*Infocommunications and Radio Technologies*, vol. 5, no. 1, pp. 108–116, 2022.
*Инфокоммуникационные и радиоэлектронные технологии.* 2022. Т. 5, № 1. С. 108—116.
ISSN: 2587-9936
DOI: 10.29039/2587-9936.2022.05.1.09

UDC 66.011

# Non-Thermal Air Arc Plasma Assisted Biomass Gasification

Qingdong Deng, Qijia Guo[@], Rui Li,
Guangyuan Yang, Yan Liu, and Zhaochang He

*Huadong Photoelectric Technology Institute,*
*International Joint Research Center for Research and Application of THz Devices*
*Wuhu, Anhui, 241002, China*
*guoqijia@163.com*

Received: May 10, 2022
Peer-reviewed: June 5, 2022
Accepted: June 5, 2022

***Abstract:*** *A novel small-scale biomass gasification system assisted by a non-thermal air arc plasma is introduced in this paper and the gasification experiment setup, procedure and gasification results are described in detail. The results show that the production of syngas (CO and $H_2$) is in the range of 1.14 $Nm^3/h$ to 1.46 $Nm^3/h$ during the system normal operation at plasma power consumption 120 W and biomass feed rate 3360 g/h, and the volume fraction of syngas in produced gas is in the range of 20.2% to 23.89%. The maximum cold gasification efficiency is 44.56% and the minimum specific energy consumption (defined as the ratio of plasma power consumption to the heat power content of the produced gas) of the gasification system is 2.18%, which is much lower than that of gasification system with thermal plasma.*

***Keywords:*** *biomass; non-thermal plasma; gasification.*

***For citation (IEEE):*** Qingdong Deng, Qijia Guo, Rui Li, Guangyuan Yang, Yan Liu, and Zhaochang He, "Non-Thermal Air Arc Plasma Assisted Biomass Gasification," *Infocommunications and Radio Technologies*, vol. 5, no. 1, pp. 108–116, 2022, doi: 10.29039/2587-9936.2022.05.1.09.

## 1. Introduction

Biomass resource has been considered as the largest potential alternative renewable energy source that can replace fossil fuels [1]. Among different biomass conversion methods, biomass gasification can be used simultaneously for different purpose such as providing fuels, electricity and heat, which has been considered as a effective way to convert biomass into energy and chemical ma-

terials [2]. However, due to the dispersion character of biomass, conventional biomass gasification systems face the problem of high cost on biomass collection [1]. And a small, quick start and shut down, reliable and low cost gasification technology is considered in this context. Plasma technology has been looked at as a viable method for biomass gasification in compact gasification system [3–4]. The high gas temperature, the abundant active species and the high radiation intensity of plasma can excite and accelerate the reactions that are hardly activated under normal condition, and these advantages are beneficial to reduce the size of the gasification system. Different kinds of thermal plasma technology has been used in biomass gasification research, such as microwave plasma [5] and direct current arc plasma [6–8], however, the application of thermal plasma technology in gasification is limited due to its imperfections, such as the limited electrode lifespan due to moisture and the penalized gasification efficiency due to high energy consumption of thermal plasma torch [4,9]. Compared with thermal plasma, the non-thermal plasma has lower power consumption, much longer electrode lifespan and more simple plasma generation device [10], which has been utilized in tar decomposition [11–12] and other various fields of chemical industry [13].

In this paper, a novel small-scale biomass gasification system assisted by a non-thermal air arc plasma is introduced. The gasification procedure and gasification results are described in detail and the effect of air flow rate on the gasification process is investigated. The role of non-thermal arc plasma and factors affect the gasification process are discussed.

## 2. 2. Materials and Method

### 2.1. Experimental Setup

The schematic diagram of the gasification system assisted by non-thermal air arc plasma is shown in Fig. 1. The gasification system mainly includes an air source pump, an air mass flowmeter (Sevenstar D08), a twin screw powder feeder, a high voltage power supply, a non-thermal arc plasma torch, a cyclone separater and a produced gas combustion apparatus. The non-thermal arc plasma torch consists of an inner columnar high voltage electrode, an external cylindrical ground electrode with a nozzle and a cylindrical teflon for insulating the high voltage electrode and the ground electrode. The high voltage electrode and the ground electrode are coaxial. The length and external diameter of the torch is about 120 mm and 60 mm, respectively. The air flow and biomass powder inlet is on the ground electrode of the plasma torch as shown in Fig. 1. The inner face of the powder inlet is cylindrical and the diameter of it is 10 mm.

