



7th International Workshop and Exhibition on Plasma Assisted Combustion (IWE PAC)

13-15 September 2011
Excalibur-Hotel & Casino
Las Vegas, Nevada, USA

International Plasma Technology Center
www.plasmacombustion.org

Sponsored by Applied Plasma Technologies, LLC
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Synopsis

IWEPAC-7 will have eight separate sessions: (1) plasma generation, diagnostics, and modeling; (2) plasma ignition and flame control; (3) fuel activation and reformation; (4) plasma kinetics and flow dynamics; (5) coal, bio-mass, and waste into energy processing; (6) water treatment; (7) power sources; and (8) new plasma effects and prospective applications. Each section will be followed by a round table session to facilitate discussions on prospective directions of activity and the creation of international research collaborations for joint project development and implementation.

IWEPAC-7 is expected to have from 30 to 35 oral presentations (30 minutes in duration, including questions and answers), and from 10 to 20 poster presentations.

IWEPAC-7 pioneers a new form of participation – **Electronic Posters**. This is a way for workshop non-attendees to still participate by submitting an abstract and PowerPoint presentation file. For a fee of \$155, abstracts and presentation files will be included in the workshop proceedings and the authors will receive a copy of the proceedings.

IWEPAC-7 will be hosted by the International Plasma Technology Center (IPTC), sponsored by Applied Plasma Technologies, LLC, and held September 13 to 15, 2011 in the **Excalibur-Hotel, 3850 Las Vegas Blvd South, Las Vegas, NV 89109 USA**.

During the workshop, we plan to honor new members of the International Council of Experts in the field of PAC, announce new international projects and research teams, provide support to junior scientists, and select papers for publication in the IEEE Transactions on Plasma Science Special Issue on Plasma-Assisted Combustion. IWEPAC-7 proceedings will be available in two formats: a color booklet with abstracts and an after-meeting memory stick. The cost is included in the registration fee.

IWEPAC-7 has two new sessions – water treatment and power sources. This reflects our transition. From the workshop presentations and associated discussions, it is clear that many attendees desire that the Workshop grow into a broader venue, that is, expanding the sessions to cover more areas for the application of plasma technologies. IWEPAC attendees are prolific idea generators. They see that the same or similar plasma devices that are applied to PAC could be applied in new areas and even with much higher commercial potential and/or faster implementation. So, to that end, we are expanding the coverage of IWEPAC to include other plasma technology applications and have changed the name of the workshop to the International Conference on Plasma Assisted Technologies (ICPAT). We realize that there are many plasma conferences held around the world. However, most of those tend to preferentially concentrate on fundamental research and de-emphasize technological applications to a great extent. We wish to be different: ICPAT is meant to include fundamental research, but will emphasize technology, particularly as it applies to commercial applications. We believe that this will distinguish ICPAT from other conferences and provide a unique forum for the ‘nuts and bolts’ of plasma-assisted R & D, while preserving the core idea of IWEPAC – namely an emphasis on the scientific chain from ideas and fundamentals to practical applications.

ICPAT (2012) sessions/topics

1. Plasma Generation, Diagnostics, and Modeling
2. Plasma Ignition and Flame Control
3. Fuel Reformulation and Activation
4. Plasma Kinetics
5. Plasma Flow Dynamics
6. Plasma Propulsion
7. Power sources/power supplies/modulators
8. Air quality control
9. Water treatment
10. Coal, bio-mass, and waste processing
11. Clean energy production
12. New materials – sintering, modification, and processing
13. New plasma effects and prospective applications
14. Business forum

IWEPAC – 7

Tentative Agenda

Monday, 12 September

16.00 – 18.00

Registration: Excalibur-Hotel, Lobby
3850 Las Vegas Blvd South, Las Vegas, NV 89109 USA
Phone: 1-877-750-5464, <http://www.excalibur.com/hotel>

Tuesday, 13 September

8.30 – 9.00

Registration: Luxembourg Room

9.00 – 9.30

IWEPAC-7 OPENING

Welcome remarks from:

- *Dr. Igor Matveev* (Applied Plasma Technologies, LLC)
- *Dr. Louis Rosocha* (Los Alamos National Laboratory, DOE and Applied Physics Consulting)

Announcements

9.30 – 12.15

PLASMA GENERATION, DIAGNOSTICS, AND MODELING

Chaired by *Dr. Igor Matveev*, Applied Plasma Technologies, LLC; USA

9.30 – 10.00

Thermal Plasma Jet Generated by Gas-Water Torch: Properties and Applications

Prof. M. Hrabovsky, Dr. M. Konrad, V. Kopecky, Dr. T. Kavka, O. Chumak, V. Sember, A. Maslani (Institute of Plasma Physics AS CR, Czech Republic)

10.00 – 10.30

High Efficient Vortex Steam Plasma Torch – Preliminary Study

Dr. L. Charokhovski, A. Marquesi, Prof. Ch. Otani, G. Petraconi Filho, R. Bicudo, A.S. da Silva Sobrinho, M. Massi, Dr. A. V. Gorbunov (Technological Institute of Aeronautics, Brazil)

Prof. H.S. Maciel (Instituto de Pesquisa e Desenvolvimento-IP&D/UNIVAP, Brazil)

10.30– 11.00

Analysis of Transport Properties of Contaminated Plasmas in 300 kW Transferred Arc DC Reactor Under Gasification and Vitrification of High-Ash Fuels and Wastes

Dr. A. V. Gorbunov, Prof. H.S. Maciel, A.F. Bublikovsky, S.I. Kas'kova, V.A. Gorbunova, A.A. Galinovsky (Technological Institute of Aeronautics, Brazil)

