Generation and Spectroscopic Investigation of an Atmospheric Pressure Water Vapour Plasma Jet

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ABSTRACT

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Water vapour plasma technologies could be used for the conversion of biomass to hydrogen rich synthetic gas and for the neutralization and utilization of hazardous wastes. Formation of water vapour plasma has been investigated using a linear direct current plasma torch with stair stepped anode. A new device with a unique structure, operating at atmospheric pressure has been designed and tested at Lithuanian Energy Institute, Plasma Processing Laboratory for the innovative and environmental friendly plasma treatment of organic materials. The main operating conditions of plasma torch and main parameters of water vapour plasma jet were investigated. The power of plasma torch was 25–45kW; arc current was 140–180 A, the arc voltage was 172–231 V, the efficiency was 0.5–0.78. The average temperature of water vapour plasma jet in exhaust nozzle was 2600–3500 K, and the plasma jet velocity was 200–310 m/s.

Emission lines, registered by the optical emission spectrometer AOS4-1, are analysed to observe the chemical composition of water vapour plasma jet. The optical emission spectrum measurement shows that the water molecule in the plasma is decomposed into H, OH and O radicals. Hydrogen is very desirable in the formation of high caloric synthetic gas ($CO+H_2$) during thermal plasma gasification of organic materials.

The summarized results can help to calculate and design gasification systems of biomass, to establish optimal parameters for stable operation of plasma generator and regulate the process parameters.

Keywords: water vapour, plasma, optical emission spectroscopy, plasma torch.

1. INTRODUCTION

Water vapor plasma technology offers some unique advantages for biomass conversion, neutralization and utilization of hazardous wastes such as providing high temperature and heating rate, in comparison to other thermal methods. A very intensive heat exchange causes organic compounds in the waste to dissociate into very simple atoms and molecules such as hydrogen, carbon dioxide, carbon monoxide, methane, etc. very quickly and provide a potential solution for the problems that occur in conventional pyrolysis processes [1]. Atmospheric pressure water vapour plasma generated by means of novel designed direct current (DC) water vapour plasma torch at Lithuanian Energy Institute, Plasma Processing Laboratory. At present here is considerable current interest for a wide range of applications of plasma technology in the gasification/vitrification for treatment of hazardous waste [2, 3], as well as in pyrolysis/gasification of organic compounds for the production of synthetic fuels [4, 5], in environmental protection for effective destruction of hydrofluorocarbons (HFCs) [6], perfluorcarbons (PFCs) [7], and volatile organic compounds (VOCs) [8]. Plasma technology is also employed for new materials and surface treatment, welding, cutting and etc.

Besides measurements of electrical and thermal characteristics of water vapour plasma generator (PG) and investigation of plasma jet parameters such as temperature and velocity, optical emission spectroscopy (OES) has been used for plasma diagnostics as non-invasive and *in situ* method. It provides valuable information for the determination of the chemical elements and their species, exited atomic and molecular states with a very differing cost performance ratios and time consumption. Also, enables to determine the rotational, vibrational, and electronic excitation temperatures of the plasma and thus the level of non-equilibrium and the gas temperature, and sometimes electron temperature [9, 10]. Reference [11] has investigated the measurements of rotational temperature, hydrogen atomic temperature, electron and excitation temperatures at an atmospheric pressure DC microplasma jet (98% Ar-2% H_2).

In this research only emission spectra parameters of water vapour plasma jet were investigated in order to better understand the behavior and composition of water vapour at high temperatures. The main focus is to carry out and identify species in the emission spectra of ionized water vapour. The identification of species in the emission spectra of atmospheric pressure air and nitrogen plasmas using OES method was reported in [12], radio frequency (RF) cold plasma in [13], DC low pressure discharges in [14].

In this work, the emission spectra of atmospheric pressure plasmas generated by DC electrical arc discharge in water vapour with admixture of argon as shielding gas and using different types of electrodes of the plasma generator were carried out, by well-known OES method.