The axis of cylindrical powder inlet deviates from the axis of the cylindrical plasma torch 15 mm to form a swirling air gas flow which is beneficial for plasma uniformity and enhancing the effect of plasma on biomass powder. The plasma torch nozzle connected with cyclone separater which includes three turn stainless steel tube coils. The external diameter of the coil is about 150 mm, and the inner diameter of the stainless steel tube is 25 mm. The reaction products of the mixture of biomass and air arc plasma ejected from the plasma torch nozzle into the stainless steel tube, and then the produced gas and the solid products are separated by cyclone separater. The height and external diameter of the cyclone separater is about 500 mm and 180 mm, respectively. A combustion apparatus is placed on the outlet of the cyclone separater for disposing of the produced flammable gas and assessing the gasification process by flame status. The poplar powder is used as typical biomass in the gasification process, and the powder was screened through a 20-mesh sieve. The lower heating value (LHV) of the poplar powder is 13.14 kJ/g which is obtained through bomb calorimeter (U-Therm YX-ZR9302).

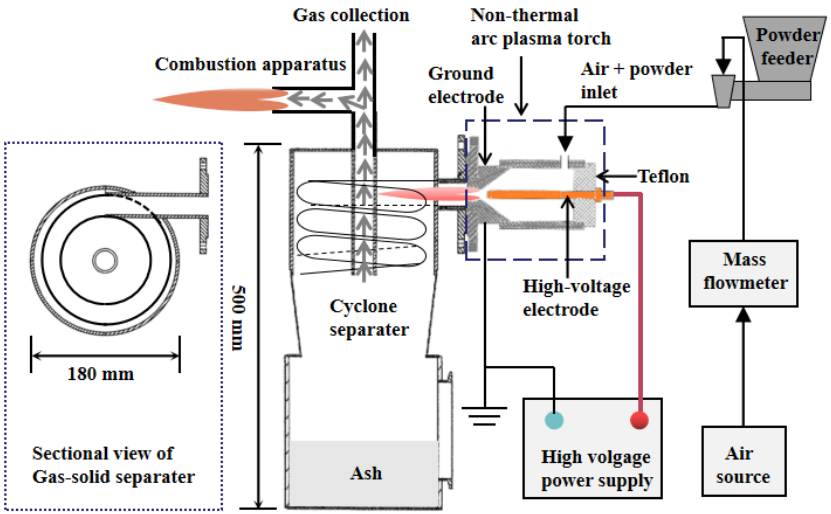


Fig. 1. The schematic diagram of the gasification system assisted by non-thermal plasma

## 2.2. Experiment Procedure

The gasification system is working at atmospheric pressure and air is used as biomass gasification agent and plasma working medium. The feed air flow rate is regulated by mass flowmeter and the volume flow rate of air ($\dot{V}_{air}$) is in the range of 2.7 $Nm^3/h$ to 4.5 $Nm^3/h$. The popular powder is fed into the

gasification system by a twin screw powder feeder, and the feeding rate is 3360 g/h at the experiments. The input power of the high voltage power supply measured by a power meter (UNI-T UT230E) is approximate as the power consumption of the non-thermal arc plasma torch, and the power consumption is in the range of 120 W to 250 W at the experiments. The experiments procedure are carried out in order as follows: starting the air source pump, regulating the air flow well, starting the high voltage power supply for generating arc plasma, starting the powder feeder and well regulated, collecting the produced gas in bags after the flame stable at combustion apparatus, analyzing the produced gas by gas chromatograph (BFRL SP-3420A).

