

Thermodynamic analysis on Microwave Plasma Gasification Performance of Sawdust

Aytaç ŞANLISOY, Melda Ö. ÇARPINLIOĞLU

*Faculty of Engineering, Department of Mechanical Engineering, Gaziantep University, Turkey

Abstract

In this study, the thermodynamic performance of hornbeam sawdust (HSD) is examined regarding to content conversion performance, system energy efficiency and hot gas efficiency. The thermodynamic performance of hornbeam sawdust in case of 50 and 100 sL/min air flow rate and varied powers between 3 kW and 6 kW is presented. The syngas content conversion performance of hornbeam sawdust is varied between 336% and 604%. The system energy efficiency of hornbeam sawdust is varied between 20.6 % and 32.57 %. The hot gas efficiency of sawdust is varied between 28.1 % and 46.31%.

Key words: Plasma, syngas, system efficiency, hot gas efficiency,

1. Introduction

Plasma gasification; powered by an external energy source, operates at very high temperatures in an oxygen starved environment to decompose input waste material down to elemental molecules. Products are syngas and inert vitreous (glass-like) materials. The final products can be used to generate electricity or liquid fuel production. Plasma gasification system consists of gasification furnace; feeding system; equipment to handle the slug, ash, tar and char; syngas treatment system; and a monitoring and control system. Thermal plasma gasification performance can change depending on the plasma power [1, 2], reactor temperature [3], plasma gases flow rate and type of plasma gases [4], and residence time of material in reactor [5], size and type of material [6-8] and moisture content in the reactor [9]. Gasification process is a thermochemical process and the performance of plasma gasification systems can be evaluated in terms of thermodynamic analysis.

In this study, the thermodynamic analysis of hornbeam sawdust gasification performance is examined. For the modelling of the process, the reactor is chosen as control volume and the syngas content conversion performance, the system energy efficiency and the hot gas efficiency are defined and the effects of plasma power from 3 kW to 6 kW and air flow rate from 50 sL/min to 100 sL/min are examined.

2. Materials and Method

Microwave plasma gasification system MCw Gasifier (Figure 1) consists of the following sub-components; Microwave plasma system, solid waste feeding and fluid supply systems, gasification

*Corresponding author: Aytaç Şanlısoy Address: Faculty of Engineering, Department of Mechanical Engineering, Gaziantep University, Turkey. E-mail address: aytacsanlisoy@gmail.com, Phone: +903423171591

reactor, process outputs collection system and the measurement - data acquisition system. The experimental system explanation is also given in the presented papers [10-12]. For the thermodynamic evaluation of gasification system the gasification reactor is chosen as control volume. The mass and energy balance equations are derived for the system. The air flow supplied to the reactor at steady conditions. Also, the plasma heats the reactor with steady power. However, the 250 g of sawdust dosed to the reactor in each case. The sawdust is handled in the reactor at an adequate time period. Because of the time dependent handling of fuel in the reactor, the system is analyzed by transient process equations as given in thesis of author [13] and project report of authors [14].

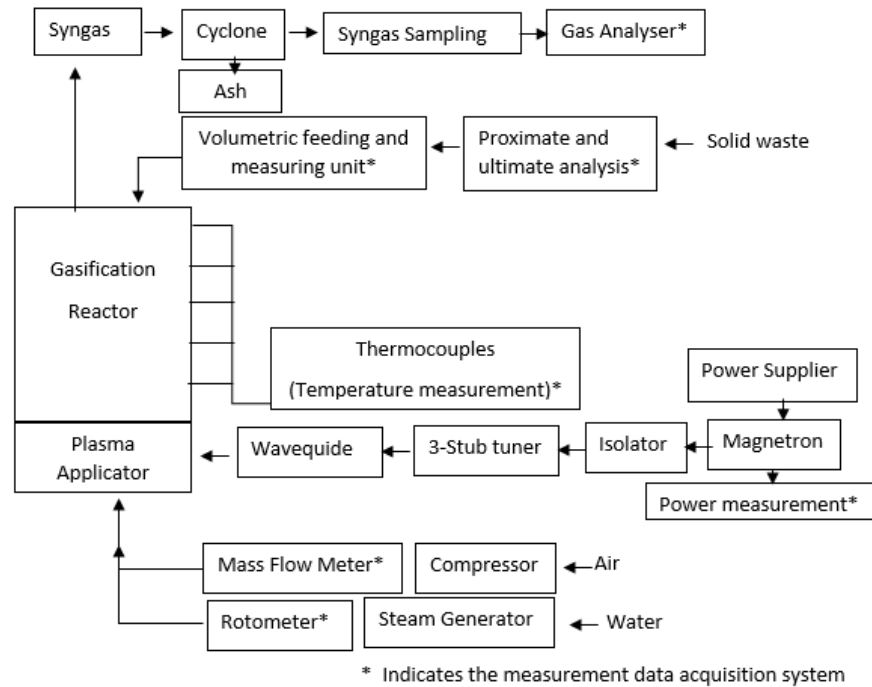


Figure 1. Block diagram of MCw Gasifier

2.1 Mass balance in gasification reactor

In order to determine the energy content of individual species, the mass balance should be referred in equation 1:

