the air plasma environment were obtained when the ER, airflow rate, and the plasma torch's power were equal to 0.16, 4.56 g/s, and 54.9 kW, respectively. Accordingly, the synthesis gas concentration and the H_2/CO ratio were equivalent to 60% and 0.8, respectively. The carbon conversion efficiency, energy conversion efficiency, and specific energy requirement accounted for 97.21%, 29.24%, and 193.27 kJ/mol (1.79 kWh/kg), respectively. Additionally, the

energy and mass balance evaluation revealed that producer gas energy content was equal to 103 kWh. The generated producer gas can potentially produce 15–18 kWh of electrical energy and 111–114 kWh of thermal energy when 20.73 kg/h of wood pellets is gasified. Moreover, 28 and 33% of the electricity needed for the air plasma formation can be recovered by utilizing producer gas in an internal combustion engine and microturbine. This primary experimental research showed promising results for successfully applying the newly designed plasma gasifier and whole gasification system. Further research is needed to optimize biomass/waste conversion process conditions in air plasma and other plasma environments.

Author contributions MA and RU prepared the experimental bench. DG, AT, MA, RU, and VS conducted the experimental research and collected the data. MA, DG, and AT analyzed the data and wrote the manuscript. All authors read and approved the final manuscript.

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Data availability Enquiries about data availability should be directed to the authors.

Declarations

Conflict of interest The authors declare no conflict of interest for this experimental research article.

Ethical approval This article does not contain studies involving living-being organisms, including human or animal subjects.

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