### 2.3. Experiment Procedure

Lower heating value of the produced gas ($LHV_{pg}$) [14], cold gas efficiency (CGE) and specific energy consumption (SEC) are employed to assess the performance of the gasification system, these indices are calculated as follow:

$$LHV_{pg} = 10.79Y_{H_2} + 12.62Y_{CO} + 35.81Y_{CH_4} + \\ + 63.75Y_{C_2H_6} + 59.04Y_{C_2H_4} + 56.08Y_{C_2H_2} \quad (1)$$

$$CGE = \frac{\dot{V}_{dg} \cdot LHV_{pg}}{\dot{m}_{feed} \cdot LHV_{feed} + P_{torch}} \times 100\% \quad (2)$$

$$SEC = \frac{P_{torch}}{\dot{V}_{dg} \cdot LHV_{pg}} \times 100\% \quad (3)$$

where $Y_{H_2}$, $Y_{CO}$, $Y_{CH_4}$, $Y_{C_2H_6}$, $Y_{C_2H_4}$ and $Y_{C_2H_2}$ are the volume fractions of $H_2$, CO, $CH_4$, $C_2H_6$, $C_2H_4$ and $C_2H_2$ in the produced gas, respectively. The $\dot{m}_{feed}$ and $LHV_{feed}$ correspond to the feeding rate and the lower heating value of the fed biomass, respectively. The $P_{torch}$ is the power consumption of the non-thermal arc plasma torch. The $\dot{V}_{dg}$ is the volume flow rate of dry produced gas, which is calculated from:

$$\dot{V}_{dg} = 0.78\dot{V}_{air} / Y_{N_2} \quad (4)$$

where $Y_{N_2}$ is the volume fractions of $N_2$ in the produced gas. Equation (4) is based on an assumption that the nitrogen in the feed air is balance to the nitrogen in produced gas.

## 3. Results and Discussion

### 3.1. Produced gas composition

The gaseous product of the biomass gasification detected at the experiment mainly includes $H_2$, CO, $CH_4$, $C_2H_6$, $C_2H_4$, $C_2H_2$, $CO_2$ and $N_2$. The volume fraction of $N_2$ is in the range of 56.5% to 61.6% during the system normal operation at the experiment, which is the main component of air. The volume fraction of $H_2$, CO, $CH_4$, $C_2H_6$, $C_2H_4$, $C_2H_2$ and $CO_2$ are in the range of 4.38% to 6.38%, 15.19% to 19.51%, 1.83% to 2.08%, 0.08% to 0.15%, 0.54% to 0.85%, 0.04% to 0.17%, 13.84% to 14.77%, respectively. Complex chemical reactions are occurred in the gasification process, and there are few main reactions are proposed in the process as follow [2]:

$$C + 0.5O_2 \rightarrow CO \qquad -111 \text{ MJ/kmol} \qquad (5)$$

$$C + H_2 \rightarrow CH_4 \qquad -75 \text{ MJ/kmol} \qquad (6)$$

$$C + CO_2 \rightarrow 2CO \qquad +172 \text{ MJ/kmol} \qquad (7)$$

$$C + H_2O \rightarrow CO + H_2 \qquad +131 \text{ MJ/kmol} \qquad (8)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad -41 \text{ MJ/kmol} \qquad (9)$$

$$CO + O_2 \rightarrow CO_2 \qquad -283 \text{ MJ/kmol} \qquad (10)$$

$$H_2 + 0.5O_2 \rightarrow H_2O \qquad -242 \text{ MJ/kmol} \qquad (11)$$

These reactions show the generating mechanism of $H_2$, CO, $CH_4$, and $CO_2$. The $C_2H_6$, $C_2H_4$ and $C_2H_2$ may originate from the decomposition of certain oxygenates and aromatic tar components [15–16].

Fig. 2 shows the gas composition and produced gas flow rate versus air flow rate in the range of 2.7 $Nm^3/h$ to 4.5 $Nm^3/h$ at plasma torch power consumption 120 W. It should be noted that the arc plasma shows obviously instability when the air flow rate below 2.7 $Nm^3/h$ in the gasification system, and the plasma instability leading to the gasification process shutoff. The plasma instability may be due to the high number density of poplar powder particles quenching the electron density and reducing the conductivity of plasma [3]. It can be seen from Fig. 2 that the volume fraction of $N_2$ increase with air flow rate increasing. The produced gas flow rate and the fraction of $CO_2$ increase with air flow rate in the range of 2.7 $Nm^3/h$ to 4.2 $Nm^3/h$ but show obviously decline at air flow rate 4.5 $Nm^3/h$. There is no residual oxygen detected in produced gas at air flow rate in the range of 2.7 $Nm^3/h$ to 4.2 $Nm^3/h$ but the residual oxygen fraction is 9.1% at air flow rate 4.5 $Nm^3/h$. One reason for the phenomenon may be the reduced interaction time between powder and plasma at high gas flow rate leading to inadequate gasification reaction.

