Applied Energy 108 (2013) 505–514

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Novel three-phase steam–air plasma torch for gasification of high-caloric waste

Philip G. Rutberg *, Vadim A. Kuznetsov, Evgeny O. Serba, Sergey D. Popov, Alexander V. Surov, Ghennady V. Nakonechny, Alexey V. Nikonov

Institute for Electrophysics and Electric Power RAS, Dvortsovaya nab., 18, St.-Petersburg 191186, Russia

HIGHLIGHTS

- The steam–air plasma torch volt–ampere characteristics and efficiency were experimentally determined.
- The increase in steam content of the plasma forming gas leads to voltage and power growth.
- High efficiency of the plasma torch is experimentally confirmed.
- The achieved levels of plasma energy content allow conversion of plastic waste into syngas virtually free from ballast gases.

ARTICLE INFO

Article history:
Received 19 November 2012
Received in revised form 20 March 2013
Accepted 22 March 2013
Available online 18 April 2013

Keywords:
Plasma torch
Efficiency
Electric arc
Steam–air plasma
Plasma gasification

ABSTRACT

Research results are presented for an AC electric arc that burns a mixture of steam and air in a three-phase high-voltage plasma torch and can be implemented to produce plasma for plastic waste gasification. The dependences of electric parameters on the ratio of the steam to air mass flows (H_2O/air ~1–6) at an approximately constant total mass flow of the plasma-forming gas are obtained during several experiments. During the experiments, the arc parameters were as follows: voltage drop of 1.0–1.8 kV, current of ~28.5 A and power of ~52–86 kW. The thermal efficiency of the plasma torch was ~94–95%. CCD cameras operating at 4000 fps were used to determine the average discharge length of ~798 mm. Photography with a high shutter speed (1/8000 s) was used to determine the average arc diameter (~4.47 mm). Arc temperatures were calculated (10,000–11,500 K) using the thermodynamic equilibrium approach. Experimental results indicate that increases in the steam content of the steam–air plasma lead to a reduction of the arc's temperature and electrical conductivity. Using an equilibrium approach, the main parameters of plasma gasification were estimated: syngas yield (3.62–3.48 m^3/kg), composition (H_2 – 55.5–62.5, CO – 32.8–34.1 vol.%) and energy consumption (11.0–12.3 MJ/kg).

1. Introduction

Global economic growth accompanied with the increase of the average standard of living, has led to the growth of world energy consumption. At the present time, the major movers of this process are developing countries [1]. Oil accounts for more than 40% of global energy consumption [2]. According to one study [3], "more than two thirds of current crude oil production capacity may need to be replaced by 2030 simply to keep production constant". In light of this finding, the development of new technologies to replace the shortage in oil reserves is very important. Such technologies include plasma gasification [4–6] and conversion [7] directed toward the production of liquid fuels and hydrogen because these processes allow increased yields of the end products [7,8]. To make these processes more efficient, the existence of reliable steam plasma generators with high energy content (~20 MJ/kg) is necessary as such energy allows the production of syngas consisting almost completely of hydrogen and carbon monoxide. Another advantage of steam plasma usage is the possibility to maintain high temperature, which leads to the intensification of tar cracking [9,10]. Steam-plasma gasification is a promising method of hydrogen production [11]. According to published data [12], steam-plasma gasification of oil produced by thermal pyrolysis of used tires can produce a syngas that consists more than 95% of H_2, CO and CH_4. Moreover, steam plasma is efficient for plastic waste gasification [13], and it improves the process of catalytic conversion of tars [14]. Plasma energy is effectively used for intensification of gasification and the consequent water–gas shift reaction for production of hydrogen from bio-ethanol [15]. In connection with these concerns, plasma torches using steam (or its mixture with other gases) as a working gas are notably interesting.

---

* Corresponding author. Tel.: +7 812 315 17 57; fax: +7 812 571 50 56.
E-mail address: rc@iperas.nw.ru (P.G. Rutberg).

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.03.052

2. Brief review of steam plasma torches

A majority of existing plasma torch designs are intended to generate DC arcs. As a rule, these systems are relatively low power (apart from the hybrid stabilized plasma torch WSP®H [16] and the 100 kW steam plasma torch [17]) and use cathodes from refractory materials. They are mainly made from tungsten-based alloys, which are unable to work in an oxidizing environment, and zirconium, which rapidly erodes during continuous-time operation. Inert gases are generally used to protect the cathode (mainly argon [16–19]). Table 1 tabulates the key features of these plasma torches.

Following from the above characteristics, all plasma torches have rather low arc voltage drops on the order of 200 V and lower. Consequently, to achieve the required power, relatively high currents of up to 600 A [16,17] are used, and this will inevitably affect erosion and electrode lifetime. The power of these plasma torches is ~10–100 kW and the coefficient of thermal efficiency (the efficiency of the energy transfer from arc to plasma) ranges from 51% to 85% [16,18,19].

