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ORIGINAL PAPER

Creation of linear DC plasma generator for pyrolysis/gasification of organic materials

Andrius Tamošiūnas,
Viktorija Grigaitienė,
Pranas Valatkevičius

Abstract. An experimental linear direct current (DC) plasma generator, with stepped anode, stabilized with air/water vapor, argon/water vapor and argon/air vortexes operating at atmospheric pressure had been designed and constructed in Plasma Processing Laboratory at Lithuanian Energy Institute (LEI, Kaunas). It was designed specially the innovative and environment-friendly plasma treatment of organic materials. Three different types of gas stabilization in plasma generator were experimentally investigated and their thermal and electrical characteristics were compared.

Key words: plasma generator (plasma torch) • pyrolysis • gasification • water vapor

A. Tamošiūnas✉, V. Grigaitienė, P. Valatkevičius
Plasma Processing Laboratory,
Lithuanian Energy Institute,
3 Breslaujos Str., LT-44403 Kaunas, Lithuania,
Tel.: +370 (646) 79 123, Fax: +370 (37) 351 271,
E-mail: tamosiunas@mail.lei.lt

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Introduction

For many years, plasma generators have been used for different applications, such as plasma welding, cutting, spraying, etc. Recently, new areas of research have appeared in environmental applications for the treatment of organic waste streams. Moreover, by means of high temperature gasification, high-calorie synthetic gas ($CO + H_2$) can be obtained. The syngas can then be used for the efficient production of energy, or as a raw material for the production of chemical substances [6]. The good properties of thermal plasma technologies, such as high enthalpy, rapid quenching rate and high chemical reactivity, and the limitations of conventional technologies, such as thermal incineration, catalytic oxidation and adsorption, render this technology more and more attractive. A double effect can be achieved: i) hazardous organic materials are decomposed and neutralized; ii) synthetic gas is produced during the pyrolysis/gasification process.

DC steam plasma generators were previously applied to the pyrolysis/gasification of the biomass for synthetic fuel production [4, 9, 10], and to the decomposition of organic compounds [7], used tires [2], halogenated hydrocarbon [11], hydrocarbon [8], and organic waste [3, 5].

Any plasma generation system generally requires complex subsystems such as electrical system, cooling system and the unit that supplies gas and water vapor.

A water vapor plasma system is more complicated compared to the air plasma system as it requires a additional subsystems, such as a heater, to prevent condensation of water vapor on the walls of plasma torch electrodes.

The entire plasma process is strongly dependent on the plasma torch regime and plasma jet parameters. The main aim of the research reported here was the construction and testing of a linear DC plasma generator for the pyrolysis/gasification of organic materials, operating at atmospheric pressure and stabilized with different types of gas. Another aim was to establish thermal and electrical characteristics of constructed experimental equipment.

Experimental setup

The plasma torch with various types of gas-steam vortex stabilization of an electric arc that is presented here is a DC thermal plasma generator of a linear design (Fig. 1). The system operates at atmospheric pressure conditions. Three different types of gas-steam combination: air/water vapor, argon/water vapor, and argon/air, had been chosen to stabilize the column of the electric arc in the discharge chamber. All parts of the plasma torch are water-cooled. In the case when air was used as the shielding gas, the cathode (1) of the torch was made of copper button with implemented tube of hafnium to work as an electron emitter. In the case when argon was used as the shielding gas, the tungsten-rod cathode was utilized. The copper anode (4) has a stepped shape in order to suppress the arc shunting process.

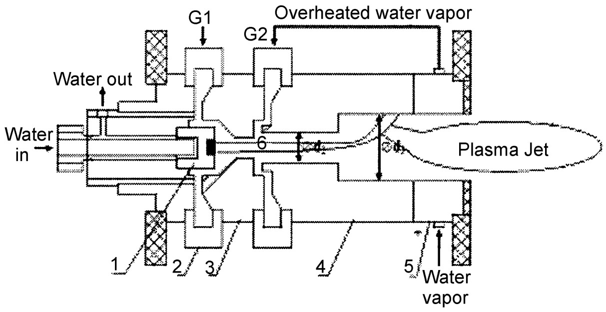

Fig. 1. A schematical drawing of the water vapor plasma torch. 1 – cathode; 2 – insulating rings; 3 – neutral section; 4 – stair-step anode; 5 – super-heater; 6 – electric arc.

Water vapor as the main plasma gas

Two operation points had been realized by choosing different gas-steam combinations for plasma torch stabilization. In the first case the air/water vapor was used and in the second case the argon (Ar)/water vapor. The basic design of the plasma torch was the same in both cases. Water vapor was used as the main plasma gas in both operation points, only the shielding gas was different. The characteristics of the plasma torch and the parameters of the plasma jet operating at these two operation points were determined from calculations based on the thermal energy conservation while measuring the current intensity in the electric arc column, the voltage drop and gas flow rates. The basic experimental parameters are given in Table 1.