The volume fraction of syngas ($H_2$ and CO) decrease from 23.89% at air flow rate 2.7 $Nm^3/h$ to 20.2% at air flow rate 4.2 $Nm^3/h$. The syngas flow rate

increase from 1.14 $Nm^3/h$ at air flow rate 2.7 $Nm^3/h$ to 1.46 $Nm^3/h$ at air flow rate 3.6 $Nm^3/h$ and then decrease to 1.38 $Nm^3/h$ at air flow rate 4.2 $Nm^3/h$.

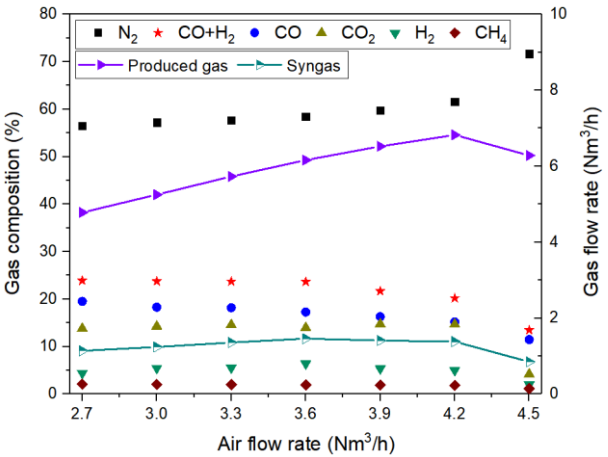


Fig. 2. Gas composition and produced gas flow rate versus air flow rate

The experiments about the effect of plasma torch power on the gas composition is also carried out but the results show that there is no obvious variation of gas composition with plasma torch power in the range of 120 W to 250 W. This phenomenon indicates that the energy required for gasification process in this system is mainly provided by combustion reactions as in conventional gasification, and the plasma may act as a catalyst contributing to generating active radicals [10, 17] and assisting biomass inadequate combustion at low equivalence ratio.

### 3.2. Performance indices of the gasification system

The lower heating value of the produced gas ($LHV_{pg}$) decreases from 4.37 $MJ/Nm^3$ at air flow rate 2.7 $Nm^3/h$ to 3.5 $MJ/Nm^3$ at air flow rate 4.2 $Nm^3/h$, as shown in Fig. 3(a). The decrease of $LHV_{pg}$ is due to the produced flammable gas diluted by more incombustible gases ($CO_2$ and $N_2$) with feed air flow rate increasing.

The cold gasification efficiency (CGE) first increase from 36.63% at air flow rate 2.7 $Nm^3/h$ to the maximum 44.56% at air flow rate 3.6 $Nm^3/h$ and then decrease to 41.91% at air flow rate 4.2 $Nm^3/h$, as shown in Fig. 3(b). It is known from equation (2) that the variation trend of CGE are determined by produced gas flow rate and $LHV_{pg}$ at constant biomass feed rate and plasma power consumption.