11.00 – 11.15	Break
11.15 – 11.45	Some Results of High Power Atmospheric Pressure RF Torches Development <i>Dr. Igor Matveev, S. Matveyeva</i> (Applied Plasma Technologies, LLC; USA) <i>Dr. S.G. Zverev</i> (Saint-Petersburg State Polytechnic University, Russia)
11.45 – 12.15	Round Table on Plasma Generation, Diagnostics, and Modeling
12.15 – 15.45	PLASMA IGNITION AND FLAME CONTROL Chaired by <i>Prof. Homero S. Maciel</i> , Technological Institute of Aeronautics, Brazil
12.15 – 12.45	Ionization and Energy Deposition in Pulsed Nanosecond Discharges in the Filamentary Regime at Different Pressures and Temperatures <i>C. Guerra Garcia, Dr. M. Martinez Sanchez</i> (Aeronautics and Astronautics Department, Massachusetts Institute of Technology, USA)
12.45 – 13.45	Lunch
13.45 – 14.15	Supersonic Ignition System Utilizing Gliding Arc Plasma <i>Hadade Neto, A. C. Pereira Filho, Prof. H. S. Maciel, M. Médici</i> (Turbotronic Tecnologia; IEAv – Instituto de Estudos Avançado; ITA – Instituto Tecnológico de Aeronáutica, Brazil)
14.15 – 14.45	Development of the Convective Cooling System for the Gas Turbine Plasma Assisted Combustor <i>Prof. Serhiy Serbin, Dr. Anna Mostipanenka, Kateryna Serbina</i> (National University of Shipbuilding, Ukraine) <i>Dr. Igor Matveev</i> (Applied Plasma Technologies, LLC; USA)
14.45 – 15.15	Ultra Lean Burn Combustion via Nanosecond Discharge Plasma Ignition <i>Lonnie Lenarduzzi</i> (Plasmatronics, LLC; USA)
15.15 – 15.45	Round Table on Plasma Ignition and Flame Control
15.45 – 16.00	Break

16.00 – 17.30

FUEL ACTIVATION AND REFORMATION

Chaired by *Prof. Serhiy I. Serbin*, National University of Shipbuilding, Ukraine

16.00 – 16.30 **Efficient Conversion of CO₂ to CO by Novel Plasma Method**

Dr. Louis Rosocha, Dr. Yong Ho Kim (Los Alamos National Laboratory, USA)

Prof. Yuri Korolev (Institute of High Current Electronics, Russia)

16.30 – 17.00 **Methane Oxidation in a Plasma Torch of Nonsteady State Plasmatron**

Prof. Yu.D. Korolev, O.B. Frants, S.I. Galanov, O.I. Sidorova, V.S. Kasyanov (Institute of High Current Electronics, Russia)

Dr. Y. Kim, Dr. L.A. Rosocha (Los Alamos National Laboratory, USA)

Dr. Igor Matveev (Applied Plasma Technologies, LLC, USA)

17.00 – 17.30 Round Table on Fuel Activation and Reformation

18.00 – 22.00 Welcome Reception (Kent Hall)

Wednesday, 14 September

9.00 – 10.30

PLASMA KINETICS AND FLOW DYNAMICS

Dr. Louis Rosocha, Los Alamos National Laboratory, DOE and Applied Physics Consulting

9.00 – 9.30 **Kinetics and Plasma Chemistry of Nanosecond Pulse Discharges and Fast Ionization Wave Discharges**

Dr. Keisuke Takashima, Prof. Igor V. Adamovich (Department of Mechanical and Aerospace Engineering The Ohio State University, USA)

9.30 – 10.00 **Development of Synthesis Gas Afterburner Based on Injector Type Plasma Assisted Combustion System**

Prof. Serhiy Serbin, Serhiy Vilkul (National University of Shipbuilding, Ukraine)

Dr. Igor Matveev (Applied Plasma Technologies, LLC; USA)

10.00 – 10.30 Round Table on Plasma Kinetics and Flow Dynamics

10.30 – 10.45 Break

10.45 – 15.15

COAL, BIO-MASS, AND WASTE INTO ENERGY PROCESSING

Chaired by *Dr. Edberto Leal-Quiros*, University of California, USA

10.45 – 11.15 **Gasification of Pyrolytic Oil from Scrap Tires by Thermal Plasma**

Prof. M. Hrabovsky, Dr. M. Konrad, M. Hlina, Dr. T. Kavka, O. Zivny, O. Chumak, A. Maslani (Institute of Plasma Physics AS CR, Czech Republic)

11.15 – 11.45 **Production of Synthesis Gas with Atmospheric Pressure Plasma Processing of Coffee Grounds (Borra de Café) and Other Organic Waste**

Dr. E. Leal-Quiros, G. Diaz, N. Sharma, S. Pineda, S. Fleming, I. Hussein, A. Robles (University of California, USA)

11.45 – 12.15 **Features of the Working Process in Three-Stage Plasma Coal Gasification System**

Prof. Serhiy Serbin, Nataliia Goncharova (National University of Shipbuilding, Ukraine)

Dr. Igor Matveev (Applied Plasma Technologies, LLC; USA)

12.15 – 13.15 Lunch

13.15 – 13.45 **Thermochemical Assessment of Arc Plasma Gasification Efficiency for Brazilian Subbituminous Coal and Related Feedstock**

Prof. H. S. Maciel (Institute for Research and Development – IP&D/UNIVAP, Brazil)

