4th International Symposium on High-Temperature Metallurgical Processing
Edited by: Tao Jiang, Jiann-Yang Hwang, Phillip J. Mackey, Onuralp Yucel, and Guifeng Zhou
TMS (The Minerals, Metals & Materials Society), 2013

THERMAL PLASMA TORCHES FOR METALLURGICAL APPLICATIONS

L. Rao[1], F. Rivard[1] and **P. Carabin*[1]

[1] *PyroGenesis Canada Inc.,*
1744 rue William,
Suite 200, Montreal, QC, H3J 1R4
*(*Corresponding author: pcarabin@pyrogenesis.com)*

ABSTRACT

Advances in thermal plasma torches have resulted in this technology becoming a commercially viable solution for chemical and metallurgical processes. The main advantages of plasma are its ability to control process chemistry and to build small footprint reactors due to its high energy density and reactivity of the free radicals that are produced. This paper focuses on thermal plasmas produced by DC torches and their applications for waste treatment, production of high purity metals, and nanomaterials. Both transferred and non-transferred torches have been used as either a source of heat or as a reagent in various industrial processes. Retrofitting plasma torches in place of fuel oil burners lead to lower operating costs, capital cost and greenhouse gas emissions.

KEYWORDS

Thermal Plasma Torches, Waste Treatment, Advanced Materials, Thermal Plasma Applications

INTRODUCTION

Plasma technology has become an ideal solution for many industrial chemical, metallurgical and mechanical processes [1]. Thermal plasma powered systems are typical used for their unique characteristics such as high energy densities, high temperatures, small installation sizes, rapid start-up and shutdown features, controlled process chemistry and use of electrical energy as a heating source resulting in decoupling the heat source from the oxygen flow rate [2]. Depending on the nature of the main plasma forming gas used, thermal plasma systems offer a high temperature heating source coupled with a highly reactive plasma plume rich in free radicals and ions which promote otherwise hard to drive chemical reactions, as well as high heat transfer rates.

Industrial plasmas can be broadly classified as thermal plasmas and non thermal plasmas. Thermal plasmas are atmospheric pressure plasmas characterized by local thermodynamic equilibrium [3]. Thermal plasmas are typically established between any two current conducting electrodes separated by an insulator. A plasma forming gas is blown between the two conducting electrodes resulting in a high temperature plasma plume. A plasma torch generates and maintains an electrically conducting gas column between the two electrodes: a cathode (negative electrode) and an anode (positive electrode) [4]. If both electrodes are housed in a single housing, resulting in an arc enclosed inside the plasma torch, then such plasma generating torches are termed as non-transferred (NT) plasma torches, whereas, if the second electrode is external to the torch, creating an arc transferred between the cathode and the working piece, then such plasma torches are termed as transferred (T) plasma torches. Depending on the source of the electricity which can be either direct current (DC), alternating current (AC) at main network frequency or at radio frequency (RF), the plasma torches are classified as DC, AC or RF plasma torches [1].

For the past 20 years, PyroGenesis Canada Inc., (PCI) has been developing non transferred direct current plasma torches and has been using them for a wide range of applications. This paper focuses on the design, characteristics and typical applications of the plasma torches developed by PCI. It also covers the economic and environmental advantages of replacing fuel oil burners with plasma torches in existing and future facilities equipped with such burners.

PCI DEVELOPED NON TRANSFERRED PLASMA TORCHES

PCI has been developing and marketing non transferred DC plasma torch systems for some of the most demanding applications. PCI's has developed a series of different thermal plasma torch systems namely:

i) Reverse polarity high enthalpy plasma torch – RPT™
ii) Air Plasma Torch – APT™
iii) Steam Plasma Torch – SPT™

Each of these torch designs, their typical characteristics and their applications are described below.