In the case of water vapor as the working gas, the plasma torch requires additional sub-systems, such as the water vapor generator ($1.6 \div 3.1 \times 10^{-3}$ kg·s^{-1}) and the heater. There are also some additional systems, such as the argon supply (5.2×10^{-4} kg·s^{-1}), the air supply (7×10^{-4} kg·s^{-1}), the cooling water supply (0.1×10^{-3} kg·s^{-1}), and the DC-power supply.

The water vapor as a working gas was tangentially supplied through the blowholes of the insulating ring (G_2). The condensation of the water vapor on the walls of the plasma torch results in the erosion of the electrodes. To avoid this negative consequence, the water vapor was preheated by a super-heater (5) to temperatures of the order of $473 \div 573$ K, before it was introduced into the reactor. Moreover, the electrode walls were kept at a temperature larger than 373 K. The water vapor had been chosen because it is a reagent and a heat carrier at the same time. It is very convenient for the production of synthetic gas in pyrolysis/gasification process, due to the fact that the water molecule contains two hydrogen atoms. These molecules are characterized as high enthalpy and participate in the formation of high-calorie syngas at high temperature gasification.

As a shielding gas to protect the cathode from erosion, the air and argon were used at two operation points. The amounts of air and argon that are required for shielding depend on the value of the current and the type of main plasma gas used. They were in the range of $19 \div 28\%$ of the total mass flow for air and $15 \div 24\%$ for argon.

Table 1. The experimental parameters of air/water vapor and Ar/water vapor plasma torch and plasma jet

Parameters	Type of plasma gas	
	Air/water vapor	Ar/water vapor
Arc current (A)	$141 \div 187$	$139 \div 182$
Arc voltage (V)	$206 \div 250$	$179 \div 260$
Arc power (kW)	$33 \div 44$	$30 \div 40$
Power loss to the cooling water (kW)	$7 \div 11$	$11 \div 16$
Output power (kW)	$24 \div 32$	$16 \div 26$
Plasma torch efficiency, η	$0.71 \div 0.78$	$0.51 \div 0.7$
Air/Ar gas flow rate, G_1 (10^{-4} kg·s^{-1})	7	5.2
Water vapor flow rate, G_2 (10^{-3} kg·s^{-1})	$1.7 \div 3$	$1.6 \div 3.1$
Total mass flow rate, G (10^{-3} kg·s^{-1})	$2.5 \div 3.7$	$2.1 \div 3.6$
Plasma jet mean temperature at the torch outlet nozzle (K)	$2700 \div 3000$	$3300 \div 3500$
Plasma jet mean velocity at the torch outlet nozzle (m·s^{-1})	$155 \div 240$	$210 \div 310$
Diameter of step-formed anode, d_2 (10^{-3} m)	8	8
Diameter of step-formed anode, d_3 (10^{-3} m)	14	14

Table 2. The experimental parameters of Ar/air plasma torch and plasma jet

Parameters	Type of plasma gas Ar/air
Arc current (A)	133÷197
Arc voltage (V)	127÷280
Arc power (kW)	22÷42
Power loss to the cooling water (kW)	5÷15
Output power (kW)	10÷32
Plasma torch efficiency, η	0.44÷0.7
Argon gas flow rate, G_1 (10^{-4} kg·s^{-1})	6.5
Air flow rate, G_2 (10^{-3} kg·s^{-1})	2.1÷6.3
Total mass flow rate, G (10^{-3} kg·s^{-1})	2.8÷7
Plasma jet mean temperature at the torch outlet nozzle (K)	2800÷3100
Plasma jet mean velocity at the torch outlet nozzle (m·s^{-1})	148÷399
Diameter of stair-step anode, d_2 (10^{-3} m)	8
Diameter of stair-step anode, d_3 (10^{-3} m)	14

Air as the plasma gas

Besides the water vapor as the plasma gas, this torch system had been operated with the air as the plasma gas and argon as the protective gas. The characteristics of the plasma torch and the parameters of the plasma jet are given in Table 2.

No changes to the construction of the torch was made while operating directly with this gas, but subsystems such as the steam generator and the heater (8) were unnecessary. The argon/air plasma torch has more stable working parameters at the same operation point compared to the air/water vapor and argon/water vapor plasma torches, i.e. the oscillations of the plasma jet are negligible. However, this gas is not as desirable as water vapor, because the quality and the enthalpy of the produced syngas are much higher when the water vapor is used as the plasma gas at high temperature gasification. Another problem is that at temperatures above 3000 K toxic contaminations such as NO_x are formed [1].