In [20], a plasma torch is described that runs on steam and has an extremely low power of ~1 kW. The steady operation time of the zirconium cathode at currents up to 10 A was about an hour. These demonstrated results are of limited interest to the design of powerful systems.

Moreover, one study [21] addresses the problem of erosion of the copper electrodes when working on pure steam and mixtures of argon with steam, hydrogen and oxygen at currents up to 100 A.

3. Development of industrial plasma torches

Certainly, high power plasma torches with high efficiency are primarily of concern in industrial applications. At the present time, the power of plasma torches that work on air has already reached 600 kW, and their total efficiency (taking into account the efficiency of the power supply system and energy transmission from the arc to plasma) is more than 90% [22,23]. These devices have a long lifetime (thousands of hours) due to the high voltage drop, and this makes their industrial application very attractive. However, the creation of systems using steam and its mixtures with other gases requires a number of special features. In particular, it is necessary to work at relatively low currents to ensure long lifetime, and the arc voltage drop must be high (several kilovolts). To accomplish this, the use of stabilized long arcs is required as well as a power supply system using AC-power lines, which will significantly reduce the cost and simplify the power system. These factors are a pre-condition for high total efficiency of the system [23].

To successfully design a high-powered system, it is essential to know several parameters about the AC long arc: the intensity, conductivity, temperature and charge carrier concentration. It is necessary to develop methods and techniques to make an independent estimation of these quantities depending on the working gas composition for a given current density. It is extremely important to obtain correct experimental data for steam–air mixtures.

4. Experimental installation

The experimental installation was created to allow for work on steam and on its mixtures with air and other gases. The setup includes a plasma torch with power up to 100 kW with a high-voltage power supply system; a system to supply the plasma-forming gases; a cooling system; and a diagnostic system for measurement and registration of the electrical and geometrical parameters of arcs, flow rates of the plasma-forming gases, the flow rate of the cooling agent and heat losses in the plasma torch body (thermal efficiency). Fig. 1 shows a photo of the working plasma torch. The plasma torch used in the installation can be applied in several processes (e.g., gasification, methane conversion and tar cracking). In addition, it is a prototype of more powerful plasma generators (~1–2 MW) intended for work on the same gases.

The hardware–software measurement system, which is based on an industrial computer with digital and analog signal-processing units, was used for collecting, processing and recording the experimental operating parameters [24]. Analog signals from the current and voltage sensors are processed by a 12-bit A-to-D converter with a 10 kHz sampling rate on each channel. Specially developed software allows the calculation of the effective current and voltage values and the power of the plasma torch using the instantaneous values, and the software also records the oscillograms. The obtained data are automatically registered by the industrial computer. Current sensors are used for current measurements. The current sensor has the following properties: measurement range runs from −70 to 70 A, accuracy is ±0.65%, nonlinearity is less than 0.15%, delay time is less than 1 μs for 90% of the maximum value of the measurement range and frequency range is 0–200 kHz. Voltage transformers and voltage sensors are used for voltage measurement. The voltage sensor has the following properties: range runs from 100 to 4500 V, accuracy is ±0.7%, nonlinearity is less than 0.1% and delay time is 20–100 μs for 90% of the maximum value of the measurement range.

Fig. 2 shows the schematic diagram of the plasma torch power supply system. The power supply system includes a three-phase

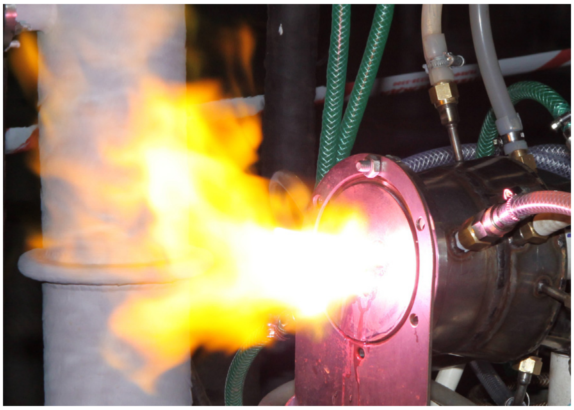

Fig. 1. Three-phase air–steam 1 AC plasma torch with power up to 100 kW.

Table 1
Key features of various steam plasma torches.

Power (kW)	Voltage drop (V)	Current (A)	Efficiency (%)	Steam flow rate (g/s)	Protective gas	Protective gas flow rate (g/s)	Cathode material	References
36–114	120–170	300–600	77–84	0.23–0.36	Argon	0.30–0.54	Zirconium	[16]
50–200	250–460	210–560	n.d.	1–5	None, argon, nitrogen	n.d.	Tungsten	[17]
8–32	120–160	100–190	65–85	0.3–0.7	Argon	0.04–0.18	Tungsten	[18]
29–39	179–260	138–182	51–70	1.71–1.78	Argon	0.24	Tungsten	[19]
1	124–142	7	90	0.05	-	n.d.	Zirconium	[20]