World Academy of Science, Engineering and Technology
International Journal of Physical and Mathematical Sciences
Vol:6, No:11, 2012

Water Vapor Plasma Torch: Design, Characteristics and Applications

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***Abstract*—**The atmospheric pressure plasma torch with a direct current arc discharge stabilized by water vapor vortex was experimentally investigated. Overheated up to 450K water vapor was used as plasma forming gas. Plasma torch design is one of the most important factors leading to a stable operation of the device. The electrical and thermal characteristics of the plasma torch were determined during the experimental investigations. The design and the basic characteristics of the water vapor plasma torch are presented in the paper.

Plasma torches with the electric arc stabilized by water vapor vortex provide special performance characteristics in some plasma processing applications such as thermal plasma neutralization and destruction of organic wastes enabling to extract high caloric value synthesis gas as by-product of the process. Syngas could be used as a surrogate fuel partly replacing the dependence on the fossil fuels or used as a feedstock for hydrogen, methanol production.

***Keywords*—**Arc discharge, atmospheric pressure thermal plasma, plasma torch, water vapor.

I. Introduction

THERMAL plasma, with the properties as the high concentration of energy in the small volume, high temperatures and rates of chemical reactions etc., has attracted the attention as an important element of industrial technologies enabling processes with extremely high rates to be achieved, whereas the existing conventional are limited to solve. Due to the high enthalpy and high energy density thermal plasma is applied in metallurgy, metal welding and cutting, material processing involving plasma spraying, waste treatment with the production of hydrogen-rich synthetic gas etc. [1]–[5]. There are many kinds of thermal plasma generators such as transferred and non-transferred direct (DC) or alternating (AC) current arc plasma torches [6]. Despite the advantages of the plasma torches mentioned previously, there are some disadvantages regarding the life-time of the electrodes and expensive electrical energy to run a device.

Plasmas can be generated at reduced and atmospheric pressures [7], but only the atmospheric pressure plasma sources will be represented. Regardless of the existence of a large number of design solutions of plasma torches differing from each other mainly in the methods of stabilization of the discharge, only the most widely used type of plasma generators – linear plasma torches – will be introduced [8].

The further application of plasma technologies is associated with improvement of all characteristics of plasma torches. The semiempirical methods based on the theory of similarity are invoked for calculation of the electrical and thermal characteristics of linear plasma torches.

Resulting from different areas of application various types of gases and their mixtures could be used to form a plasma flow. The developed plasma torch at Lithuanian Energy Institute, Plasma Processing laboratory, operates on overheated water vapor. In consequence of two hydrogen atoms the enthalpy of water vapor is around six times higher compared to air mass enthalpy, most commonly gas used for plasma generation. With water vapor being used as a reagent and heat carrier at once it is very convenient to apply a DC linear plasma torch for technologically advanced plasma gasification/pyrolysis and organic materials decomposition reported in [9]–[11].

The goal of this experimental research was determination of the electrical and thermal characteristics of the atmospheric pressure linear plasma torch depending on its design and prospective application for organic wastes treatment.

II. Experimental Setup and Methodology

The experimental DC plasma torch of linear design used in this work is showed in Fig. 1. A cylindrically shaped cathode is made of copper in which a tungsten rod is inserted. The cathode works as electrons emitter to ionize the injected gas into the discharge chamber of the plasma torch. A cylindrical anode is positioned along the axis in one line with the cathode. A stair-shaped form of the anode is used to fix the mean arc length. Sudden expansion of the anode channel leads to the prevention and minimization of a large-scale shunting of the electric arc [8]. Electrodes of the plasma torch are separated by the neutral section and the insulation rings made of glass textolite. The rings have an inlet holes for tangential supply of shielding and plasma forming gas.

Argon (Ar), with flow rate of 0.5 g/s, was used as shielding gas to protect the cathode from erosion, whereas overheated water vapor to stabilize the arc and form a plasma flow. The mass flow rate of Ar depends on the current intensity and plasma forming gas.

Water vapor was produced using 5 bar of pressure water steam generator GAK-50. Before the injection into the discharge chamber the produced dry saturated water vapor

This research was funded by a grant (no. ATE-10/2012) from the Research Council of Lithuania.

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was overheated up to 450K by a superheater. This is essential condition to avoid condensation of water vapor on the walls of the discharge chamber which leads to the shorter life-time of the electrodes due to the erosion, higher amplitude of the large-scale shunting and pulsations of the formed plasma flow. The flow rate of water vapor was kept in range of 2.6–4.5×10^{-3} kg/s.