2. EXPERIMENTAL SETUP

2.1. Water vapour plasma torch

The experimental water vapor plasma system, operating at atmospheric pressure, was projected and designed at Lithuanian Energy Institute by staff of Plasma Processing Laboratory (Fig. 1.) Plasma torch – is an electric arc gas heater in which electric energy is converted into thermal energy by means of Joule heat in the discharge [15]. The electric arc in the PG of a linear design is stabilized with gas-water vapour vortex. The torch is 30–53 kW of power with button type hot tungsten cathode working as electron emitter and step-formed copper or stainless steel anode.

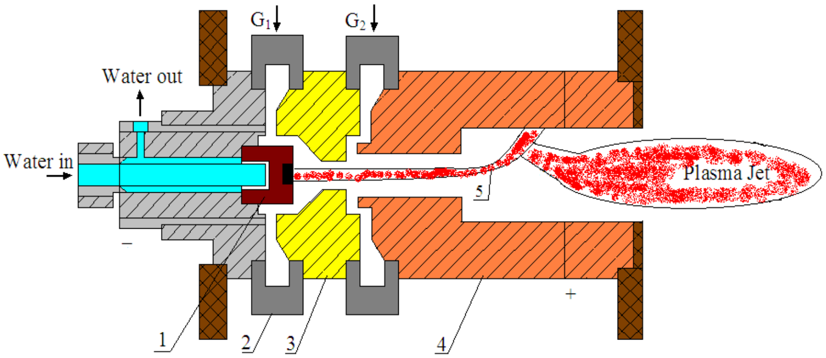

Fig. 1. A scheme of water vapour plasma torch. 1 – cathode, 2 – insulating rings, 3 – neutral section, 4 – anode, 5 – electric arc.

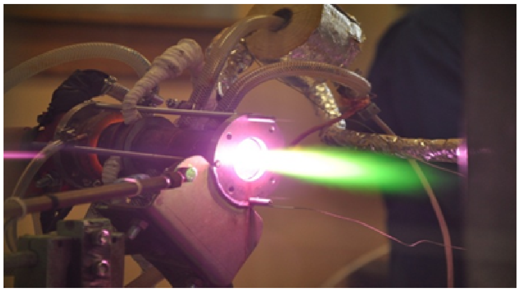

Fig. 2. Water vapor plasma torch in operation.

The plasma generation system generally requires complex sub-equipment to enable stable work of PG. The subsystems are as following: power supply and control, torch cooling $0.1 \cdot 10^{-3}$ kg $\cdot$ s^{-1}, shield gas feeding $5.2 \cdot 10^{-4}$ kg $\cdot$ s^{-1}, water vapour generation $1.48–4.48 \cdot 10^{-3}$ kg $\cdot$ s^{-1} and system of water vapour overheating (to 450 K). The combined operation between mentioned systems allows generating plasma with stable parameters. Electrodes of plasma torch are separated by insulating rings avoiding a short circuit. The rings have the inlet holes for tangential supply of shielding and plasma forming gas.

Argon (Ar) has been used as shielding gas, protecting tungsten cathode form erosion; whereas overheated water vapour (up to 450 K) was used as plasma forming gas produced using 5 bar of pressure water steam generator. Water vapor plasma generator in operation is presented in Fig. 2. Water vapour is ionized by high voltage electric arc in the discharge chamber of the plasma torch, i.e. dissociates into atomic elements such as atoms, molecules and radicals.

2.2. Optical emission spectrometer

The emission spectra of exhaust water vapour plasmas jet at the exit nozzle of PG was measured by means of AOS4-1 spectrometer. The experimental set-up is presented in Fig. 3.

