

DESIGN AND OPERATING CHARACTERISTICS OF WATER VAPOR PLASMA TORCH FOR ENVIRONMENTALLY FRIENDLY PROCESSES

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Abstract. This research presents the application of the novel developed plasma technology for environmental protection. The following main tasks of this research have been carried out at Lithuanian Energy Institute: a) an experimental plasma torch facility has been designed and tested at Plasma Processing Laboratory; b) water vapor plasma generation was practically realized; c) thermal and electrical characteristics of novel designed plasma torch were investigated and plasma jet characteristics were established.

An experimental DC (direct current) plasma torch of a linear scheme operating on gas-water vapor vortex at atmospheric pressure has been used. The button type hot tungsten-rod cathode working as electron emitter and confusor-type cooper anode has been used to form the electric arc in the discharge chamber. All parts of plasma torch were water-cooled. The characteristics of plasma torch and the parameters of plasma jet were determined employing the theory of similarity while measuring current intensity in the electric arc column, voltage drop and gas flow rates.

Experimental results confirmed that water vapor plasma has superiority over other plasma forming gas due to its unique properties – extremely high enthalpy, environmentally friendly conditions, relatively low cost and endless amount of plasma forming gas.

This work also includes analysis of operating characteristics of plasma torch and plasma jet, which were investigated in the range of plasma source parameters: power of plasma torch 30-53 kW, electric current intensity 130-210 A, the voltage 230-330 V, the efficiency 0.58-0.78, the mean temperature of plasma jet at the torch exhaust nozzle 2300-2900 K and mean velocity 340-700 m/s. The analysis of obtained results shows that this plasma technology could be easily employed for environmental protection such as destruction of hazardous substances and conversion of biomass to synthetic gas.

Keywords: plasma technology, plasma torch, environmental protection, plasma gasification, water vapor.

1. Introduction

As the anthropogenic activities have been growing up rapidly during past few decades, it induced to take in hand means protecting our environment. A lot of methods and technologies have been developed such as thermal incineration, chemical oxidation, low temperature oxidation, gasification, pyrolysis, heterogeneous catalysis (Бернардинер *et al.* 1990; Jackman and Powell 1991; Fehlner 1986; Satterfield 1991). Most of these methods are not desirable considering environmental regulations. Recently, a new method has been developed called thermal plasma gasification (Mosse *et al.* 2003; Супис *et al.* 1990).

Plasma gasification is a technologically advanced and environmentally friendly method based on high temperature (2000-3000 K) gasification of materials. Good properties such as high enthalpy, rapid quenching rate and high chemical reactivity render this technology attractive. The conversion of carbon-based material is in excess of 99 %. Non-carbon-based materials are con-

verted into vitrified glass or slag, which could be used as cheap by-product in road building. Plasma gasification consistently exhibits much lower environmental levels for both air emissions and slag leachate toxicity than other thermal technologies (Moustakas *et al.* 2005).

To obtain high temperatures, plasma torches are being used. Plasma torch – is electric arc gas heater in which electric energy is converted into thermal energy by means of the generation of Joule heat in the discharge (Zhukov 2007). Miscellaneous gases and their mixtures can be used to form plasma. Novel designed DC water vapor plasma torch has been developed and tested at Lithuania Energy Institute, Plasma Processing Laboratory. The torch operates at atmospheric pressure. It is going to be used for destruction of hazardous substances and conversion of organic materials producing high-caloric synthetic gas.

Applications of DC plasma torch for decomposition of organic compounds have been reported in (Watanabe *et al.* 2009), halogenated hydrocarbon (Watanabe and Tsuru 2008), hydrocarbon (Vaidyanathan *et al.* 2007),

used tires (Chang *et al.* 1996), pyrolysis/gasification of biomass for synthetic fuel production (Kezelis *et al.* 2004; Van Oost *et al.* 2009; Van Oost *et al.* 2006) and PCB (polychlorinated biphenyl) (Kim *et al.* 2003).

Water vapor is used as plasma forming gas. It's well known that molecular composition of water molecule is made of two hydrogen and oxygen atoms. In consequence of two hydrogen atoms the enthalpy of water vapor is about six times higher in comparison with air mass enthalpy. Another advantage is ecological cleanness. Water vapor is a reagent and a heat carrier at once.

Plasma generation system consists not only of the plasma torch. It has complex subsystems such as electrical, cooling and supply of gas and water steam generator. Consequently, whole plasma jet forming process strongly depends on the plasma torch regime and smooth operation of all subsystems. The goals of this research are practical realization of water vapor plasma torch, investigation of thermal and electrical characteristics of novel designed experimental setup and establishment of plasma jet parameters.