REVERSE POLARITY HIGH ENTHALPY PLASMA TORCH (RPT™) DESIGN, CHARACTERISTICS AND TYPICAL APPLICATIONS

Figure 1 shows a picture of the assembled reverse polarity high enthalpy plasma torch. This plasma torch consists of co-axial mounted refractory metal lined copper electrodes, which are water cooled. A stainless steel body houses the co-axially mounted electrodes along with the water cooling channels and gas flowing conduits, carved out of high temperature plastic such as Vespel™. A self sustaining plasma column is established between a tubular cathode and a tubular shaped anode and is stabilised using gas vortex generators. Similar to the Minigun design, this plasma torch design does not require any external magnetic fields to stabilize the arc column. Powered from a DC source, this plasma torch works with any oxygen free inert gas, such as argon, nitrogen, helium and/or a mixture of the above gases, as the plasma forming gas. Similar to the Minigun design, the maximum gross power of this plasma torch is dependent upon the working gas used i.e., if pure argon is used as the plasma forming gas then this torch can delivery a maximum power of 80 kW however, if a mixture of argon and hydrogen is used as the plasma forming gas, under similar operating conditions, it can deliver a maximum gross power of 100 kW.

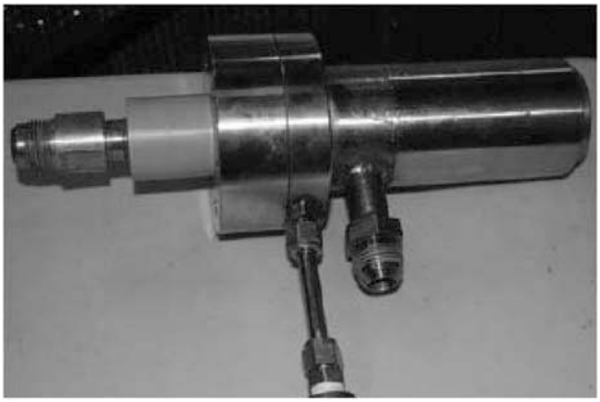

Figure 1 – A picture of the assembled reverse polarity high enthalpy plasma torch

The RPT™ plasma torch design offers many advantages such as:

i) high thermal efficiency reaching up to 70%,
ii) a wide range of torch power turn down ratio ranging from 5 kW gross power to 80 kW gross power,
iii) long electrode life with electrodes lasting over 1000 hrs,
iv) low erosion rates, on the order of 0.01 ng/C at 40 kW, making it ideal for high purity material production
v) ability to run on many inert gases and their mixtures, and
vi) high enthalpy plasma plume, almost double that of the Minigun™.

Figure 2 shows a graph of plasma torch gross power vs. plasma plume enthalpy for pure argon as the plasma forming gas. As shown in Figure 2, when operated with pure argon as working gas, this plasma torch can be operated at high plasma plume enthalpy above 5.6E+06 J/kg up to 1.7E+07 J/kg. This feature of this plasma torch design is used for applications which require higher plasma plume enthalpies such as the production of carbon nano tubes (CNT's) [5,6].

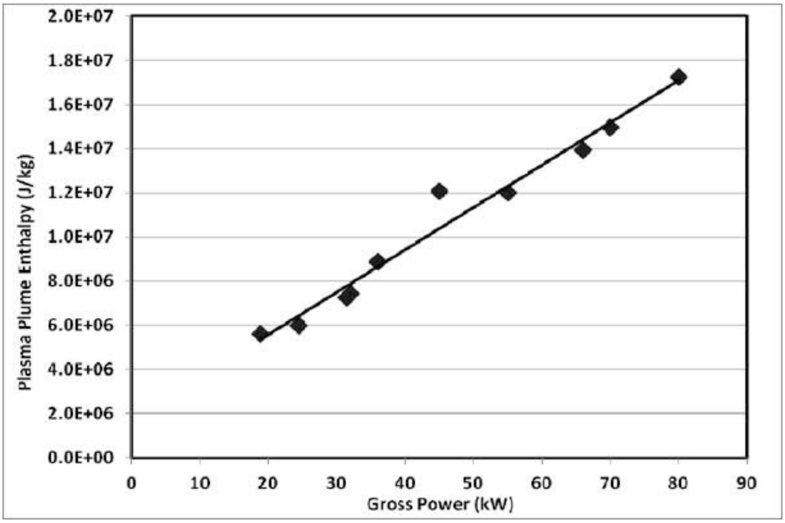

Figure 2 – Gross Power vs. Plasma Plume Enthalpy for reverse polarity high polarity plasma torch with pure argon as the plasma forming gas.