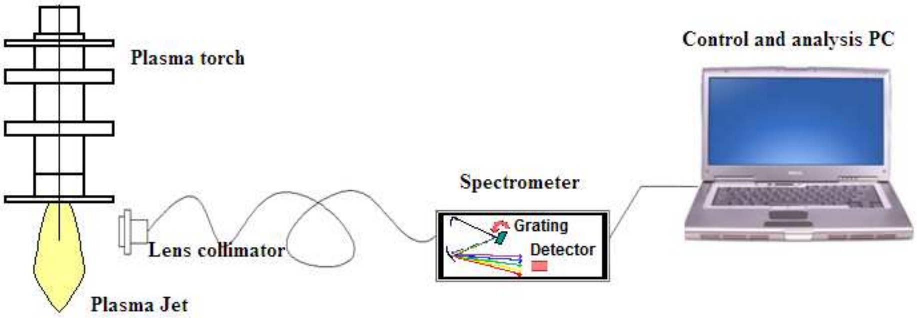

Fig. 3. A scheme of experimental set-up for optical emission spectroscopy.

The spectrometer with the spectral resolution of 0.05 nm (at 250 nm) and 0.5 nm (at 800 nm) is able to measure radiation emitted from a light source in near UV-VIS spectral range of 250-800 nm wavelength. Time resolution of the spectrometer can vary within the limits from 5 to 100 ms. The AOS4-1 measurement head consists of RF-synthesizer, RF-amplifier with cooler, crystal monochromator, fiber optic-collimator (0.2 mm) and photo detector with detector cable. The spectrometer is controlled via standard USB 2.0 interface from laptop. The “IntelliSpec” software is used for measurements and manipulation of obtained emission spectra.

In contrast with conventional spectrometers, in which the spectral dispersion of a broadband optical signal is performed by diffraction gratings, prisms or Fourier Transforming methods, an acousto-optic tunable filter (AOTF) made of quartz (SiO_2) crystal is used as a narrow band fast tunable wavelength filter, ensuring calibration of optical system. That means the AOS4-1 allows detecting extremely small amounts of light.

The optical fiber directs the emission from the plasma into an optical interface located at the entrance pinhole of the grating spectrometer. The focal distance was 0.05 m. The emitted light from plasma jet was deflected by means of lens collimator via optical fiber aperture to the crystal monochromator of the spectrometer, where a photomultiplier (PMT) converted photons into electrical signal.

3. RESULTS AND DISCUSSION

Applying plasma generator for thermal treatment applicatios the main operational parameters are temperature and velocity of plasma jet. The operational parameters and stable work of the system depend on the construction of PG and its thermal and electrical characteristics. The main operational characteristics of plasma torch and plasma jet were estimated and are given in Table I.

TABLE I: THE OPERATIONAL 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^{-1})	5.2
Water vapor flow rate, G_2 (10^{-3} kg · s^{-1})	1.48 – 4.48
Total mass flow rate, G (10^{-3} kg · s^{-1})	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^{-1})	200 – 310

The emission spectrum analysis of DC electric arc discharge in the argon-water vapour mixture in the range of wavelength from 300 to 800 nm was performed. Fig. 4 and Fig. 5 present the optical emission spectrum measured for the argon/water vapour plasma jet at the 5 mm distance from the nozzle exhaust of anode. The experiment conditions in emission spectra measuring (Fig. 4) were the following: the power of plasma torch P=36.2 kW, the electrode of copper was used, argon flow rate 5.2 · 10^{-4} kg · s^{-1} and water vapor flow rate 2,63 · 10^{-3} kg · s^{-1}. In the another case (Fig. 5), the power of plasma torch P=36.2 kW, the electrode of stainless steel was used, argon flow rate 5.2 · 10^{-4} kg · s^{-1} and water vapor flow rate 2,9 · 10^{-3} kg · s^{-1}