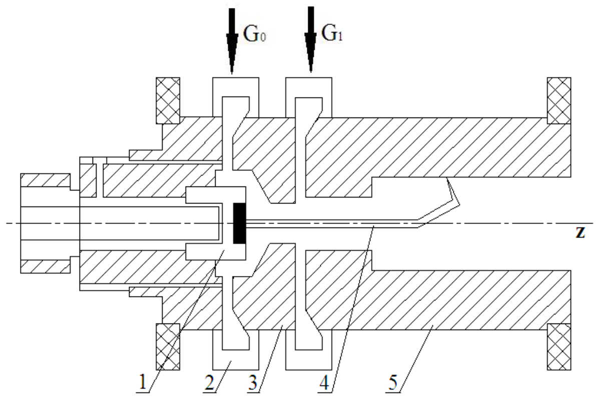

Fig. 1 A sketch of the linear water vapor plasma torch. 1 – cathode, 2 – insulating rings, 3 – neutral section, 4 – electric arc, 5 – stair-shaped anode. G_0, G_1 – gas supply

The power of the torch, which varied from 38 to 64 kW, depended on the current intensity and the flow rate of plasma forming gas. Besides the DC plasma torch operating at the atmospheric pressure, the experimental setup also contains sub-systems such as an electrical power source, measurement and cooling systems, as well as gas supply and overheating.

The current intensity and the voltage of the arc were measured using a remote control block with voltmeter and ammeter inside connected to the electrical power source (VTPE 400-750). The distribution of the potential and the strength of the electrical field of the arc in a cylindrical channel were measured by a multimeter Mastech MS8218. Thermal and electrical characteristics of the plasma torch were generalized using a theory of similarity.

III. Results and Discussion

Tangentially injected overheated water vapor was ionized by means of the electric arc with current intensity in range of 120–200A. The keystone parameters required in the technological process is temperature and velocity of the generated plasma flow. At the same time, the efficiency of the plasma torch is also very important. The main experimental parameters are presented in Table I.

TABLE I
The Experimental Parameters of the Plasma Torch and Plasma Flow

Parameter	Range
Arc current, A	120 – 200
Arc voltage, V	220 – 400
Plasma torch power, kW	38 – 64
Plasma torch efficiency, %	53 – 76
Mean Plasma flow temperature, K	2400 – 3000
Mean Plasma flow velocity, m/s	200 – 400

A stable work of the plasma torch must be ensured during the operation. In that case, the electrical and thermal characteristics help to determine and design plasma torches with stable operation parameters, higher efficiency and etc. Thermal and electrical characteristics of plasma torches stabilized with different types of gas mixtures are reported in [12].

A. Electrical Characteristics of the Water Vapor Plasma Torch

The most important electrical characteristic of the plasma torch is the volt-ampere characteristic (VAC). The form of this characteristic determines the selection of the parameters of the power source and the electrical efficiency of the torch.

The drooping VAC creates a certain difficulties in the matching of the plasma torch with the electric power source. Therefore, to ensure a stable arcing, a ballast rheostat should be included in the electrical circuit. This reduces electrical efficiency of the plasma system and initiates pulsations of arc voltage determined by the large-scale shunting.

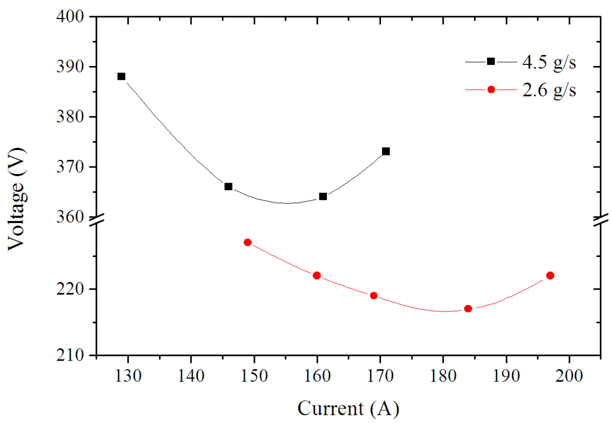

Fig. 2 Volt-ampere characteristics of the linear water vapor plasma torch for given flow rates of water vapor 2.6 g/s and 4.5 g/s, respectively

These shortcomings may be eliminated using a stair-shaped cylindrical anode with sudden expansion of the channel. The experimentally obtained VAC of the arc in this case is U-shaped and showed in Fig. 2. The plasma torches with the fixed arc length by the ledge are simple, reliable in service and do not have many of the shortcomings typical of the plasma torches with the self-setting arc length [13].