This RPT™, because of its ability to provide high plasma plume enthalpies, is chiefly employed in applications which require very high energy densities such as production on CNT's, fullerenes, nano metallic powders and in small scale waste treatment applications, and research and development applications. For example, Figure 3 shows as example of spherical metallic powders produced using the RPT [7].

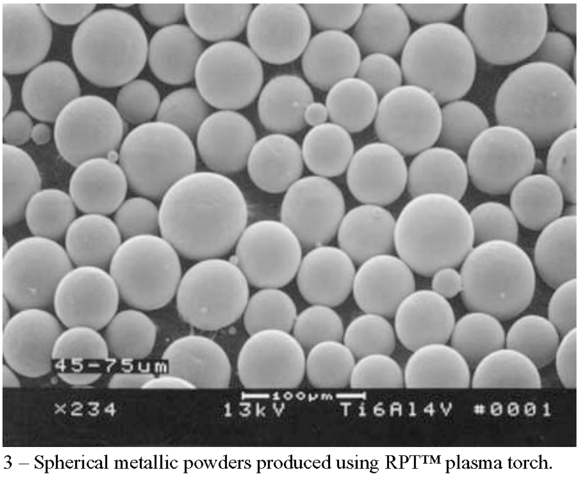

Figure 3 – Spherical metallic powders produced using RPT™ plasma torch.

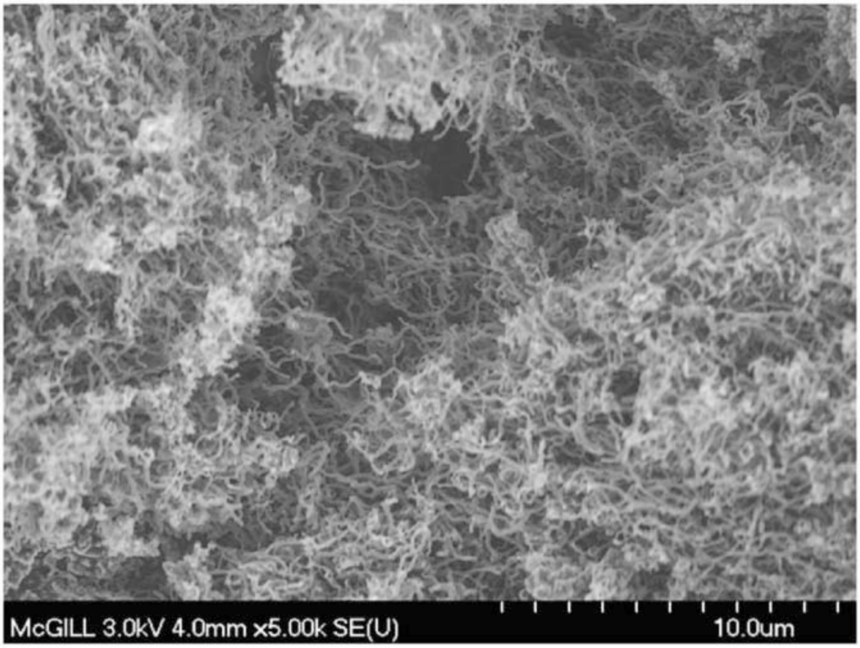

Figure 4 – Carbon nanotubes produced with an RPT torch (Photo courtesy of McGill University)