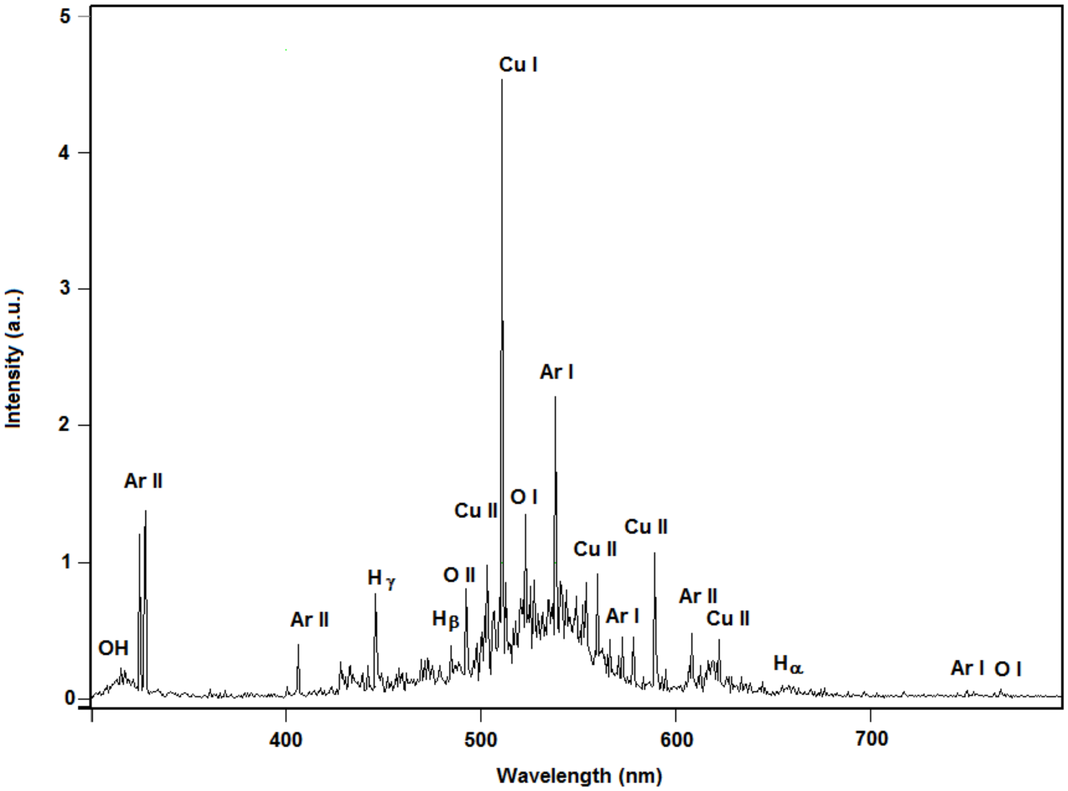

Fig. 4. Optical emission spectra of Ar/water vapour plasma jet at P=36.2 kW, flow rate of water vapour $G_2=2.63 \cdot 10^{-3}$ kg · s^{-1}