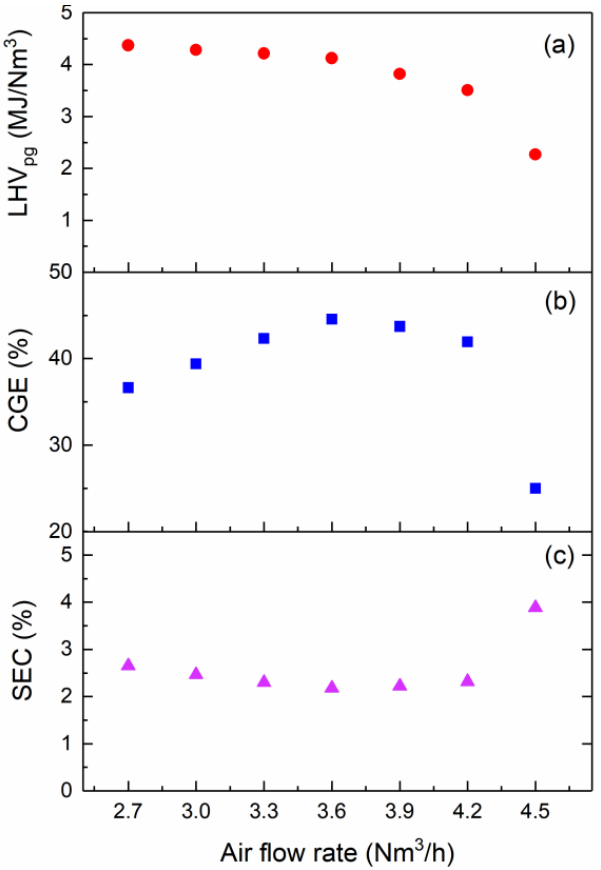


Fig. 3. (a) LHV, (b) CGE and (c) SEC versus air flow rate

The specific energy consumption (SEC) is defined as the ratio of plasma power consumption in the gasification process to the heat power content of the produced gas. The SEC decrease from 2.65% at air flow rate 2.7 Nm$^3$/h to the minimum 2.18% at air flow rate 3.6 Nm$^3$/h and then increase to 2.32% at air flow rate 4.2Nm$^3$/h, as shown in Fig. 3(c). The SEC of non-thermal plasma assisted gasification system is much lower than that of gasification system with thermal plasma which usually in the range of 46% [9] to 137% [4].

### 3.3. Discussion of the Factors Affect the Gasification Process

It is known from the experiment results that there is a lower and a upper limit of air gas flow rate at given biomass powder feeding rate in the gasification process assisted by non-thermal arc plasma. The intrinsic factors of

the phenomenon may be related to number density of powder particles in air flow, plasma power, interaction time between powder particles and plasma. Generally, increasing plasma power and interaction time between powder particles and plasma is beneficial for stability of the gasification process. And the number density of powder particles should not be too high to affect the stability of the plasma. The exactly relationship among these factors and gasification process should be further studied.

## 4. Conclusions

Biomass gasification is realized by a non-thermal arc plasma assisted gasification system. The energy required for gasification in this system is mainly provided by combustion reactions assisted by non-thermal plasma. The volume fraction of syngas (CO and $H_2$) decrease with feed air flow rate increasing. The maximum lower heating value of the produced gas is 4.37 MJ/Nm$^3$, and the maximum cold gasification efficiency is 44.56%. The minimum specific energy consumption of non-thermal assisted gasification system is 2.18%, which is much lower than that of gasification system with thermal plasma.

## Acknowledgements

This work is supported by Anhui Provincial Natural Science Foundation [grant number 2108085QA36].

## References

[1] Y. A. Situmorang, Z. K. Zhao, A. Yoshida, A. Abudula, G. Q. Guan, “Small-scale biomass gasification systems for power generation (<200 kW class): A review,” *Renew. Sust. Energ. Rev.* vol. 117, no. 109486, 2020, doi: 10.1016/j.rser.2019.109486.

[2] A. A. Ahmad, N. A. Zawawi, F. H. Kasim, A. Inayat, and A. Khasri, “Assessing the gasification performance of biomass: A review on biomass gasification process conditions, optimization and economic evaluation,” *Renewable and Sustainable Energy Reviews*, vol. 53, pp. 1333–1347, Jan. 2016, doi: 10.1016/j.rser.2015.09.030.

[3] G. S. J. Sturm, A. N. Munoz, P. V. Aravind, and G. D. Stefanidis, “Microwave-Driven Plasma Gasification for Biomass Waste Treatment at Miniature Scale,” *IEEE Transactions on Plasma Science*, vol. 44, no. 4, pp. 670–678, Apr. 2016, doi: 10.1109/tps.2016.2533363.

[4] E. Delikonstantis et al., “Biomass gasification in microwave plasma: An experimental feasibility study with a side stream from a fermentation reactor,” *Chemical Engineering and Processing – Process Intensification*, vol. 141, p. 107538, Jul. 2019, doi: 10.1016/j.cep.2019.107538.

[5] Y.-C. Lin, T.-Y. Wu, S.-R. Jhang, P.-M. Yang, and Y.-H. Hsiao, “Hydrogen production from banyan leaves using an atmospheric-pressure microwave plasma reactor,” *Bioresource Technology*, vol. 161, pp. 304–309, Jun. 2014, doi: 10.1016/j.biortech.2014.03.067.