Dr. A. V. Gorbunov, A.R. Marquesi, Prof. P.T. Lacava (Technological Institute of Aeronautics, Brazil)

13.45 – 14.15 **Effect of Gas Dynamic Mixing of Thermal Plasma Jets with Spray of Coal Slurry / Hydrocarbon-Based Feedstock on the Operation of Plasma Gasifier System**

Dr. A. V. Gorbunov, A.R. Marquesi, Prof. C. Otani (Technological Institute of Aeronautics (ITA), Brazil)

Prof. H. S. Maciel (Institute for Research and Development – IP&D/UNIVAP, Brazil)

A.A. Galinovsky, V.A. Gorbunova (Belarus State Technological University, Minsk, Belarus)

14.15 – 14.45 **Plasma Coal Burner**

Dr. Igor Matveev (Applied Plasma Technologies, LLC; USA)

14.45 – 15.15 Round Table on Coal, Bio-Mass, and Waste into Energy Processing

15.15 – 15.30 Break

15.30 – 17.30

WATER TREATMENT

Chaired by *Dr. Isaiah Blankson*, NASA Glenn Research Center, USA

15.30 – 16.00 **An Overview of Water Treatment by Plasmas – Advanced Oxidation/Reduction Technologies AO/RTs**

Dr. Louis Rosocha (Applied Physics Consulting, USA)

16.00 – 16.30 **Non-Equilibrium Plasma Applications for Water Purification Supporting Human Spaceflight and Terrestrial Point-of-Use: Organic Chemical Decomposition via HV Nanosecond Plasma Discharge**

Dr. Isaiah Blankson (NASA Glenn Research Center, USA)

Dr. John E. Foster (University of Michigan, USA)

16.30 – 17.00 **Water Treatment and Power Co-Generation Using Hydro-Thermal, Supercritical Water Produced by Pulsed Electric Discharges**

Dr. W. Lowell Morgan (Kinema Research & Software, LLC; USA)

Dr. Louis A. Rosocha (Applied Physics Consulting, USA)

17.00 – 17.30 Round Table on Water Treatment

Thursday, 15 September

9.00 – 11.45

POWER SOURCES

Chaired by *Prof. Yuri Korolev*, Institute of High Current Electronics, Russia

9.00 – 9.30 **Power Supply for Discharges in Gas Flow**

Prof. Yu.D. Korolev, V.G. Geyman, O.B. Frants, V.A. Panarin, S.B. Alekseev (Institute of High Current Electronics, Russia)

Dr. Y. Kim, Dr. L.A. Rosocha (Los Alamos National Laboratory, USA)

C. Cassarino, T. Frambes (Leonardo Technologies, Inc.; USA)

9.30 – 10.00 **Power Supplies for Non-Thermal Torches**

Dr. Igor Matveev (Applied Plasma Technologies, LLC; USA)

Sergey Zakharov (ZS Systems, LLC; USA)

10.00 – 10.15	Break
10.15 – 10.45	An Overview of Recent Innovations in Power Sources for Advanced Plasma Processes <i>Dr. Pawel Grabowski</i> (HUETTINGER Electronic Inc.; USA)
10.45 – 11.15	Main Requirements to Prospective Power Supplies for High Power 1+ Bar Pressure RF Torches <i>Dr. Igor Matveev, Evgeniy Petrov</i> (Applied Plasma Technologies, LLC; USA)
11.15 – 11.45	Round Table on Power Sources
11.45 – 12.00	Break
12.00 – 15.00	NEW PLASMA EFFECTS AND PROSPECTIVE APPLICATIONS Chaired by <i>Dr. Rajan Bamola</i> , Surface Modification Systems, Inc., USA
12.00 – 12.30	Current Status of Plasma Spray Coatings <i>Dr. Rajan Bamola, Dr. Vasudevan Srinivasan</i> (Surface Modification Systems, Inc., USA)
12.30 – 13.00	Advantages of High Pressure RF Torches with Reverse Vortex Stabilization for Plasma Sprayed Coating and Powders Treatment <i>Dr. Igor Matveev</i> (Applied Plasma Technologies, LLC; USA) <i>Prof. Serhiy Serbin</i> (National University of Shipbuilding, Ukraine)
13.00 – 14.00	Lunch
14.00 – 14.30	Matching Electric Power to Processing <i>Dr. E.J.M. van Heesch, A.J.M. Pemen, F.J.CM. Beckers, W.F.L.M. Hoben, K. Yan, G.J.J. Winards</i> (Eindhoven University of Technology, Netherlands)
14.30 – 15.00	Round Table on New Plasma Effects and Prospective Applications
15.00 – 16.00	DISCUSSIONS, NEGOTIATIONS Conference Closing
ELECTRONIC POSTERS	
	Non-Selfmaintained Gas Discharge Ignition System for Impact on Flammable Gas Mixtures <i>Prof. V. L. Bychkov et al</i>
	Experiments With Discharge Created Fireballs <i>Prof. V. L. Bychkov et al</i>

Thermal Plasma Jet Generated by Gas-Water Torch: Properties and Applications

*Prof. M. Hrabovsky, Dr. M. Konrad, V. Kopecky, Dr. T. Kavka, O. Chumak, V. Sember, A. Maslani
Institute of Plasma Physics AS CR, Prague, Czech Republic*

Introduction

Thermal plasmas are commonly generated either in non- transferred dc electric arcs that are stabilized by flowing gas, or in inductively coupled discharges.