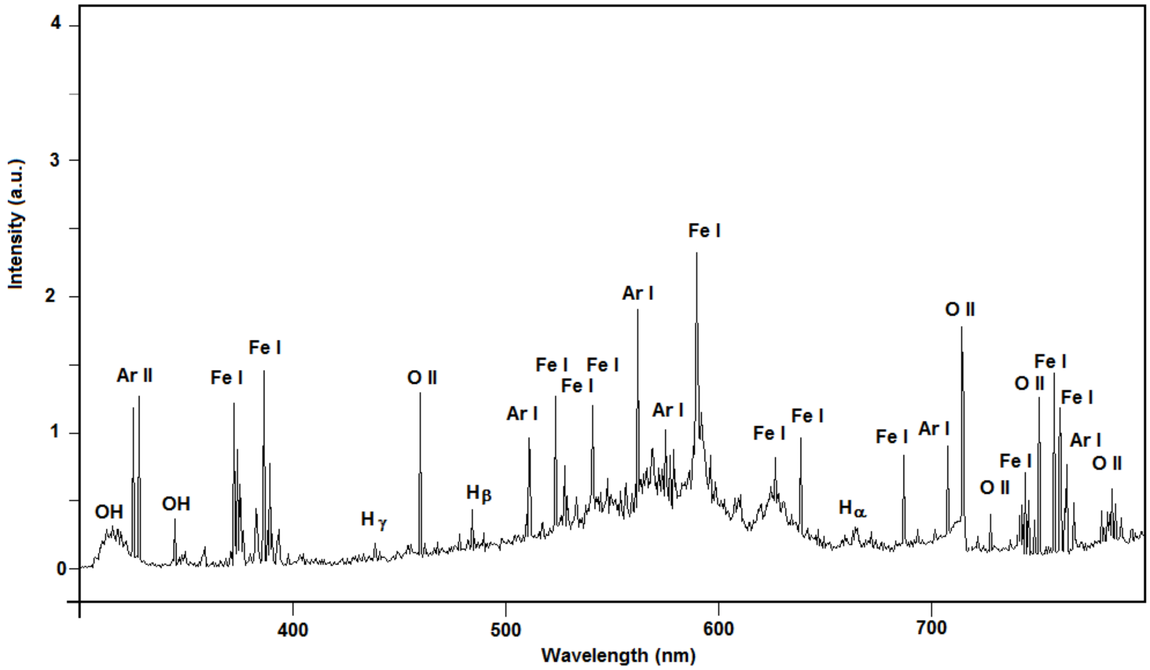

Fig. 5. Optical emission spectra of Ar/water vapour plasma jet at P=37.4 kW, flow rate of water vapour $G_2=2{,}9 \cdot 10^{-3}$ kg · s^{-1}.

The main species observed in Ar/water vapour plasma were: Ar (I), Ar (II) OH, H, O (I), O (II), Cu (I), Cu (II), Fe (I). The emission spectra showed the peaks of hydrogen atoms: H_α (656.2 nm), H_β (486.1 nm) and H_γ (434.1 nm), which belong to Balmer series of H_2. Visually, the H_α line tends not to be seen well due to human's eye's lack of sensitivity in the deep red part of the spectrum, but the H_β line tends to come fairly intense. The temperature of plasma jet at the nozzle exhaust of the plasma torch is high, due to the intense collisions between molecules, but the energies of exited species (H_α) are low, because the mean free path is short. The peaks of Cu(I), Cu(II) in Fig. 4 and Fe(I) in Fig. 5 show an intensive erosion process and evaporation of used electrodes. More detailed examinations are required to optimize the plasma system.

Therefore, the performed emission spectra measurements confirmed that water vapour was decomposed into H, O and OH radicals by high voltage dc electric arc. Beside these important groups of spectral lines, the spectrum contains a large number of other lines with variable intensities, making the plasma emission spectrum rather complicated. The summarized results can help to calculate and design thermal waste treatment, gasification systems of biomass, to establish optimal parameters for stable operation of plasma generator and regulate the process parameters.

4. CONCLUSIONS

The optical emission spectroscopy method has been used to study the emission spectra of Ar/water vapour plasma generated by DC plasma torch at atmospheric pressure. The performed optical emission spectra measurements of the Ar/water vapour plasma jet by means of AOS4-1 spectrometer confirmed that water vapour was decomposed into H, O and OH radicals by high voltage dc electric arc. Beside these important groups, the emission spectrum contains other emission lines such as Ar (I), Ar (II), Cu (I), Cu (II), Fe(I). Copper and stainless steel anodes strongly evaporated. More detailed examinations are required to optimize the plasma system.

The emission intensities of obtained species were sensitive to the changes in the flow rate of water vapour and the power of the plasma torch. The spectra also showed the peaks of H_α (656.2 nm), H_β (486.1 nm) and H_γ (434.1 nm), which belong to the Balmer series describing the spectral line emissions of the hydrogen atoms. The thermal and electrical characteristics of the water vapor plasma torch were carried out to ensure the stable work of the plasma generator. The results will be useful projecting new plasma equipment, designed for the decomposition of biomass and organic waste.