Results and discussion

Thermal characteristics of air/water vapor, argon/water vapor and argon/air torches

Thermal and electrical characteristics are very important for designing and testing new plasma torches operating with different plasma gases. The parameters of the plasma torch and the plasma jet will be useful in the process of designing and construction of the new plasma-chemical reactor for pyrolysis/gasification of organic materials.

The thermal efficiency of the torch is defined as the ratio of the heat absorbed by the gas from the plasma torch per unit time, to the arc power [12]. It mainly depends on the flow rate of the working gas, magnitude of the electric current and the construction of the torch (Fig. 2). The increase in the magnitude of the current in the electric arc reduces the thermal efficiency of the torch. Thus, the increase of the current results in the

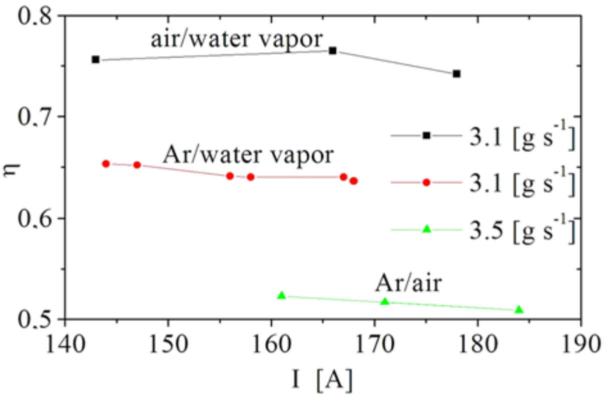

Fig. 2. The dependence of the plasma torch thermal efficiency on the magnitude of the current and the rate of flow of the working gas.

increase of the diameter of the electric arc, accompanied by a simultaneous decrease of the thickness of the boundary layer in the working gas, which constricts the arc column. The heat is removed by forced laminar or turbulent convection.

The maximal thermal efficiency of the air/water vapor plasma torch, $\eta = 0.78$, was achieved at the current $I = 164$ A, voltage $U = 245$ V, and the mass flow rate of working gas 3.7 g·s^{-1}. The maximum thermal efficiency of the Ar/water vapor plasma torch was $\eta = 0.7$, at the current $I = 139$ A, voltage $U = 260$ V, and the total mass flow of gas $G = 3.6$ g·s^{-1}. The maximum thermal efficiency of the Ar/air plasma torch was $\eta = 0.7$, at the current $I = 133$ A, voltage $U = 280$ V, and the total mass flow rate of gas 7 g·s^{-1}. However, the most stable work of the torch, operating on different kinds of gas, was achieved when the mass flow rate of these gases was in the range of 2–3.5 g·s^{-1}.

The generalized thermal efficiency of the plasma torch determines the ratio of the heat losses in the plasma torch to the heat content of the plasma jet. The plasma torch thermal efficiency (Fig. 3) was estimated for the torch operating on different plasma gases, using the theory of similarity [12]. The results for each of the working gases are given below:

Air/water vapor:

$$\frac{1-\eta}{\eta} = 1.02\times10^{-7}\left(\frac{I^2}{Gd_2}\right)^{0.75} \tag{1}$$

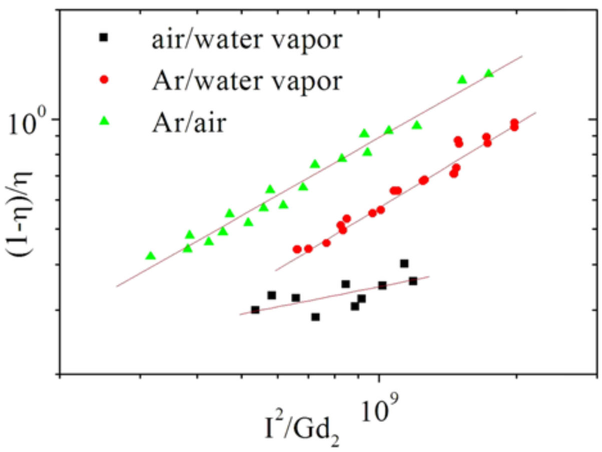

Fig. 3. The generalized thermal efficiency of plasma torches.

Ar/water vapor:

$$\frac{1-\eta}{\eta} = 1.65\times10^{-3}\left(\frac{I^2}{Gd_2}\right)^{0.26} \tag{2}$$

Ar/air:

$$\frac{1-\eta}{\eta} = 1.03\times10^{-7}\left(\frac{I^2}{Gd_2}\right)^{0.77} \tag{3}$$

where η is the thermal efficiency, I is the arc current (A), G is the total mass flow (kg·s^{-1}), and d_2 is the diameter of the anode (m). The combination I^2/Gd_2 plays the role of the energy criterion. It determines the rate of energy exchange between the column of the electric arc and the heated medium.

These results should be taken into account while designing a plasma torch for the pyrolysis/gasification of organic materials.