Averaged temperatures in torches with gas stabilization are usually in the range from 8 000 K to 16 000 K [1]. Average plasma enthalpies vary from 1 to 100 MJ/kg. Further increase of plasma temperatures and enthalpies is limited, as flowing gas protects the arc chamber walls from thermal overloading and thus a minimum possible gas flow rate exists for given arc power. Higher thermal loading is possible if the walls are created by liquid and an arc is stabilized by wall evaporation. Liquid-stabilized arcs can be utilized as sources of thermal plasmas with extremely high temperatures and enthalpies. Besides apparent advantage that no gas supply is needed, there are many other differences between gas and liquid generators in plasma processes, plasma properties and especially in performance characteristics in plasma processing.

The arc with the stabilization of arc column by water vortex was first described about ninety years ago by Gerdien and Lotz [2]. Basic experimental investigations of water stabilized (Gerdien) arcs were performed in the fifties of the last century. By means of emission spectroscopy the authors have found very high plasma temperatures in the arc column, with up to 50 000 K in the centerline position. The principle of arc stabilization by water vortex was utilized in the plasma torch designed for plasma spraying and cutting [3]. In the last decades water-stabilized arcs have been intensively investigated and basic processes in the arc column have been described [4,5].

The new type of torch with combination of gas and water vortex arc stabilization (hybrid torch) was designed to widen torch operation characteristics, mainly to increase plasma mass flow rate, plasma velocity, and plasma density.

Basic processes in DC Gerdien arc and properties of plasma jet

The properties of the generating plasma jet are given by the processes in the arc chamber of a torch. Scheme of a dc plasma torch with Gerdien arc is in Fig.1. The arc chamber is divided into several sections, where water vortex is created by tangential injection of water. Cathode is consumable graphite rod, copper anode with internal cooling rotates to reduce electrode erosion.

The plasma is produced by absorption of radial heat flux from arc core in water wall. The water is evaporated, heated, ionized and overpressure of steam (hydrogen – oxygen) plasma moves the plasma to the exit nozzle. Plasma flows into the ambient atmosphere as a plasma jet. The decisive processes are mechanisms of radial energy transport to the water wall and the heat utilization for evaporation and ionization.

Specific characteristics of plasma jets generated by Gerdien arc are given by two factors:

- 1) Material properties of steam plasma, mainly high thermal conductivity, high enthalpy and sound velocity at given temperature compared to other gases.
- 2) Mechanism of plasma formation – low fraction of total radial heat flux is spent for

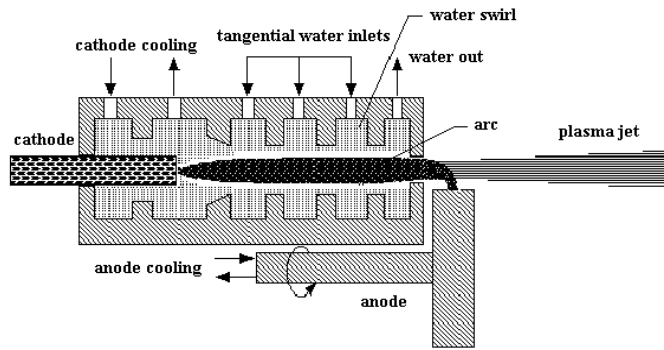


Fig. 1. Scheme of plasma torch with Gerdien arc

evaporation, while absorption of heat in vapor is relatively high. This leads to low mass flow rate of plasma, on the other hand to very high temperature (therefore to high plasma enthalpy) and high velocity of plasma flow. The radial inflow of steam plasma constricts the arc channel and also increases plasma temperature.

Basic parameters of the torch and comparison to other plasma media are in Table 1.

Table 1. Parameters of DC arc torches for different plasma media.

Plasma gas	I, A	P, kW	G, g/s	T_b , K	H_b , MJ/kg
H ₂ O	300	84	0.2	15800	252
H ₂ O	600	176	0.33	17500	320
N ₂	700	180	40	3000	3.6
Ar/H ₂ (33/10)	750	25	0.98	12100	13.5

I - current, U - arc voltage, G - plasma mass flow rate, T_b - plasma bulk temperature, H_b - plasma bulk enthalpy

The measured radial profiles of temperature at the vicinity of torch nozzle and dependence of plasma velocity on axial distance from nozzle for different arc currents are given in Fig. 2a and Fig. 2b.

The need to cover the region of operation parameters between gas and water torches has lead to the design of hybrid torch.