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REFERENCES

[1] TENDLER, M.; RUTBERG, P.; VAN OOST, G. Plasma based waste treatment and energy production. Plasma Phys. Contr. F., 2005, 47 (5A), p. 219-230.

[2] WATANABE T., Water plasma generation under atmospheric pressure for waste treatment. ASEAN J. Chem. Eng., 2005, No.1 Vol. 5, 30-34.

[3] VAN OOST, G., HRABOVSKY, M., KOPECKY, V., KONRAD, M., HLINA, M., KAVKA, T. Pyrolysis/gasification of biomass for synthetic fuel production using a hybrid gas-water stabilized plasma torch. Vacuum, 2009, No. 83, p. 209-212.

[4] VAN OOST, G., HRABOVSKY, M., KOPECKY, V., KONRAD, M., HLINA, M., KAVKA, T., CHUMAK, A., BEECKMAN, E., VERSTRATEN, J. Pyrolysis of waste using hybrid argon-water stabilized torch. Vacuum, 2006, No. 80, p. 1132-1137.

[5] NISHIKAWA, H., MASAAKI, I., TANAKA, M., TAKEMOTO, T., USHIO, M. Effect of DC steam plasma on gasifying carbonized waste. Vacuum, 2006, No. 80, 1311-1315.

[6] WATANABE, T., TSURU, T. Water plasma generation under atmospheric pressure for HFC destruction. Thin Solid Films, 2008, No. 516, p. 4391-4396.

[7] KIM, D. Y., PARK, D. W. Decomposition of PFCs by steam plasma at atmospheric pressure. Surface and Coatings Technology, 2008, No. 202, p. 5280-5283.

[8] ODA, T. Non-thermal plasma processing for environmental protection: decomposition of dilute VOCs in air. Journal of Electrostatics, 2003, No. 57, p. 293-311.

[9] LAUX, C. O., SPENCE, T. G., KRUGER, C. H., ZARE, R. N. Optical diagnostics of atmospheric pressure air plasmas. Journal of Plasma Sources Science and Technology, 2003, No. 12, p. 125-138.

[10] BROEKAERT, Jose A. C. Analytical Atomic Spectroscopy with Flames and Plasmas. Wiley-VCH Verlag GmbH & Co, 2002. 347 p. ISBN 3-527-60062-0.

[11] SISMANOGLU, B. N., AMORIM, J., SOUZA-CORREA, J. A., OLIVEIRA, C., GOMES, M. P. Optical emission spectroscopy diagnostics of an atmospheric pressure direct current microplasma jet. Spectrochimica Acta Part B, 2009, No. 64, p. 1287-1293.

[12] MACHALA, Z., JANDA, M., HENSEL, K., JEDLOVSKY, I., LEŠTINSKA, L., FOLTIN, V., MARTIŠOVITŠ, V., MORVOVA, M. Emission spectroscopy of atmospheric pressure plasmas for bio-medical and environmental applications. Journal of Molecular Spectroscopy, 2007, No. 243, p. 194-201.

[13] KIM, J. H., KIM, Y. H., CHOI, Y. H., CHOE, W., CHOI, J. J., HWANG, Y. S. Optical measurements of gas temperatures in atmospheric pressure RF cold plasmas. Surface and Coatings Technology, 2003, No. 171, p. 211-215.

[14] JAMROZ, P., ZYRICKI, W. Optical emission spectroscopy study for nitrogen-acetylene-argon and nitrogen-acetylene-helium 100 kHz and dc discharges. Vacuum, 2010, No. 84, p. 940-946.

[15] ZHUKOV, M. F; ZASYPKIN, I. M. Thermal Plasma Torches: Design, Characteristics, Applications. Cambridge International Science Publishing Ltd, 2007. 600 p. ISBN-13: 978-1-904602-02-6.