AIR PLASMA TORCH (APT™) DESIGN, CHARACTERISTICS AND TYPICAL APPLICATIONS

Figure 5 shows a picture of the assembled air plasma torch. This plasma torch consists of three electrodes namely, a pen shaped refractory metal lined copper cathode, a tubular copper ignition electrode and a tubular copper anode. All three electrodes are water cooled using high pressure deionised water flowing in a closed circuit. A stainless steel body houses the co-axially mounted electrodes along with the water cooling channels and gas flowing conduits, carved out of high temperature plastic such as Ultem™. A self sustaining plasma column is ignited between the cathode and the ignition electrode and is transferred to the working anode. Any oxygen free inert gas such nitrogen and/or argon is used as a shroud gas to protect the refractory metal lined cathode. The main plasma forming which is air is introduced between the ignition electrode and the working anode, through a swirl generator, consisting of tangentially drilled holes. The shroud gas typically represents 10% by volume of the main plasma forming gas. Powered by a DC source, this plasma torch typically works with compressed air as the main plasma forming gas.

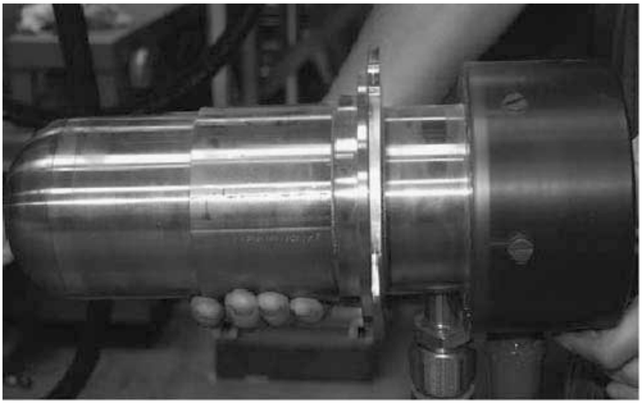

Figure 5 – A picture of the assembled air plasma torch

This plasma torch design offers many advantages such as:

i) high thermal efficiency reaching up to 70%,

ii) a wide range of torch power turn down ratio ranging from 50 kW gross power to 500 kW gross power,

iii) long electrode life with electrodes lasting over 1000 hrs for the cathode and ignition anode, 600 hours for the main anode

Figure 6 shows a graph of the plasma torch gross power vs. plasma plume enthalpy. As shown in Figure 6, this plasma torch design offers various ranges of plasma plume enthalpy, ranging form 2 to 4 kWh/kg, running on air as the plasma forming gas. Hence, depending on process requirement, enthalpy could be doubled.

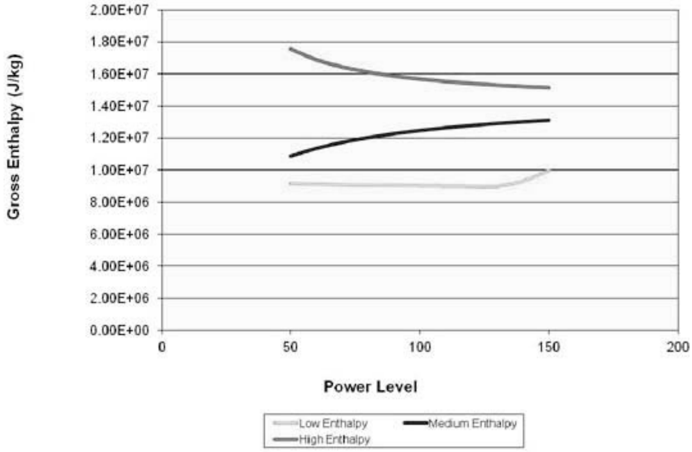

Figure 6 – Gross Power vs. Plasma Plume Enthalpy for air plasma torch.

This plasma torch design was originally developed for waste treatment applications from PCI. PCI has successfully used this plasma torch design in its Plasma Arc Waste Destruction System (PAWDS) and in Plasma Resource Recovery Systems (PRRS) for waste combustion and waste to energy applications respectively (Heberlein and Murphy, 2008). In addition to its application for waste treatment, this plasma torch system can be used for other applications such as gas heating [4], plasma assisted ignition and combustion of coal [8], plasma melting, scrap melting [9], ladle heating, chemical synthesis and plasma cutting and welding applications [1].