$$m_{input} - m_{output} = (m_2 - m_1)_{CV} \text{ (kg)} \quad (1)$$

The mass balance defined above on a conceptual basis can be expressed in equation 2:

$$m_{air} - m_{syn} - m_{ash} = (0 - m_{fuel})_{CV} \text{ (kg)} \quad (2a)$$

$$m_{fuel} + m_{air} = m_{syn} + m_{ash} \text{ (kg)} \quad (2b)$$

The process performance is directly related to the decomposition of hornbeam sawdust into its end products of syngas and ash. Since the profit or the required output is syngas, content conversion performance for the syngas (CCP_{syn}) can be defined in terms of syngas mass (m_{syn}) and mass of hornbeam sawdust, (m_{fuel}) as follows in equation 3:

$$CCP_{syn}[\%] = \frac{m_{syn}}{m_{fuel}} \times 100 \quad (3)$$

2.2 Energy efficiency of gasification reactor

All the input and output energy forms should be defined to write the efficiency terms. There are hornbeam sawdust and plasma energy as input energy while the output is the syngas. In here, the ash is disregarded because of negligible amount of energy content, the air supply is not taken into consideration because of the supplying air in ambient conditions. Heat transfer from reactor is not defined because it is in irreversibility part and causes the reduction of efficiency. The methodology presented here to evaluate the gasification of sawdust is given in details in the other study of authors [15].

The definition of syngas energy and fuel energy are given in equation 4 and 5. The input plasma energy is given in equation 6:

$$E_{syn} \text{ (kJ)} = m_{syn} \text{ (kg)} \cdot HHV_{syn} \text{ (kJ/kg)} \quad (4)$$

$$E_{fuel} \text{ (kJ)} = m_{fuel} \text{ (kg)} \cdot HHV_{fuel} \text{ (kJ/kg)} \quad (5)$$

$$E_{plasma} \text{ (kJ)} = W_{plasma} \text{ (kW)} \cdot t_g \text{ (s)} \quad (6)$$

The heating value of gas spaces are tabulated in thermodynamic textbook. The related gases heating value is given in Table 1.

Table 1. Heating values of gas species at 25°C (taken from Cengel and Boles, 2007 [16])

Substances	HHV (kJ/kg)	LHV (kJ/kg)
CO	10,100	10,100
H ₂	141,800	120,000
CH ₄	55,530	50,050
C ₂₊	50,900	48,000

Since energy efficiency parameters are based upon the determination of higher heating value (HHV); HHV of the sawdust can be calculated by using equation 7 described by Channiwala and Parikh, 2002 [17].

$$HHV = 0.3491C + 1.1783H + 0.1005S - 0.1034O - 0.0151N - 0.0211ash \left(\frac{MJ}{kg} \right) \quad (7)$$

In this equation, C, H, S, O, N and ash are the weight percentage of carbon, hydrogen, Sulphur, oxygen, nitrogen and ash respectively. The weight percentage of these elements is determined by proximate and ultimate analysis and results are presented in the following section. The measurement methodology is also presented in authors paper [11].

System energy efficiency is defined in equation 8.

$$\eta_{ES}[\%] = \frac{E_{syn} (kJ)}{E_{fuel} (kJ) + E_{plasma} (kJ)} \times 100 \quad (8)$$

In these efficiency definitions, the temperature of the syngas (T_{syn}) or the sensible energy level of the syngas is the critical parameter. Hot gas efficiency (η_{HG}) is taken into account for the cases of syngas temperature (T_{syn}) is higher than the ambient temperature (T_0). The system hot gas efficiency (η_{HG}) is given in equation 9. The syngas temperature for the power and air flow rate are presented in results section.

$$\eta_{HG}[\%] = \frac{E_{syn} (kJ) + m_{syn}(kg) \cdot [c_{p(syn)} \left(\frac{kJ}{kg \cdot K} \right) \cdot (T_{syn} - T_0)(K)]}{E_{fuel} (kJ) + E_{plasma} (kJ)} \times 100 \quad (9)$$

3. Results

In this study, the hornbeam sawdust is taken as fuel for the plasma gasification. The proximate and ultimate analysis are given in Table 2.

