Biomass gasification to hydrogen-rich syngas by thermal arc discharge plasma

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Introduction

Global warming mostly caused by anthropogenic impact due to increasing use of fossil fuels for energy production is currently a vital issue. Therefore, in order to diminish this negative impact many countries have turned to renewable energy production from available local resources, such as biomass/waste, hydro, wind or sun. Moreover, waste is a permanently and extensively available source generated by each society (Chan *et al* 2019). Thus, biomass and waste utilization to energy and/or value-added chemicals production contributes to the reduction of greenhouse gases (GHG) and waste streams.

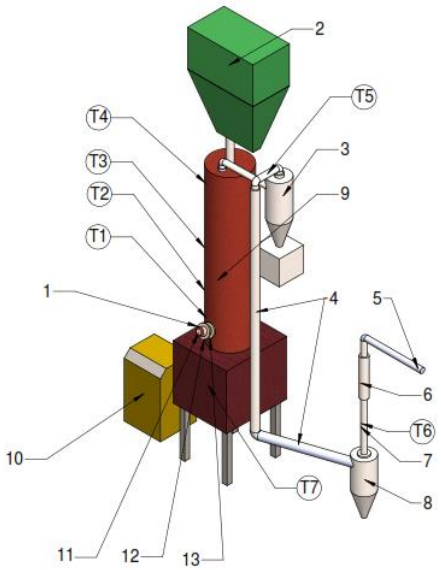
Recently, plasma-assisted technologies have received much attention as an emerging technology for waste and/or biomass utilization to recover energy and/or value-added products (Bosmans *et al* 2013). The use of plasma may overcome limitations specific for conventional waste treatment methods (esterification, anaerobic digestion, incineration, pyrolysis, 'traditional' gasification) and enables to recover not only energy but also the chemical value of waste (Inayat *et al* 2020). Huang and Tang (2007) distinguishes two main groups of plasmas: the high temperature, or fusion, plasmas and the low temperature plasmas. The low temperature plasmas may further be divided into thermal plasmas in which a quasi-equilibrium state between electrons and ions is fulfilled, and cold plasmas characterized by a non-equilibrium state. Due to unique properties of thermal plasma such as high density of energy, high chemical reactivity, very high temperatures (10^3–10^4 Kelvin), easy and flexible control, fast start-up/shut-down, less environmental impact, etc. makes plasma promising and attractive method for waste-to-X. However, high consumption of electrical energy, periodic replacement of wearing parts (e.g. electrodes) and power supply source issues, prevents this technology from a wider commercial application for solid waste treatment.

In this paper, a direct current (DC) thermal arc plasma torch operated on a mixture of air/water vapor was used for biomass (wood pellets) gasification to synthesis gas. The effects of different gasification parameters such as the flow rate and the power on the efficient biomass conversion were investigated. The performance of the plasma gasification system was also evaluated.

Experimental setup and Methodology

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

Figure 1. Plasma gasification system.



The main parts of the system consists of: 1 – an atmospheric pressure DC arc plasma torch, 2 – a feedstock hopper with a screw feeder, 3 – a cyclone, 4 – a gas cooling, 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 hopper, 11 – a power supply, 12

– plasma-forming and shielding gas supply, 13 – a plasma torch cooling, T1, T2, T3, T4, T5, T6, T7 – thermocouples. The plasma-chemical reactor used in this study is 1.3 m long with the 0.2 m inner diameter.

Wood pellets of 6 mm in diameter were used as a feedstock material for syngas production. The feedstock was fed from the hopper through a screw feeder. Woody biomass was chosen as a reference well known material to start the experiments with. In the nearly future, other feedstocks, such as municipal solid waste (MSW), refused-derived fuels (RDF), plastics, etc., are planned to be tested. Superheated water vapor was used as a plasma-forming gas, a heat carrier and a reactant. A small constant portion of air 2.16 kg/h was used as a shielding gas to protect the hafnium cathode from erosion.