2. Experimental setup

The experimental DC water vapor plasma torch used in this study is shown in Fig 1. The developed plasma torch of a linear design, with gas-water vapor vortex stabilization of the electric arc, operates at atmospheric pressure. The torch is 30-53 kW of power with button type hot tungsten cathode (Fig 1, position 1) working as electrons emitter, and confusor-type copper anode (Fig 1, position 4). The experimental equipment also contains systems of power supply and control, torch cooling (0.1×10^{-3} kg/s), gas feeding (5.2×10^{-4} kg/s), water vapor generation ($1.48-4.48 \times 10^{-3}$ kg/s) and system of water vapor overheating (450 K). Electrodes of plasma torch are separated by the insulation rings (Fig 1, position 2) avoiding a short circuit. These rings have inlet holes for tangential supply of shielding gas and plasma forming gas.

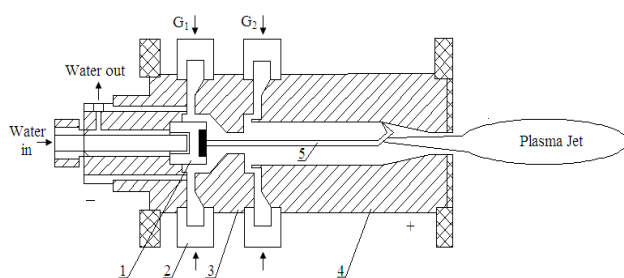


Fig 1. A scheme of water vapor plasma torch. 1 – cathode, 2 – insulating rings, 3 – neutral section, 4 – confusor-type anode, 5 – electric arc

Argon (Ar) has been used as shielding gas, protecting cathode from erosion, whereas water vapor is used as plasma forming gas. The amount of Ar depends on the current intensity and plasma forming gas. During experiment it was kept in the range of 10 to 25 % of the total

mass flow rate. The main plasma forming gas is overheated water vapor, produced using 5 bar of pressure water steam generator.

Confusor-type anode is used to sustain axial stabilization of the electric arc in the discharge chamber of the torch, although it strongly distorts barometrical ambience inside. Practically, a confusor doesn't have the influence on the change of pressure gradient near the walls in the discharge chamber, but increases it significantly approaching to the axis. This leads to the increase of axial stabilization of the arc, simultaneously suppressing the danger of electrical breakdown (shunting) into discharge chamber walls. Moreover, symmetrical gas dynamical pinch of the arc, at the end of narrow section of the confusor, increases the effect of arc stabilization also.

Primary temperature of water vapor as plasma forming gas also improves stabilization of the electrical arc in the discharge chamber of the torch. Consequently, before inject into the reaction chamber, water vapor is overheated by a superheater, up to 450 K. Hereby, a triple effect is being reached: the condensation of water vapor on the walls of the electrodes is avoided, prolongation of their life-time is achieved and higher thermal efficiency of the torch is obtained. Water vapor is ionized by the electric arc of the plasma torch with current intensity of 130-210 A. Dissociated particles (ions, atoms, electrons and neutrals) participates in the formation of synthetic gas during chemical reactions.

3. Results and discussion

Applying plasma generator (PG) for environmental applications a keystone parameters are temperature and velocity of plasma jet. However, mentioned parameters depend on the construction of PG and its thermal and electrical characteristics. These characteristics are very important while designing the experimental equipment with stable operating parameters. The main operational characteristics of plasma torch and plasma jet are given in Table 1.

Table 1. The experimental parameters of the plasma torch and plasma jet

Arc current (A)	130 – 210
Arc voltage (V)	230 – 330
Arc power (kW)	30 – 53
Power loss to the cooling water (kW)	8 – 18
Output power (kW)	24 – 36
Plasma torch efficiency, η	0.58 – 0.78
Argon gas flow rate, G_1 (10^{-4} kg/s)	5.2
Water vapor flow rate, G_2 (10^{-3} kg/s)	1.48 – 4.48
Total mass flow rate, G (10^{-3} kg/s)	2 – 5
Mean temperature of plasma jet at the torch outlet nozzle (K)	2300 – 2900
Mean velocity of plasma jet at the torch outlet nozzle (m/s)	340 – 700

A stable work of water vapor plasma torch is required applying for environmental applications. There-

fore, electrical and thermal characteristics are very important controlling the processes of destruction of hazardous substances and gasification of biomass.

To ensure a stable work of PG, rising or steady voltage-current characteristics (VCC) are desirable. Nevertheless, static plasma torch VCC is descending Fig 2. Arc shunting is one of the reasons for the formation of a dropping VCC of the arc, restricting the temperature of heated gas, and requiring inclusion of a ballast resistance in the electrical circuit. Equally, the VCC of water vapor plasma torch are strongly dependent on the geometrical dimensions of the electric arc chamber, type of plasma forming gas and its mass flow rate. The PG works steady than the flow rate of water vapor is in the range of $2.5\text{-}3.5 \times 10^{-3}$ kg/s and the current intensity of the electric arc varies from 138 to 182 A. Physical characteristics of the gas such as density, viscosity, conductivity and etc. have an influence on the VCC also.