Table 2. Proximate and ultimate analysis of the hornbeam sawdust

Solid fuel	Moisture (%)	Volatile matter (%)	Fixed carbon (%)	Ash (%)	
Hornbeam sawdust	17.39	72.58	10.02	0.69	
Solid fuel	Carbon (%)	Hydrogen (%)	Oxygen (%)	Nitrogen (%)	Sulphur (%)
Hornbeam sawdust	36.15	6.24	56.92	0.00	0.00

The variation of syngas temperature, supplied air amount, produced syngas amount, syngas content by changing power and air flow rate is given in Table 3. The syngas temperature increases by rising up the plasma power.

Table 3. Variation of syngas temperature, air amount, syngas amount and syngas content by changing plasma power and air flow rate

	Power (W)	T _{syn} °C	m _{air} (kg)	m _{syngas} (kg)	O ₂ , %	CO ₂ , %	CO, %	H ₂ , %	CH ₄ , %	N ₂ , %
Hornbeam sawdust-50sL/min	3000	759	0.87	1.12	0.73	24.73	6.87	0.16	1.00	66.51
	3600	831	0.81	1.06	0.85	21.03	8.70	0.31	1.02	68.09
	4200	915	0.79	1.04	0.92	17.63	9.13	0.36	1.02	70.93
	4800	1007	0.71	0.96	0.78	17.63	14.12	0.40	1.04	66.02
	5400	1096	0.67	0.92	0.96	17.25	15.39	0.49	1.04	64.86
	6000	1175	0.59	0.84	1.04	16.94	19.48	0.64	1.06	60.86
Hornbeam sawdust-100sL/min	3000	621	0.63	0.88	1.25	31.82	4.28	0.13	1.21	61.32
	3600	762	0.59	0.84	1.30	30.85	5.04	0.26	1.21	61.34
	4200	887	0.55	0.80	1.34	30.55	5.54	0.28	1.20	61.07
	4800	937	0.51	0.76	1.42	29.63	6.02	0.35	1.19	61.38
	5400	1008	0.44	0.69	1.41	26.70	7.66	0.40	1.19	62.64
	6000	1129	0.41	0.66	1.50	25.22	9.39	0.48	1.22	62.19

Because the energy density in the medium increases by increase of power. However, the increase of air flow rate reduces the syngas temperature. The supplied air amount reduces by increase of plasma power. The increase of plasma power reduces the gasification duration and air is supplied to the reactor steadily. This fact reduces the produced syngas amount too. Because the produced syngas amount is consist of fuel and air. The supplied fuel is constant in all the cases (250g). The syngas production decreases approximately 25 % by increasing the plasma power from 3 kW to 6 kW. Similarly, the increase of air flow rate also effects the supplied air amount and produced syngas adversely even the supplied air flow rate rises. Because, the increase of air flow rate is also reduces the gasification duration significantly. The reduction in the syngas production is 21.43 % when the flow rate increases from 50 sL/min to 100 sL/min. As quantity of syngas production varies with plasma power and air flow rate, the quality of syngas varies by changing plasma power and air flow rate too. The O₂ percentage in syngas increases approximately 42 %, CO₂ percentage in syngas reduces approximately 31.5 %, CO percentage in syngas increases approximately 131 %, H₂ percentage in syngas increases approximately 183 %, CH₄ percentage in syngas increases approximately 6 % and N₂ percentage in syngas reduces approximately 8.5 % by increasing power from 3 kW to 6 kW at 50 sL/min air flow rate. The O₂ percentage in syngas increases approximately 20 %, CO₂ percentage in syngas reduces approximately 20 %, CO percentage in syngas increases approximately 119 %, H₂ percentage in syngas increases approximately 269 %, CH₄ percentage in syngas increases approximately 0.8 % and N₂ percentage in syngas increases approximately 1.4 % by increasing power from 3 kW to 6 kW at 100 sL/min air flow rate. The O₂ percentage in syngas increases approximately 44 %, CO₂ percentage in syngas increases approximately 49 %, CO percentage in syngas decreases approximately 52 %, H₂ percentage in syngas reduces approximately 25 %, CH₄ percentage in syngas increases approximately 21 % and N₂ percentage

in syngas reduces approximately 7.8 % by increasing air flow rate from 50 sL/min to 100 sL/min at 3 kW plasma power. The O₂ percentage in syngas increases approximately 71 %, CO₂ percentage in syngas increases approximately 29 %, CO percentage in syngas decreases approximately 38 %, H₂ percentage in syngas reduces approximately 19 %, CH₄ percentage in syngas increases approximately 15 % and N₂ percentage in syngas reduces approximately 2.1 % by increasing air flow rate from 50 sL/min to 100 sL/min at 6 kW plasma power.