The gas analyser SWG 300^{-1} and an Agylent 7890A gas chromatograph equipped with dual-channel thermal conductivity detectors (TDCs) and a valve system were used for gaseous products analysis. The tar content in the producer gas was also measured.

In order to determine the performance of the plasma gasifyer, it was quantified in terms of H_2 and CO yield, H_2/CO ratio, lower heating value, carbon conversion efficiency, cold gas efficiency, and a specific energy requirement according to the methodology described by (Albarelli *et al* 2011; Tamošiūnas *et al* 2016).

Results and Discussion

Feedstock characterization

Full proximate and ultimate analysis of wood pellets used as a feedstock material for the thermal plasma gasification to syngas is described in Table 1.

Table 1. Proximate and ultimate analyses of wood pellets.

Parameter	Wood pellets
Ultimate analysis (wt.%)	
Carbon	51.69±1.1
Hydrogen	6.17±0.02
Nitrogen	<0.01
Sulphur	0.011±0.001
Oxygen (by difference)	42.12
Chlorine	0.005±0.001
Proximate analysis (wt.%)	
Volatile matter	78.2±2.84
Fixed carbon (calculated)	13.62
Ash	0.30±0.01
Moisture	7.88±0.84
HHV, MJ/kg	19.55±0.41
LHV, MJ/kg	18.28±0.45

Effect of the mixture of air/water vapor on the gasification process performance

Biomass conversion to syngas was performed at the wood pellets flow rate of 19.2 kg/h, water vapor flow rate 8.64–16.7 kg/h and the plasma torch power of 56–62 kW, which depended on the flow rate of water vapor at a constant arc current of 180 A. The main reaction products after the gasification are summarized in Table 2.

Table 2. Concentrations of the produced gases.

Wood pellets (kg/h)	H_2O Flow Rate (kg/h)	H_2 (vol.%)	CO (vol.%)	CO_2 (vol.%)	CH_4 (vol.%)	C_2H_2 (vol.%)	N_2 (vol.%)	O_2/Ar (vol.%)
19.2	11.88	39.5	31.12	10.62	4.36	1.12	6.65	5.71

At the optimal biomass-to-water vapor ratio of 1.61, the obtained H_2/CO ratio was 1.27. The LHV of the produced syngas was around 10.4 MJ/nm^3 and didn't depend much on the water vapor flow rate and the plasma torch power. The tar content measured in the producer gas was 7.235 g/m^3, which was quite high due to short residence time to completely crack it. Dominant tar compounds found were benzene 2.957 g/m^3 followed by naphthalene 1.565 g/m^3 and acenaphthylene 1.292 g/m^3, respectively. The residence time might be increased by increasing the size (length and/or diameter) of the plasma-chemical reactor or by reducing the flow rate of the feedstock and plasma-forming gas.

The remaining solid char and ash after the plasma gasification of biomass comprised around 10% of the initial feedstock mass. This has a potential to be reduced to 5–6% by improving the design of the grate. However, the ultimate and proximate analyses of the remaining char in the ash bunker have showed that the ash content was only 3 wt.% with the rest being as a fixed carbon (around 87.21 wt.%) and a small fraction of volatiles (6.13 wt.%) and moisture (3.58 wt.%).

Conclusions

In this experimental study, the thermal arc plasma was used to gasify woody biomass to syngas. Main reaction products obtained were hydrogen and carbon monoxide with total concentration of 62.24 vol.%. At the optimal biomass-to-water vapor ratio of 1.61, the obtained H_2/CO ratio was 1.27 and the LHV 10.4 MJ/nm^3. A relatively high content of tars of 7.235 g/m^3 was determined in the producer gas due to short residence time. The remaining solid char/ash after the reaction was rich in carbon. The fixed carbon content was around 87.21 wt.%, whereas the ash content was only 3 wt.%.

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