Since the existing analytical methods are not capable to describe the processes occurring in the electric arc plasma torches, we can refer to the theory of similarity to generalize the volt-ampere characteristics of the arc (Fig. 3) and deduce these experimental results in the criterial form expressed by relation (1).

$$\frac{Ud}{I} = 34 \cdot \left(\frac{I^2}{Gd}\right)^{-0.7} \cdot \left(\frac{G}{d}\right)^{0.23} \cdot \left(pd\right)^{0.48}. \qquad (1)$$

Here units are expressed in SI system. U is a voltage, d – diameter, I – current intensity, G – gas flow rate, p – pressure.

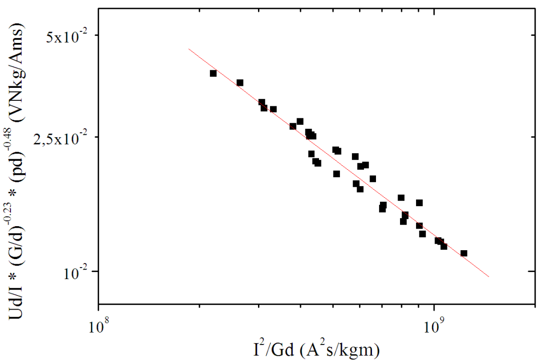

Fig. 3 The generalized VCC of the arc of the water vapor plasma torch

Knowing the magnitude and distribution of the electrical field of the arc and the potential along the axis z it is possible to optimize the selection of the electrical circuit of the plasma torch regarding the increase of the heat content of the gas at the minimum losses of electric energy. The variation of the strength of the electrical field of the arc E is usually separated into three characteristic zones determined by the interaction of the arc with the surrounding gas. The first zone is an initial zone which corresponds to a constant electric field. The second is a transitional zone characterized by an increase of the E along the discharge channel. The third zone is called turbulent with a constant maximum value of E. The strength of the electrical field of the arc depends on the channel diameter, the gas flow rate and pressure, intensity of current and etc [8].

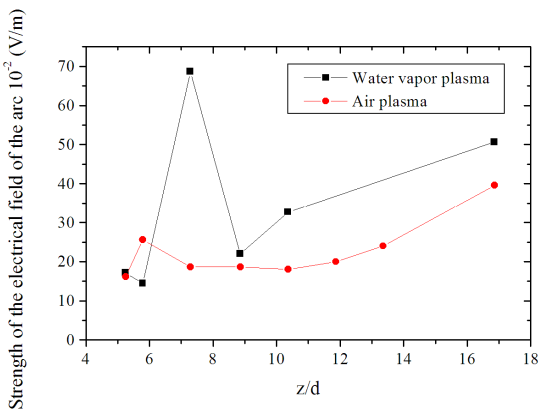

Fig. 4.Distribution of the strength of the electrical field of the arc along the axis of the discharge channel in water vapor and air plasmas. $I = 180$ A, $G_0 = 5 \cdot 10^{-4}$ kg/s, $G_1 = 3.5 \cdot 10^{-3}$ kg/s, d = $1 \cdot 10^{-2}$ m for water vapor plasma, $I = 150$ A, $G_0 = 5 \cdot 10^{-4}$ kg/s, $G_1 = 4.5 \cdot 10^{-3}$ kg/s, d = $1 \cdot 10^{-2}$ m for air plasma

The described characteristic zones of the strength of the electrical field of the arc in the discharge chamber of the plasma torch are quite well seen in the experiments performed by using air as plasma forming gas in Fig. 4.

In the zone of the gas supply at z/d = 5–7 there is a local increase of the strength of the E. This is possible due to the boundary layer interaction with the blown gas and its displacement by the gas from the wall producing a local narrowing of the channel, which increases the value of the strength of the electrical field. Furthermore, the properties of the gas used and the diameter of the discharge chamber have an impact on the value of E too. The strength of the electrical field of the arc stabilized by water vapor vortex, with design conditions of the plasma torch being equal, is higher than in air plasma (Fig. 4).