Variation of syngas content conversion performance, syngas energy, fuel energy, plasma energy, system energy efficiency and hot gas efficiency by changing plasma power and air flow rate are given in Table 4. The content conversion performance of syngas (CCP_{syn}) reduces approximately 32 % in case of 50 sL/min air flow rate and 40 % in case of 100 sL/min air flow rate by increasing the plasma power from 3 kW to 6 kW. On the other hand, the increasing air flow rate enhanced the content conversion performance of syngas (CCP_{syn}). The increment in the content conversion performance of syngas (CCP_{syn}) is 35 % for 3 kW and 28 % for 6 kW when the flow rate increases from 50 sL/min to 100 sL/min. The highest content conversion performance of syngas (CCP_{syn}) is 604 % at 3 kW plasma power, 100 sL/min while the lowest content conversion performance of syngas (CCP_{syn}) is 336 % at 6 kW plasma power, 50 sL/min. The system energy efficiency (η_{ES}) goes up approximately 37 % in case of 50 sL/min air flow rate, and 15 % in case of 100 sL/min air flow rate by increasing the plasma power from 3 kW to 6 kW. Also, the increment in the system energy efficiency (η_{ES}) is 29.6 % for 3 kW plasma power and it reduces 3.6 % for 6 kW plasma power when the flow rate increases from 50 sL/min to 100 sL/min. While the highest system energy efficiency (η_{ES}) is 32.57 % at 6 kW plasma power and 50 sL/min air flow rate, the lowest system energy efficiency (η_{ES}) is 20.6 % at 3 kW plasma power and 50 sL/min air flow rate.

Table 4. Variation of syngas content conversion performance, syngas energy, fuel energy, plasma energy, system energy efficiency and hot gas efficiency by changing plasma power and air flow rate.

	Power (W)	CCP _{syn} (%)	Syngas energy (kJ)	Fuel energy (kJ)	Plasma energy (kJ)	η_{ES} [%]	η_{HG} [%]
Hornbeam sawdust-50sL/min	3000	446	1643.98	5338.23	2640.00	20.64	28.10
	3600	423	1985.28		2952.00	23.90	32.03
	4200	415	2078.47		3360.00	23.90	32.93
	4800	383	2464.50		3456.00	27.97	37.70
	5400	368	2602.79		3672.00	28.89	39.43
	6000	336	2903.46		3600.00	32.57	43.59
Hornbeam sawdust-100sL/min	3000	604	1935.86		1920.00	26.75	34.19
	3600	573	2227.48		2160.00	29.71	40.15
	4200	541	2203.98		2352.00	28.62	41.28
	4800	509	2242.27		2496.00	28.56	41.48
	5400	454	2280.28		2430.00	29.24	42.44
	6000	431	2479.18		2520.00	31.38	46.31

The hot gas efficiency (η_{HG}) increases approximately 35 % in case of 50 sL/min air flow rate and 26 % in case of 100 sL/min air flow rate by increasing the plasma power from 3 kW to 6 kW. Also,

the increment in the hot gas efficiency (η_{HG}) is 22 % for 3 kW plasma power and it rises 6.2 % for 6 kW plasma power when the flow rate increases from 50 sL/min to 100 sL/min. While the highest hot gas efficiency (η_{HG}) is 46.31 % at 6 kW plasma power and 100 sL/min, the lowest hot gas efficiency (η_{HG}) is 28.1 % at 3 kW plasma power, 50 sL/min.

4. Discussion

The syngas temperature increases by increase of plasma power while it reduces by increasing the air flow rate. Because the energy density in the plasma region is the critical. When the power increases, the energy density rises in plasma region but increasing air flow rate reduces the energy density and lowers the temperature. The produced syngas amount depends on the supplied air amount, plasma power and gasification duration. When the power increases, the gasification time reduces and it lowers the syngas production. Similarly, increasing air flow rate lowers the gasification duration. The reduction in gasification time also lowers the supplied air amount to the reactor and it affects the produced syngas amount reversely. Syngas energy rises by increase of plasma power. Because the temperature and energy density of the medium gases increase. On the other hand, the air flow rate has reverse effect on the syngas energy. Increasing plasma power also increases the system energy efficiency and hot gas efficiency even the supplied plasma power (consumption) increases. Because the syngas energy is effected much more with plasma power. Also, the supplied air flow rate effects the system energy efficiency and hot gas efficiency favourably.