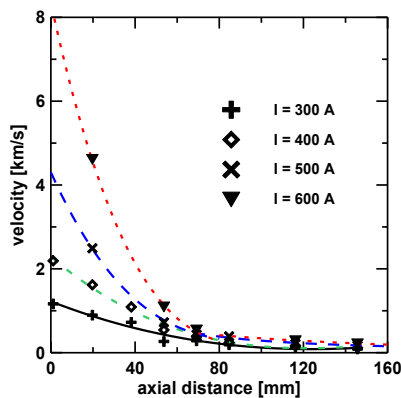


Fig. 2a. Radial profiles of plasma temperature

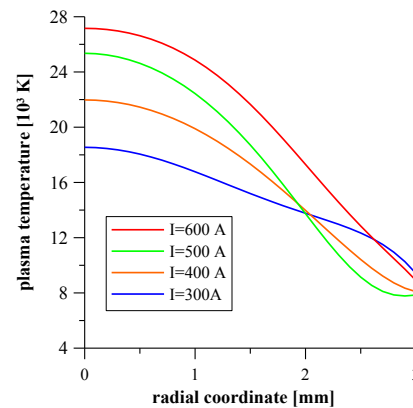


Fig. 2b. Plasma velocity vs distance from nozzle

Hybrid plasma torch

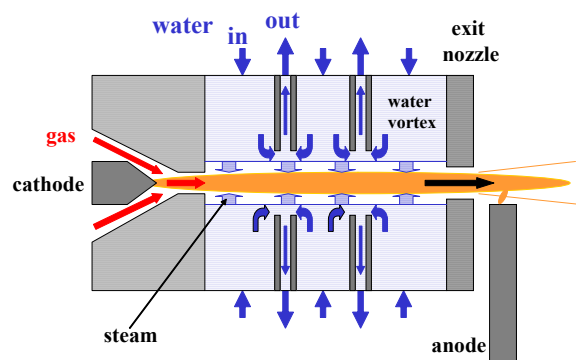


Fig. 3. Scheme of hybrid gas/water torch

Scheme of hybrid gas-water torch is in Fig. 3. Gas is supplied along tungsten cathode, the gas plasma flows from cathode region into second part, where arc column is surrounded by water vortex. If low enthalpy gas like argon is used, the voltage drop and power of the cathode part of arc is low and the properties of the arc are mainly given by the properties of the water stabilized part. Plasma temperature and all characteristics controlled by energy balance are close to water torch. The argon flow increases the mass flow rate of the plasma and the plasma velocity, on the other hand, the plasma temperature is slightly lower.

Technological applications of torches with water stabilization

The plasma jet generated in a torch with gas/water stabilization has been used mainly for plasma spraying. High plasma temperature, high plasma enthalpy, and low plasma density result in very high efficiency of utilization of plasma enthalpy for heating of material injected into plasma jet. Also high thermal conductivity of hydrogen/oxygen plasma is advantageous as heat fluxes to injected particles are high. The torch provides 5 to 10 times higher spraying rates than common gas torch at the same power. At power 160 kW the spraying rate is 25 - 45 kg/h for ceramics powder and 80 - 100 kg/h for metal powder. Large area coatings or production of self-supporting ceramics parts are examples of main applications.

Lately, the research of waste treatment and gasification of organic materials for syngas production has been started. The advantages are, besides the mentioned ones for plasma spraying, high level of turbulence (intensive mixing with treated material) and ideal plasma composition.

Acknowledgement. The work was supported by the Grant Agency of the Czech Republic under the project P 205/11/2070.

References

- [1] P. Fauchais, A. Vardelle, "Thermal plasmas," *IEEE Trans. on Plasma Science*, vol. 25, pp. 1258-1280, 1997.
- [2] H. Gerdien, A. Lotz, "Wasserstabilisierter Lichtbogen," *Wiss. Veroeffentlichungen Siemenswerk*, vol. 2, pp. 489-492, 1922.
- [3] B. Gross, B. Grycz, K. Miklossy, *Plasma Technology*, London: Illife Books Ltd., 1968.
- [4] M. Hrabovsky et al., "Processes and Properties of Electric Arc Stabilized by Water Vortex," *IEEE Trans. on Plasma Science*, vol. 25, pp. 833-839, 1997.
- [5] M. Hrabovsky et al., "Properties of Hybrid Water/Gas DC Arc Plasma Torch," *IEEE Trans. on Plasma Science*, vol. 34, pp. 1566-1575, 2006.

High-Efficient Vortex Steam Plasma Torch-Preliminary Study

*Dr. L. Charakhovski, A. Marquesi, Prof. Ch. Otani, G. Petraconi Filho, R. Bicudo, A.S. da Silva Sobrinho, M. Massi, A. Gorbunov
Instituto Tecnológico de Aeronáutica (ITA), S. Jose dos Campos, Brazil*

Prof. H.S. Maciel

Instituto de Pesquisa e Desenvolvimento - IP&D/UNIVAP, S. Jose dos Campos, Brazil

Due to unique properties – high enthalpy, oxidizing-reducing nature, ecological compatibility, not scarce resources, etc., water plasma is very suitable for many applications [1]. Among different types of plasma generators vortex plasma torches are the best by their

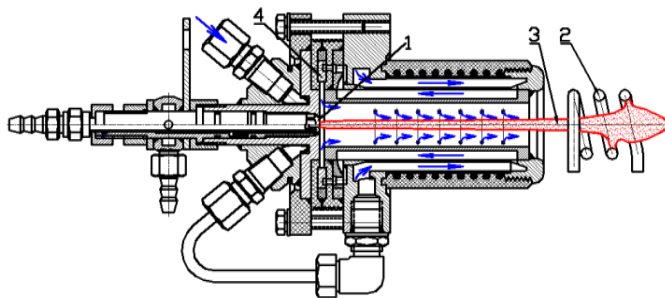


Fig. 1. Torch W1 with distributed injection of gas at smooth channel:

1 - cathode, 2 - anode, 3 – arc, 4 - vortex chamber

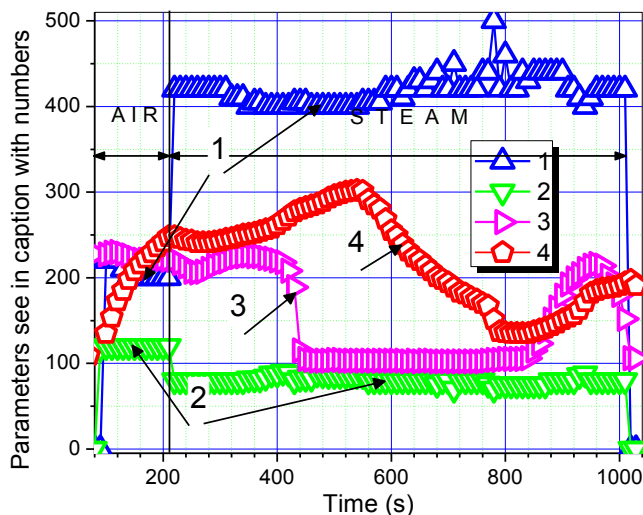


Fig.2. Data acquisition during testing of torch. 1 – arc tension, V; 2 – arc current, A; 3 – steam temperature at inlet of plasma torch; 4 – steam temperature in vortex chamber