STEAM PLASMA TORCH AND TYPICAL APPLICATIONS OF STEAM PLASMA TORCH

This plasma torch consists of three electrodes namely, a pen shaped refractory metal lined copper cathode, a tubular copper ignition electrode and a tubular copper anode. All three electrodes are water cooled using high pressure deionised water flowing in a closed circuit. A stainless steel body houses the co-axially mounted electrodes along with the water cooling channels and gas flowing conduits, carved out of high temperature plastic such as Ultem™. A self sustaining plasma column is ignited between the cathode and the ignition electrode and is transferred to the working anode. Any oxygen free inert gas such nitrogen and/or argon is used as a shroud gas to protect the refractory metal lined cathode. The steam plasma torch is ignited on air and then gradually switched to steam torch. The main plasma forming is introduced between the ignition electrode and the working anode, through a swirl generator, consisting of tangentially drilled holes. Powered from a DC source, this plasma torch works with super heated steam as the plasma forming gas and can operated between 50 kW to 150 kW gross power.

This plasma torch design offers many advantages such as:

i) a wide range of torch power turn down ratio ranging from 50 kW gross power to 150 kW gross power,

ii) long electrode life with electrodes lasting over 200 hrs for the anode and 1000 hrs for the ignition electrode and the cathode.

This plasma torch design was originally developed for destruction of hard to destroy hazardous substances such as halogenated hydrocarbons such as chlorofluorocarbons and brominated hydrocarbons. PCI has successful demonstrated that the steam plasma torch can be used to destroy R-12 refrigerants to a destruction and removal efficiency of 99.9999%. Other potential applications of steam plasma torch include, steam reforming [10], coal gasification, steam arc cutting [11], rapid decontamination of large surfaces [12] etc.

ADVANTAGES OF PLASMA TORCHES OVER CONVENTIONAL BURNERS

As demonstrated previously, plasma torches offer high energy densities making them suitable in a wide variety of applications. In addition, they can be retrofitted in applications where fossil fuel burners are used to provide heat to a process, with the advantages of lower operating costs and greenhouse gas emissions.

With the current and forecasted increases in oil prices, there is growing interest in solutions that allow replacing the expensive fuel with more economic alternatives. In this context, plasma torches offer a very interesting option since they use electricity as a source of energy. Table 1 shows the operating costs of a 2 MW net fuel oil burner (bunker C or fuel oil no. 6) vs. a 2 MW net air plasma torch. As can be seen, there is a significant reduction in operating costs with the use of an air plasma torch. Considering applications such as iron ore pellet induration furnaces, cement kilns and various metallic ore roasters, which usually include multiple burners and sometimes more than 100 burners per plant, the costs savings becomes even more interesting.

Table 1 – Operating costs of a 2 MW net bunker C burner vs. an air plasma torch

	Fuel Oil Burner	Plasma Torch
Fuel Oil Cost ($0.5/L)	$ 923,000	$0
Electricity Cost ($0.03/kWh)	$ 9,000	$600,000
Replacement Parts Cost	$ 0	$38,000
Total	$ 932,000	$638,000
% Reduction		32%

Although the use of a plasma torch increases the global electricity cost, it reduces the electrical power required by the off-gas treatment system (exhaust fans, scrubbers, particulate filters) because the off-gas flow rate is much lower than with a burner. Indeed, there is about an 80% off-gas flow rate reduction when using a plasma torch instead of a burner. Not only does this reduce operating costs of the off-gas treatment system in existing plants, it also reduces the capital cost for future plants because a smaller and less complex off-gas treatment system can be purchased.

In addition to the important costs incurred by the operation of a fuel oil burner, there is also a large amount of greenhouse gases (GHG) that is emitted due to the combustion of non renewable fossil fuel. With the increasing concerns towards the emission of GHG and the establishment of emissions trading programs (cap-and-trade) all over the world, solutions that also allow the reduction of GHG emissions are of particular interest. Depending on how it is produced, the use of electricity as a source of energy, as is the case for plasma torches, represents a great potential to reduce GHG emissions. While a bunker C fuel oil burner emits about 115 kg of carbon dioxide equivalents (CO_2e) per gigajoule of net energy considering the combustion of the fuel as well as its extraction, production and distribution, a plasma torch powered with electricity generated by hydropower emits only about 1 kg CO_2e/GJ. Therefore, for a 2 MW plasma torch retrofitted in place of a burner, this would lead to yearly reductions of more than 7,000 metric tonnes of CO_2e. Again, considering there can be more than 100 of these burners per plant, the GHG reductions are even more interesting.