Conclusions

In this study, thermodynamic performance parameters; syngas content conversion performance, system energy efficiency and hot gas efficiency are defined. The effects of air flow rate and plasma power on plasma gasification performance are revealed. The syngas content conversion performance of hornbeam sawdust is varied between 336% and 604%. The system energy efficiency of hornbeam sawdust is varied between 20.6 % and 32.57 %. The hot gas efficiency of sawdust is varied between 28.1 % and 46.31%.

Acknowledgements

The authors would like to acknowledge the financial support of this work by the Scientific and Technological Research Council of Turkey (TUBITAK) under the contract number 115M389. Also, authors are thankful for the financial support of University of Gaziantep BAP –RM16.01.

References

- [1] Yoon SJ, Yun YM, Seo MW, Kim YK, Ra HW, Lee J-G. Hydrogen and syngas production from glycerol through microwave plasma gasification. *International Journal of Hydrogen Energy* 2013;38:14559-67.
- [2] Tu W-K, et al. Products and bioenergy from the pyrolysis of rice straw via radio frequency plasma and its kinetics. *Bioresource Technology* 2009;100:2052-61.
- [3] Uhm HS, Kwak HS, Hong YC. Carbon dioxide elimination and regeneration of resources in a microwave plasma torch. *Environmental Pollution* 2016;211:191-7.
- [4] Hong YC, Lee SJ, Shin DH, Kim YJ, Lee BJ, Cho SY, Chang HS. Syngas production from gasification of brown coal in a microwave torch plasma. *Energy* 2012;47:36-40.
- [5] Yoon SJ, Lee J-G. Hydrogen-rich syngas production through coal and charcoal gasification using microwave steam and air plasma torch. *International Journal of Hydrogen Energy* 2012;37:17093-100.
- [6] Huang H, Tang L. Pyrolysis treatment of waste tire powder in a capacitively coupled RF plasma reactor. *Energy Conversion and Management* 2009;50:611-7.
- [7] Lee HG, Park H-W, Choi S, Park H-S, Park D-W. Production of Synthesis Gas from Coal by DC Non-Transferred Steam Plasma Gasification System. *Journal of Chemical Engineering of Japon* 2014;47:334-9.
- [8] Hlina M, Hrabovsky M, Kavka T, Konrad M. Production of high quality syngas from argon/water plasma gasification of biomass and waste. *Waste Management* 2014;34:63-6.
- [9] Shie J-L, Chen L-X, Lin K-L, Chang C-Y. Plasmatron gasification of biomass lignocellulosic waste materials derived from municipal solid waste. *Energy* 2014;66:82-9.
- [10] Sanlisoy A, Carpinlioglu MO, *Presentation of a Microwave Plasma Gasification System "MCw Gasifier" in Fourth European Conference on Renewable Energy Systems (ECRES2016)*. 2016: Istanbul. p. 503-6.
- [11] Sanlisoy A, Melez H, Carpinlioglu MO. Characteristics of the Solid Fuels for the Plasma Gasification. *Energy Procedia* 2017;141:282-6.
- [12] Sanlisoy A, Carpinlioglu MO. Preliminary measurements on microwave plasma flame for gasification. *Energy, Ecology and Environment* 2017:
- [13] Sanlisoy A, *An Experimental Investigation on Design and Performance of Plasma Gasification Systems*, in *Mechanical Engineering Department of Gaziantep University*. 2018, Gaziantep University.
- [14] Çarpınlioğlu MÖ. Katı Atıkların Enerji Dönüşümünde Plazma Gazlaştırma Kullanımı ile Çalışan Laboratuvar Ölçekli Bir Test Düzenekinin (Mikrodalga Gazlaştırıcı) "Mewgazlaştırıcı" Tasarım Üretim ve Performans Değerlendirilmesi-Plazma Gazlaştırma Teknolojisinin-Bilginin Üretilip Kullanılmasında Bir Vaka TUBITAK 115M389 final report 2018:
- [15] Carpinlioglu MO, Sanlisoy A. Performance assessment of plasma gasification for waste to energy conversion: A methodology for thermodynamic analysis. *International Journal of Hydrogen Energy* 2018;43:11493-504.
- [16] Çengel YA, Boles MA, *Thermodynamics: an engineering approach*. 2007, USA: McGraw-Hill.
- [17] Channiwala SA, Parikh PP. A unified correlation for estimating HHV of solid, liquid and gaseous fuels. *Fuel* 2002;81:1051-63.