Energy Conversion and Management 78 (2014) 695–703

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Experimental investigation of gas heating and dissociation in a microwave plasma torch at atmospheric pressure

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ARTICLE INFO

Article history:
Received 16 July 2013
Accepted 1 December 2013
Available online 20 December 2013

Keywords:
Atmospheric pressure microwave plasma
Gas thermal dissociation
Optical emission spectroscopy
Plasma visualization

ABSTRACT

Experimental investigations are made to understand gas heating and dissociation in a microwave (MW) plasma torch at atmospheric pressure. The MW induced plasma torch operates at 2.45 GHz frequency and up to 2 kW power. Three different gas mixtures are injected in the form of axial flow and swirl flow in a quartz tube plasma torch to experimentally investigate the MW plasma to gas energy transfer. Air–argon, air–air and air–nitrogen plasmas are formed and their operational ranges are determined in terms of gas flow rates and MW power. Visual observations, optical emission spectroscopy and *K*-type thermocouple measurements are used to characterize the plasma. The study reveals that the plasma structure is highly dependent on the carrier gas type, gas flow rate, and MW power. However, the plasma gas temperature is shown not to vary much with these parameters. Further spectral and analytical analysis show that the plasma is in thermal equilibrium and presents very good energy coupling between the microwave power and gas heating and dissociation. The MW plasma torch outlet temperature is also measured and found to be suitable for many thermal heating and chemical dissociation applications.

1. Introduction

In microwave heating, the material is subjected to an electromagnetic wave that causes the molecules in the treated material to oscillate, thereby generating heat. One of the most important advantages with microwave heating is that it provides a fast and uniform heating process, in contrast to traditional conduction heating [1]. This phenomenon has applications ranging from microwave ovens [2], through material processing in the manufacturing industry [3], plasma heating in Tokamaks [4], to industrial microwave furnaces [5]. Recently, microwave technologies have been used for heating of atmospheric pressure plasmas for gasification because such plasmas present considerable interest for a wide range of environmental, bio-medical and industrial applications [6,7] such as air pollution control [8,9], waste water cleaning [10], bio-decontamination [11] and sterilization [12], material and surface treatment [13,14], electromagnetic wave shielding [15], carbon beneficiation and nano-tube growth [16,17], and element analysis [18]. Due to the great applications of atmospheric microwave induced plasma (MIP) sources, they have been studied for decades. The operation of microwave plasma torches (MPT) benefits from strong gas ionization due to an efficient microwave coupling with the gas. It also generates a considerable amount of thermal energy that can be used to heat large volumes of gas [19]. Unlike resistors, which are commonly used to heat gases by contact with hot surfaces, heating by MPTs relies on the distribution of the electromagnetic field existing within the plasma and leading to its ionization and heating. Microwave induced plasmas are created and maintained by using an electromagnetic energy source, with frequency in the range of 300 MHz–10 GHz, in the absence of electrodes, thus limiting gas contamination. These sources have wide range of operating powers (from few watts to megawatts), required by thermal torches from very low pressures to several atmospheres. Because of these advantages, different types of atmospheric MIP sources have been developed in the last decade. In particular, the Microwave Continuous Flow Reactor (MCFR) [20,21], Surface Wave Sustained Plasma (SWSP) [22], Torch with Axial Gas Injection (TIA) [23,24], Microwave Plasma Torch (MPT) [25] and Microwave Cavity Plasma [26,27] are well-known types of MW plasma sources. On the bases of design, working conditions and plasma properties, microwave plasma torches (MPT) are known as waveguide-supplied surface-wave-discharge MPT (surfaguide) [28–30], coaxial-line-supplied coaxial-line-based nozzle-type MPT [31], waveguide-supplied coaxial-line-based nozzle-type MPT [32], waveguide-supplied coaxial-line-based nozzleless MPT [33], waveguide-supplied metal-cylinder-based nozzleless MPT [34], waveguide-supplied resonant-cavity-based MPT [35], coaxial-line-supplied strip-line-based and waveguide-supplied plasma-sheet MPTs [36,37]. MPTs can operate in both confined [38] and non-confined [39] modes, corresponding to semi-metallic torches and metallic torches, respectively. In the confined mode,

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0196-8904/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2013.12.001

the plasma is created within a quartz tube, where the gas flows through electromagnetic waves that settle generally in a cylindrical structure. In the non-confined mode, the plasma is created at the outlet of the nozzle that terminates in a coaxial waveguide. In Inductively Coupled Plasma (ICP) or MPT, mostly argon is used as a plasma gas, although it may be desirable to use other gases such as helium, nitrogen, air, oxygen, or hydrogen [40] depending on various industrial applications. However, argon is often used for gasification and waste treatment in thermal plasmas because it is relatively inert and can be obtained in ultra-pure form at a reasonable cost. It has a relatively low breakdown voltage and tends to minimize electrode wear in some plasma devices [41]. In general, high density microwave plasma torches are designed as they can provide suitable condition to dissociate molecules in the abatement systems and burn out chemical and biological warfare agents, and to atomize and synthesize new materials. Therefore, it is very important to experimentally characterize the generated microwave plasma in order to ensure that it is suitable for the desired technical application. Fundamental plasma parameters, such as gas temperature, gas velocity and active species emission profiles need to be determined in order to have a complete plasma characterization. The gas temperature is related to the energy distribution among the heavier particles in the plasma. It can differ between different species and energy modes and it may be different from the plasma electron temperature. Generally, gas temperatures are determined from the rotational temperatures of diatomic species [42,43]. They directly affect the kinetics of the chemical reactions in the plasma torch [43]. Therefore, study of the plasma gas dynamics and heating is important for gasification, and waste treatment among other applications. Thermal and non-thermal plasma have been used for organic waste treatment [44], hydrogen rich gas production [45], and thermo-chemical conversion of biomass [46]. Although several experimental methods can be used to determine the gas temperature, optical emission spectroscopy (OES) is a well-established technique because it is simple, can be used *in situ* and is noninvasive [47–49].