energetic characteristics. Vortex flows are possessed by active stabilizing and thermal-insulating effect on electric arc and therefore applied widely in vortex plasma torches. This effect appears owing to intense centrifugal accelerations arising from the fast-rotating gas in discharge channel of torch with small radius. As a result, strong radial stratification by density of gas arises at such flow. Cold and dense gas is expelled to periphery of cylindrical channel, and hot gas, including arc column, is stabilized along the axis. However turbulence and dissipation of vortex through friction give rise for gradual mixing hot and cold gas. As shown in [2] - [4], conventional diaphragmatic vortex chamber is not optimal facility for swirling gas in channel; in addition, swirling effect becomes approximate for any chamber at distance of about 6-8 diameters of channel [4]. Therefore retention of major rotational velocity along the total channel becomes very important for improvement of thermal insulation and increase of thermal efficiency. To solve this problem cylindrical channel with distributed tangential injection of gas between adjacent sections with number of vortex chambers was developed. However it was applied mainly in laboratories, but not in

industry, due to complexity and high cost of operational maintenance. In [5], [6] they applied still more complex solution - distributed swirling injection of gas along the channel together with distributed its partial exhaust from cold boundary layer so using part of gas only for maintaining intense vortex. Thereby they compensated the decrease of rotational velocity at elevated pressure by artificial increase of flow.

They attained efficiency of about 80-90% and high enthalpy; however this was done at experimental setup for testing materials and hardly is applicable for commercial technological torches. Therefore more rational appears to use smooth channel without dividing it by insulated sections and only maintaining intense swirling flow along the channel. Such approach was used in [7] for inter-electrode insertion of air plasma torch and they attained thermal efficiency of torch about 80% without application water cooling for this insert. In the present work we developed the latter approach for steam plasma torch making additional improvements for stability of vortex in smooth channel with continuously distributed injection. It is important for stability of swirl that positive gradient of density is directed from the axis towards the wall of channel. Excessive heating of wall is able to change gradient of density, provoking instability of vortex and premature arc breakdown to channel. Positive radial gradient of density arises

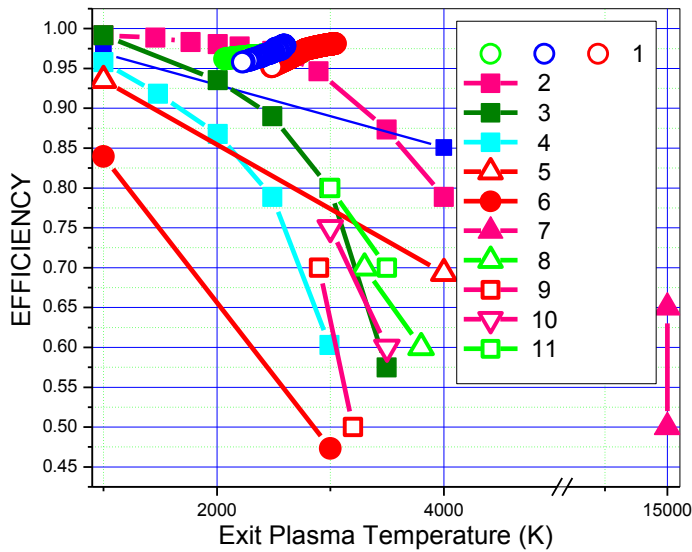


Fig.3. Comparison of efficiency of plasma torches.
1-W1; 2-WSPH-500R [8]; 3-EDP217 [8]; 4- EDP148 [8];
5-EAG-6 [8]; 6-MARC-3 [8]; 7-WSPH [9];
8-EDP217 [10]; 9-EDP166 [10]; 10-EDP211 [10];
11-EDP201[10]

due to the action of centrifugal accelerations and heating of gas in thermal boundary layer surrounding the arc. However, the walls of non-cooled channel are also being heated by arc, arc, concomitantly heating the adjacent gas. Gas flowing inside the channel is heated gradually together with the wall in downstream direction, owing to convective heat transfer. Therefore we applied counter-flow in gas-cooling jacket surrounding the channel from outside. We started injection of gas from this jacket to channel from downstream end of channel with colder gas in jacket and distributed it along the channel in direction to upstream end. At such flow organization injected upstream gas becomes hotter and layered over colder one injected before at downstream, so maintaining positive radial gradient of density inside channel and improving vortex stability. We show in Fig 1 the schematic design of the present water steam plasma torch W1 with distributed injection of steam and smooth channel. Schematic picture of distribution of steam flow inside torch is illustrated with blue arrows.