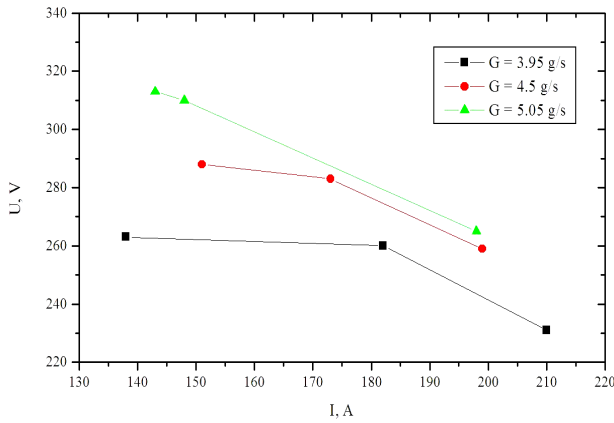


Fig 2. Voltage-current characteristics of water vapor plasma torch

A general estimating equation is used for determination of generalized VCC. It's estimated using the theory of similarity and is presented below (1). The generalized results are depicted in Fig 3. These results are essential for both calculating and designing highly efficient water vapor plasma generator.

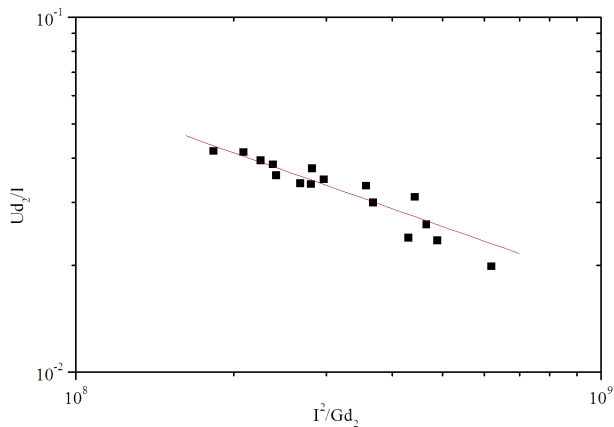


Fig 3. Generalized VCC of the water vapor plasma torch

$$\frac{Ud_2}{I} = 1.03 \times 10^4 \left(\frac{I^2}{Gd_2} \right)^{-0.65} \quad (1)$$

where U is voltage (V), d_2 – the diameter of anode (m), I – the arc current intensity (A), G – the total mass flow (kg/s).

Generalization of the thermal characteristics of the plasma torch is similar to the generalization of electrical characteristics. The general results of plasma torch thermal efficiency (Fig 4) were estimated using the theory of similarity and are presented in equation (2). Any magnitude of PG thermal efficiency could be estimated from this equation.

$$\frac{1-\eta}{\eta} = 1.34 \times 10^{-6} \left(\frac{I^2}{Gd_2} \right)^{0.66} \quad (2)$$

where η is the thermal efficiency, which depends on the heat losses in the wall of the discharge chamber I – the arc current intensity (A), G – the total mass flow (kg/s) and d_2 – the diameter of anode (m). The value $(1-\eta)/\eta$ determine the ratio of the heat losses in the plasma torch to the heat content of plasma jet.

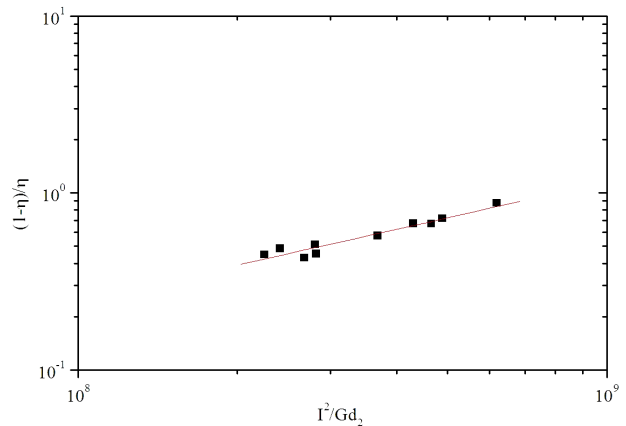


Fig 4. Generalized thermal efficiency of water vapor plasma torch

The maximum thermal efficiency of water vapor PG ($\eta=0.78$) was achieved at the current intensity of 130 A, voltage 300 V, and the $4.5\text{-}5 \times 10^{-3}$ kg/s of the total mass flow rate of Ar-water vapor.

4. Conclusions

1. An experimental DC water vapor plasma torch with a confusor-type anode operating at atmospheric pressure has been designed and tested. It was found to be suitable for environmental applications, such as destruction of hazardous substances and conversion of organic materials to synthetic gas.
2. The average temperature of plasma jet at the outlet nozzle of the torch varied within the limits of 2300-2900 K. The max PG thermal efficiency was 0.78.

High temperature is one of the main parameters for effective neutralization of materials.

3. The VCC of water vapor plasma torch are decreasing. Generalized voltage-current and thermal characteristics are summarized into equation (1) and (2), respectively.
4. Summarized results will help to calculate and design gasification and neutralization systems of organic materials, to establish optimal parameters for stable operation of plasma torch and regulate the process parameters.

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