The present investigation is intended to reveal the main trends of microwave discharge behavior with a particular focus on the dependence of the gas temperature and plasma length on the plasma torch operating conditions. The paper presents the characterization of an atmospheric microwave induced plasma torch with different gas combinations. Experiments are carried out to characterize the plasma for its suitability to waste treatment and hydrogen production. We are mainly focusing on selecting the right thermal plasma dissociation process for hydrogen production. Previous simulations have shown that a plug flow like MW plasma torch would be very suitable for such application [50]. Furthermore, spontaneous emission spectroscopy has revealed that such a plasma is in Local Thermal Equilibrium (LTE) [51]. LTE is very important for the control of chemical kinetics to get best chemical conversions. Therefore microwave heating of air–nitrogen, air–air and air–argon gas plasmas are experimentally studied and characterized. The effect of operating parameters such as microwave power, axial flow rate, and swirl flow rate on the microwave heating process are examined. Optical emission spectroscopy is used to measure the plasma temperature using the first negative system of N_2^+ to estimate the plasma gas temperature of different gas mixtures. A *K*-type thermocouple is used to measure the gas temperature at the MPT exit, and a ruler is used to measure the plasma flame length.

2. Experimental set up

A photo and schematic of the experimental set-up of the microwave plasma torch are shown in Fig. 1. Generated microwaves at 2.45 GHz and up to 2 kW are transmitted through the shortened WR248 rectangular waveguide (4 cm high and 7 cm wide) from the MW source to the quartz tube (2.54 cm diameter and 22.5 cm length) of the plasma torch. The transmission waveguide consists of an impedance tuner, a circulator and a dummy load. The circulator is used to stop reflected microwave power from reaching the generator, which otherwise can damage the magnetron. The reflected microwaves are diverted into a water-cooled dummy load for safe dissipation of energy. The tuner consists of a three stub impedance matching assembly that is used to match the overall load impedance to the internal resistance of the source which, in turn, maximizes the delivered power to the load (plasma). The experimental rig is equipped with a forward and backward power meter controller for online power measurements of the impedance matching procedure. A quartz tube is strategically positioned inside the waveguide such that the incoming and reflected microwave radiations superimpose constructively for maximum power delivery and energy efficiency. A gas flow system is connected to the plasma torch which consists of three different gas streams that can be fed simultaneously to the plasma torch. Axial and annular gas flows can be injected into the quartz tube and a hydraulically driven; spring returned tungsten wire is used for plasma ignition (Fig. 2a). The swirl flow gas is injected tangentially into the quartz tube to protect it from being damaged by the high temperature plasma. For gas flow rate measurements, pressure regulators, needle valves and pressure gauges are mounted on the axial and swirl gas lines. An Optical Emission Spectroscopy (OES) system consisting of a series of lenses, a transmission stage, an optical fiber bundle, a spectrometer, a CCD camera and a data acquisition unit is used for the plasma spectral analysis (Fig. 1). Holes are drilled into the shortened end of the brass waveguide to facilitate the optical observation of the plasma spectral emissions (Fig. 2b). A bundle of 19 optical fibers is connected to one of the holes on the waveguide while the other end is connected to the entrance slit assembly of the spectrometer. The details of the OES system for plasma temperature determination can be found in [51].

The plasma torch is designed similar to a microwave plasma torch with a coaxial field structure. In Fig. 2, microwave transmission, quartz tube and gas flow (axial and swirl) are represented for better understanding of the plasma formation and confinement by swirl flow gas. One open end of the quartz tube is positioned at the center of the width of the waveguide. The short circuit and the stubs are used to optimize the MW transmission maximizing the power coupled to the system (the plasma). The power delivered by the MW generator is controlled by a bi-directional coupler which measures the incident and the reflected powers. The electric field of the microwave radiation in a rectangular waveguide has a certain profile depending on the mode of the microwaves transmission and the frequency of operation. Using the TE10 mode of operation for the microwaves at a generation frequency of 2.45 GHz, a parabolic electric field profile is achieved with a maximum at the center of the width of the waveguide. In our device the discharge occurs at the tip of a field-shaping structure similar to that of the fully coaxial-line-based torches, but power-feeding is done from the waveguide, requiring mode conversion as well as impedance-matching. This plasma torch is designed with twofold purpose, firstly electromagnetic field distribution required to sustain a “plasma flame” and secondly efficient power transfer from the feed waveguide to the plasma. It is assumed that the plasma torch is lossless so that most of incident power that is not reflected at the input of the device is absorbed by the plasma. Plasma thickness is also important for microwave absorption to produce the plasma. The plasma cross section size, that can be efficiently large by