Wet steam can be used as effective coolant for steam plasma torch instead of liquid water. Generated in cooling jacket from wet steam, superheated steam can be used then as work-piece in the same plasma torch. Generation of dry steam directly from water inside cooling jacket is

very unstable process accompanied by water film disintegration, formation of superheated water drops and their intensive micro-explosions, destroying stability of vortex in channel and destabilizing arc. We have overcome this difficulty by superheating liquid water at elevated pressure and then by throttling it to atmospheric pressure, so generating wet steam with high content of liquid water in micro-dispersed state appropriate for following superheating without risk of explosions. We used therefore, for feeding the plasma torch, a special external two-stage steam generator. At first stage we heat water at pressure 1 MPa up to 130-140 °C, applying it further for throttling and superheating in second stage up to temperature about 200-300 °C at atmospheric pressure. During torch operation we were able to adjust power of the second stage in order to supply torch with superheated dry or wet steam. Torch was always started with air as working gas and then switched to steam after preheating of all parts up to temperature higher than 100 °C was achieved, so preventing condensation of steam. Diameter of discharge channel was 20 mm and its length - 100 mm. Torch was tested by using power supply with open circuit voltage 700 V and maximum current 120 A. Current-voltage characteristics are slightly descending. This torch with transferred arc was designed for operation with anode mounted inside of plasma reactor, for example, a conventional molten bath of metal or slag with bottom water-cooled electrode. For preliminary testing, instead of bath we used auxiliary solenoid-shaped anode with internal diameter 25 mm, which has been made from water-cooled copper tube of 6 mm diameter (see Fig. 1). The range of operational regimes was 90 -120A for air and 50-110 A for steam. The voltage of the arc was in the range of 180-220 V for air and 300-440 V for steam. The temperature of the main parts of torch was measured with thermocouples and recorded by acquisition system continuously during 15-30 minutes. We show in Fig.2 the example of record of the regimes during experiment. Torch was operated with air up to 200s, after that – with steam. During operation we decreased power of steam generator so that after 420 s the torch was supplied by wet steam with temperature about 100 °C, maintaining this regime up to 820 s. However steam temperature in vortex chamber was kept at level above 100 °C, a temperature high enough for the torch to maintain normal running (see Fig. 2). We show in Fig. 3 the comparison of efficiency of torch W1 with several published data. Efficiency was about 97% for this transferred torch both operating with steam and air, without anode. We plan to use a second similar torch as anode in the so-called “twin” configuration, and we believe to achieve the same efficiency as in the present case [11].

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Analysis of Transport Properties of Contaminated Plasmas in 300 kW Transferred Arc DC Reactor Under Gasification and Vitrification of High-Ash Fuels and Wastes

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To design plasma gasifiers (PG) and related reactors, that use various coal based raw materials, biomass, MSW and other organic (including of hazardous ones) or mixed feedstocks and wastes [1–3], is necessary to analyze transport properties of torch generated plasmas in these reactors under gasification of organic part and complete or partial vitrification of ash part of feedstock. In this paper the results of theoretical analysis are presented, which focused on some features of transport properties of plasma affected by their composition, under the conditions of reactors with such efficient class of plasma torchs as transferred dc electric arc ones, including of twin torch kind [4, 5], that developed last years for the commercial power level of 300-1000 kW.

Initial thermodynamic calculation for such typical group of feedstock as industrial grade coals with quite high ash content (by the example of Brazilian subbituminous ones [6] with $A = 27.8$ wt.%, including of near 1.0 % of K_2O) showed that systems, which composed of mixture of these coals' heating products and plasma gas (air or steam), have at the temperature range above 5000 K and pressure $P = 0.1$ MPa such high equilibrium level of potassium ion K^+ concentration as 0.03 – 0.06 mole/kg at electron concentration of 0.1–0.6 mole/kg. The similar situation is at the case of systems based on the plasma reactors for vitrification at 1600-1800 K fly ash (FA) wastes, such as produced after the boilers and fluidized bed gasifiers with wood residue or with MSW fuel, that use FA types with concentrations of SiO_2 – 25 -30 wt. % and K_2O – 12–17 %.

During following analysis atoms and ions concentrations and transport parameters (electric conductivity σ and thermal conductivity λ) of air plasma with Cu (product of torch' cold electrode erosion with intensity of 10^{-6} – 10^{-7} g/QL, ionization potential of Cu^+ $I_1 = 7.73$ eV) and with K impurities (product of coal ash vaporization, ionization potential of K^+ $I_1 = 4.34$ eV) were calculated based on the chemical model of weakly non-ideal plasma in LTE [7] and the system of ionization equilibrium Saha-Boltzmann' (S-B) equations. Ranges of defining parameters, i.e. plasma temperature and density were used as $T = 4$ – 40 kK and $\rho = 10^{-3}$ – 10^{-7} g/sm³. For these conditions of quasi-equilibrium plasma its transport properties can be described with classical kinetic Boltzmann' equation, which solution based on Chapman-Enskog' method (C-E). k -e approximation of C-E' method give the follow expression for σ

$$\sigma_k = \frac{3\sqrt{2\pi}}{8\sqrt{T}} zn \frac{Q_{2k}}{Q_{1k}}, \quad k \geq 1, \quad (1)$$

here Q_{mk} – principal diagonal minors of the infinite matrix (with elements (q_{mk} , $m \geq 1$, $k \geq 1$)), and in the calculation of lower approximations it is assumed that $Q_{21} = Q_{32} = 1$. The matrix elements are linear combinations of integrals of electron scattering by different particles:

$$q_{km} = q_{mk} = \sum_{i \geq 0} n_i \sum_{s=1,2,\dots} b_{mk}^s \Omega_i^{ls} + \sqrt{2} z n \sum_{l=2,4} \sum_{s \geq l} b_{mk}^{ls} \Omega^{ls}, \quad (2)$$

$$\Omega_i^{ls} = \int_0^\infty e^{-\xi} \xi^{s+1} d\xi \int (1 - \cos^l \theta) d\sigma_i(v, \theta, \varphi), \quad \xi = \frac{\mu_i v^2}{2T}. \quad (3)$$