CONCLUSIONS

An overview of PyroGenesis DC torches and their applications was presented for use in waste treatment, production of high purity metals, and nanomaterials.

The RPT™ provides twice the enthalpy level of the Minigun™ and also runs with any non oxygen containing gas as a plasma forming gas. It boasts very low erosion rates, making it very useful in the production of high purity materials.

The APT™ was originally developed for waste treatment. It typically uses air as the main plasma forming gas, but, due to the use of a shroud gas for the cathode, allows for a wide choice of plasma forming gas, including oxidizing gases. In addition to its application for waste treatment, this plasma torch system can be used for other applications such as gas heating, plasma assisted ignition and combustion, plasma melting, scrap melting, ladle heating, and chemical synthesis.

The SPT™ uses steam (water vapour) as the main plasma forming gas. The high reactivity of the hydroxyl ions produced by the ionization of steam allows for the destruction of highly stable hazardous substances such as chlorofluorocarbons and brominated hydrocarbons. Other applications of steam plasma include: steam reforming, coal gasification, steam arc cutting, and rapid decontamination of large surfaces.

The replacement of fuel oil burners by plasma torches provides considerable operating costs reduction for existing plants as well as a capital cost reduction for future plants. The off-gas flow rate generated by a plasma torch being much less than that generated by a burner, the off-gas treatment system can be downsized significantly. In addition, plasma torches allow a major GHG reduction by avoiding the combustion of substantial amounts of fossil fuel in burners.

REFERENCES

1. Venkataramani N, "Industrial Plasma Torches and Applications," *Current Science,* 83 (3) (2002).

2. Joachim V. Heberlein, and Anthony B. Murphy, "Thermal plasma waste treatment", *J. Phys. D: Appl. Phys,* 41 (2008).

3. Maher I. Boulos, Pierre Fauchais, and Emil Pfender, *Thermal Plasmas : fundamentals and applications Volume 1* (New York, Plenum Press, 1994) 452.

4. S. L. Camacho, "Industrial-Worthy Plasma Torches: State of the Art," *Pure and Applied Chemistry*, 60 (5) (1988), 619-632.

5. D. Harbec, et al.,"Carbon nanotubes from the dissociation of C2Cl4 using a dc thermal plasma torch," *J. Phys. D: Appl. Phys,* 37 (2004), 2121–2126.

6. David Harbec, and Jean-Luc Meunier, "Growth of carbon nanotubes above the peritectic temperature of tungsten metal catalyst," *Carbon*, 49 (7) (2011), 2206-2215.

7. M.E Smagorinski, and Peter G. Tsanrizos, "Production of Spherical Titanium Powder by Plasma Atomization", *Proceedings of PM2TEC Conference*, (2002), 3-248 – 3-260.

8. J. Sligar, "Plasma Ignition of Pulverised Coal," *Proceedings of the 25th Intersociety Energy Conversion Engineering Conference*, (1990) 454 - 458.

9. K.U. Maske. and Nic A. Barcza, "Recent Development In Pyrometallurgical Plasma Technology," *Conference: Innovation In Processing Ores and Scraps* (1983)

10. X. Zhu, et al., "Plasma steam reforming of E85 for hydrogen rich gas production," *J. Phys. D: Appl. Phys.* 44 (2011)

11. H. Pauser, J. Laimer, , and H. Stori, "Steam Plasma Arc Cutting." *IEEE International Conference on Plasma Science*, (1999), 319.

12. L. C. Farrar, et al., "Rapid Decontamination of Large Surface Areas," *IEEE Transactions on Plasma Science*, 28 (1) (2000).