Electrical characteristics of air/water vapor, Ar/water vapor and Ar/air torches

The electric arc voltage and the power of the plasma torch depend mainly on the flow rate of the working gas and its physical parameters, such as density, viscosity, conductivity, etc. Figure 4 shows the measured voltage-current characteristics (VCC) of the plasma torches, operating on different kinds of gases. The characteristics are slightly dropping because of the shunting of the electric arc, which restricts the temperature of the heated gas and requires inclusion of a shunt resistance in the electrical circuit.

In the case when the water vapor is used as the plasma gas, the arc voltage of the water vapor plasma is about three times as high as that of the air plasma. The water vapor plasma is relatively stable for currents exceeding 140 A.

The general voltage-current characteristics of the plasma torches (Fig. 5) operating on different kinds of gases were estimated using the theory of similarity [12]. Depending on the gas combination we obtain:

Air/water vapor:

$$\frac{Ud_2}{I} = 3\times10^{3}\left(\frac{I^2}{Gd_2}\right)^{-0.6} \tag{4}$$

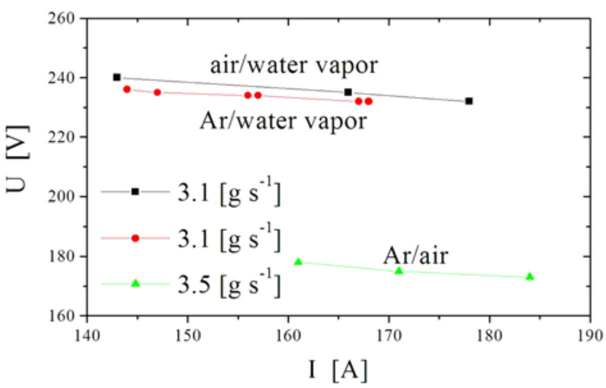

Fig. 4. The voltage-current characteristics of the air/water vapor, Ar/water vapor and Ar/air plasma torches, for different flow rates of the working gas.

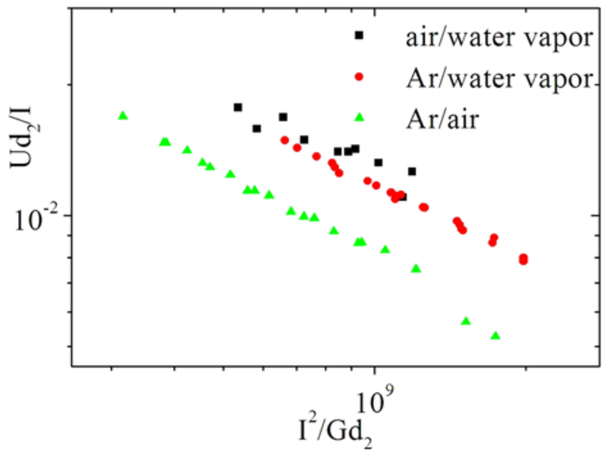

Fig. 5. The generalized VCC of the plasma torches.

Ar/water vapor:

$$\frac{Ud_2}{I} = 182\left(\frac{I^2}{Gd_2}\right)^{-0.46} \tag{5}$$

Ar/air:

$$\frac{Ud_2}{I} = 2.08\times10^{3}\left(\frac{I^2}{Gd_2}\right)^{-0.6} \tag{6}$$

where U is the voltage (V), d_2 is the diameter of anode (m), I is the arc current (A), and G is the total mass flow (kg·s^{-1}).

A stable work of the plasma torch is required to control the process and conditions in the pyrolysis/gasification of organic materials. The knowledge of the plasma torch geometry and its voltage-current and thermal characteristics helps to determine the temperature and velocity of the plasma jet at the exhaust nozzle of the anode. These are the main parameters required for the effective pyrolysis/gasification of organic materials.

Conclusions

An experimental linear DC water vapor plasma torch was constructed and tested. The torch was equipped with a stepped anode operating at the atmospheric pressure.

Different working regimes were investigated for the torch operating with air/water vapor, argon/water vapor and argon/air vortexes. The average temperature of the plasma flow at the exhaust nozzle of the torch varied within a range of 2600 to 3500 K. The maximal plasma torch thermal efficiency was 0.78 and it was achieved using the water vapor as the main plasma gas.

The operating parameters of the argon/air plasma torch were more stable compared to the air/water vapor and the argon/water vapor plasma torches, i.e. the oscillations of plasma jet were negligible, but thermal efficiency appeared lower.

The increase in the electric arc current reduces the thermal efficiency of the torch operating on various gases. Generalized thermal characteristics of the air/water vapor, Ar/water vapor and Ar/air plasma torches are characterized by Eqs. (1), (2), and (3).

The voltage-current characteristics of newly designed plasma torch, operating on different kinds of gases, are slightly dropping. The generalized VCC decreases and may be characterized by Eqs. (4), (5), and (6).

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