[6] V. Grigaitienė, V. Snapkauskienė, P. Valatkevičius, A. Tamošiūnas, and V. Valinčius, “Water vapor plasma technology for biomass conversion to synthetic gas,” *Catalysis Today*, vol. 167, no. 1, pp. 135–140, Jun. 2011, doi: 10.1016/j.cattod.2010.12.029.

[7] J.-L. Shie, F.-J. Tsou, and K.-L. Lin, "Steam plasmatron gasification of distillers grains residue from ethanol production," *Bioresource Technology*, vol. 101, no. 14, pp. 5571–5577, Jul. 2010, doi: 10.1016/j.biortech.2010.01.118.
[8] P.-C. Kuo, B. Illathukandy, W. Wu, and J.-S. Chang, "Plasma gasification performances of various raw and torrefied biomass materials using different gasifying agents," *Bioresource Technology*, vol. 314, p. 123740, Oct. 2020, doi: 10.1016/j.biortech.2020.123740.
[9] I. Janajreh, S. S. Raza, and A. S. Valmundsson, "Plasma gasification process: Modeling, simulation and comparison with conventional air gasification," *Energy Conversion and Management*, vol. 65, pp. 801–809, Jan. 2013, doi: 10.1016/j.enconman.2012.03.010.
[10] G. Ni et al., "Alternating current-driven non-thermal arc plasma torch working with air medium at atmospheric pressure," *Journal of Physics D: Applied Physics*, vol. 46, no. 45, p. 455204, Oct. 2013, doi: 10.1088/0022-3727/46/45/455204.
[11] J. Luche et al., "Plasma Treatments and Biomass Gasification," *IOP Conference Series: Materials Science and Engineering*, vol. 29, p. 012011, Feb. 2012, doi: 10.1088/1757-899x/29/1/012011.
[12] S. A. Nair et al., "Tar removal from biomass-derived fuel gas by pulsed corona discharges," *Fuel Processing Technology*, vol. 84, no. 1–3, pp. 161–173, Nov. 2003, doi: 10.1016/s0378-3820(03)00053-5.
[13] A. A. Fridman, *Plasma chemistry*. Cambridge ; New York: Cambridge University Press, pp. 1–11, 2008.
[14] L. Waldheim and T. Nilsson, *Heating value of gases from biomass gasification, IEA bioenergy agreement subcommittee on thermal gasification of biomass*, 2001. URL: http://gasificationofbiomass.org/download.php?file=files/file/publications/HeatingValue.pdf.
[15] D. Chen, H. P. Rebo, A. Grønvold, K. Moljord, and A. Holmen, "Methanol conversion to light olefins over SAPO-34: kinetic modeling of coke formation," *Microporous and Mesoporous Materials*, vol. 35–36, pp. 121–135, Apr. 2000, doi: 10.1016/s1387-1811(99)00213-9.
[16] Y. Zhang, S. Kajitani, M. Ashizawa, and Y. Oki, "Tar destruction and coke formation during rapid pyrolysis and gasification of biomass in a drop-tube furnace," *Fuel*, vol. 89, no. 2, pp. 302–309, Feb. 2010, doi: 10.1016/j.fuel.2009.08.045.
[17] C. Du, J. Mo, and H. Li, "Renewable Hydrogen Production by Alcohols Reforming Using Plasma and Plasma-Catalytic Technologies: Challenges and Opportunities," *Chemical Reviews*, vol. 115, no. 3, pp. 1503–1542, Dec. 2014, doi: 10.1021/cr5003744.

## Information about the authors

**Qijia Guo,** Dr. Sci., Huadong Photoelectric Technology Institute, Wuhu, China, guoqijia@163.com

**Rui Li,** Associate Researcher, Huadong Photoelectric Technology Institute, Wuhu, China.

**Guangyuan Yang,** Engineer, Huadong Photoelectric Technology Institute, Wuhu, China.

**Yan Liu, Engineer,** Huadong Photoelectric Technology Institute, Wuhu, China.

**Qingdong Deng,** Senior Engineer, Huadong Photoelectric Technology Institute, Wuhu, China.

**Zhaochang He,** Associate Researcher, Huadong Photoelectric Technology Institute, Wuhu, China.