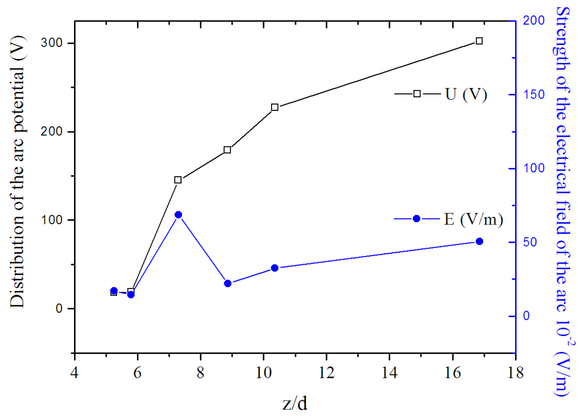

Fig. 5 Distribution of the potential and the strength of the electrical field of the arc along the axis of the discharge channel of the water vapor plasma torch. $I = 180$ A, $G_0 = 5 \cdot 10^{-4}$ kg/s, $G_1 = 3.5 \cdot 10^{-3}$ kg/s, d = $1 \cdot 10^{-2}$ m

According to Fig. 4 and Fig. 5, where in the latter the distribution of the potential and the strength of the electrical field of the arc in the water vapor plasma are showed, the conditions with a constant maximum value of E corresponding to the developed turbulent flow zone are not reached. It is possible due to a short smooth cylindrical discharge channel (without a ledge) where the flow was not fully turbulized yet, and the power of the arc was insufficient.

B. Thermal Characteristics of the Water Vapor Plasma Torch

Despite the investigated electrical characteristics of the plasma torch, simultaneously, thermal characteristics were also carried out. Thermal coefficient of efficiency of the plasma torch is determined by processes taking place in the column of the electric arc, and also heat exchange between the arc, the gas and the walls of the discharge chamber. Therefore, the integral coefficient of heat transfer of the atmospheric pressure DC water vapor plasma torch is presented in Fig. 6 and was expressed in a general form as the function of the main criterial complexes:

$$\frac{(1-\eta)}{\eta} = 2.22 \cdot 10^{-2} \cdot \left(\frac{I^2}{Gd}\right)^{0.22} \cdot \left(\frac{G}{d}\right)^{-0.38} \cdot \left(\frac{l}{d}\right)^{-0.8}. \quad (2)$$

Here η is a thermal efficiency of the plasma torch, I – current intensity, G – gas flow rate, d – diameter, l – electric arc length.

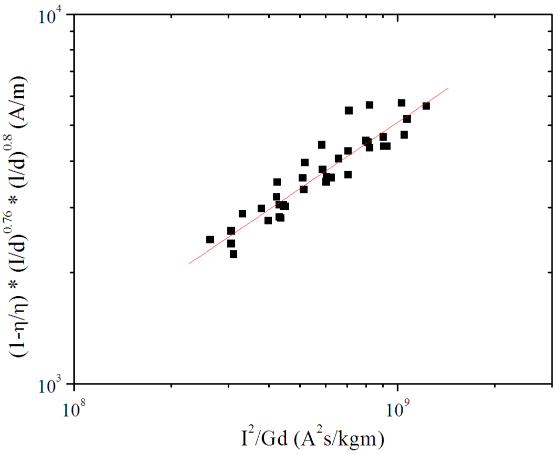

Fig. 6 The generalized thermal characteristics of the water vapor plasma torch

The presence of the generalized thermal characteristics for the water vapor plasma torch helps to optimize the energy losses of any plasma process giving attention not only to the total losses of energy determined by the VAC of the plasma torch.

An experimental investigation showed that the main role in heat losses between the arc, the heated gas and the walls of the discharge chamber is played by radiation and convection, while the conductive heat flux was negligible. The total heat losses into the separate parts of the plasma torch were studied in [14]. It was determined that the radiant heat flux is approximately constant along the overall discharge channel, whereas the most intensive heat transfer occurred by convective flow. The ability to compare the experimental results with a classical convective heat transfer in a cylindrical channel appeared only at the end of the plasma torch at a distance of 14–17 gauges (the developed turbulent flow section) where the determining gas temperature may be represented by the mean mass temperature of the heated gas. In a wide range of variation of the working parameters such as the type of gas, temperature and pressure, the convective heat flow into the wall of the discharge chamber may be determined by the following equation:

$$Nu_d = 0.0255 \, \mathrm{Re}_d^{0.8} \, \mathrm{Pr}^{0.43}. \quad (3)$$

Here Nu is Nusselt number, Re – Reynolds number and Pr – Prandtl number.

IV. Conclusion

The electrical and thermal characteristics of the DC linear water vapor plasma torch operating at the atmospheric pressure were investigated. The obtained experimental results will help to improve the design of the system dedicated for the thermal plasma gasification/pyrolysis process.

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