Here μ_i – reduced mass of interacting particles, $d\sigma_i$ – differential scattering cross section. First summand of (3) describes scattering of electrons by heavy particles and second one – by electrons. Concentrations of atoms, ions and populations of excited levels were calculated on the system of ionization equilibrium S–B equations in a Debye’ ring approximation:

$$\frac{n_{i+1}}{n_i} n_e = 2 \left(2\pi m_e kT / h^2 \right)^{3/2} \frac{U_{i+1}^{el}}{U_i^{el}} \exp \left[-\beta (I_i - \Delta I_i) \right]. \quad (4)$$

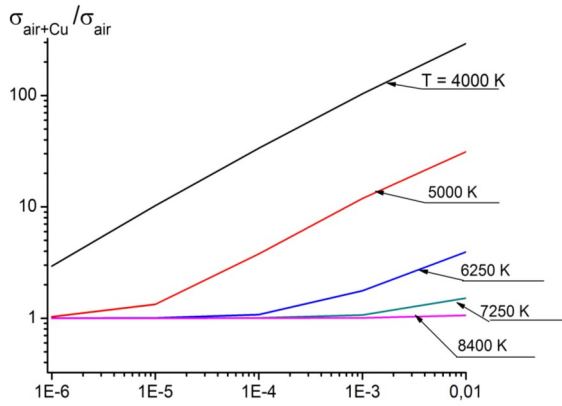


Fig. 1. Dependences of ratio of electric conductivity σ_{air+Cu} of air plasma with copper impurity (10^{-4} – 1 %) to the conductivity σ_{air} of pure air plasma vs. copper concentration in air plasma. $P = 0.1$ MPa

case of industrial reactors’ plasma mixture of air with 0.1-1.0% potassium and with additional impurity of copper with lower (in 10 times) concentration (0.01-0.1 wt.%) per on total mass of air. According to calculation of σ , λ for this mixture over the entire temperature range is independent on the presence of Cu and consist with (at accuracy of 2%) the cases of data for air+0.1–1 % K.

The comparison of kinetic and thermodynamic data on the intensity of oxide ash components vaporization for plasma reactor conditions was also carried out. The data obtained show that during operation of twin plasma torch into reactor is possible reducing arc voltage and power (at constant arc current) not only because of effect of Cu^+ ions on arc electric conductivity increase, but due to additional ionization (in range of $T = 4.0$ – 8.5 kK) by K^+ impurity.

Here U^{el} – partition function of the electronic states and ΔI_i – decrease of the ionization potential, calculated taking into account the interaction of charged particles in the ring approximation of macrocanonical ensemble. Fig. 1–3 are examples of the calculated concentration curves for plasmas, that contaminated with a copper and potassium, as well as temperature dependences of composition of air plasma with potassium. These K–atoms as one of the main plasma ionizers at $T < 8.5$ kK were selected with taking into account of ionization potentials of ash components that can get into arc (with $T \geq 7$ K [4–7]) and other zones of plasma with lower T .

The calculation of the temperature dependences of transport parameters (σ , λ) were also carried out for the most adapted to

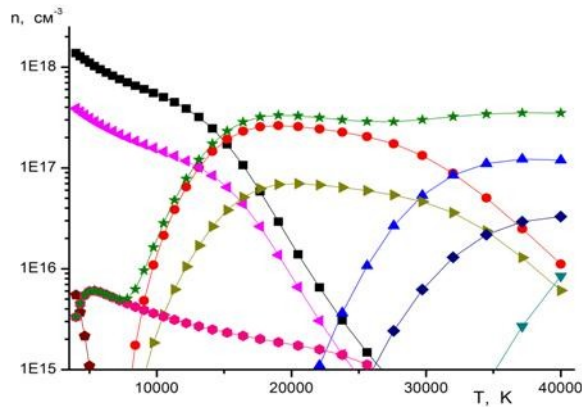


Fig. 2. Temperature dependences of concentrations (cm^{-3}) of atoms, ions and electrons into air plasma with 1 wt. % potassium at $P = 0.1$ MPa. Symbols: ■ – N atom, ● – N^+ ion, ▲ – N^{2+} ion, ▼ – N^{3+} ion, ◆ – O atom, ► – O^+ ion, ◻ – O^{2+} ion, ○ – K atom, ● – K^+ ion, ○ – electrons

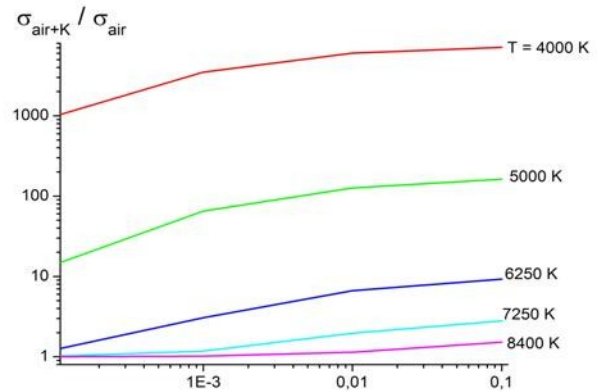


Fig. 3. Dependences of ratio of electric conductivity $\sigma_{\text{air+K}}$ of air plasma with potassium (10^{-2} – 10%) to σ_{air} of pure air plasma vs. potassium dose in plasma. $P = 0.1$ MPa

That is this influence must be the most achieved in the regimes with relative moderate temperature and arc current of the torch. Similar effect of emission of heated and partially ionized feedstock on the arc mode was detected for process in steel-making tundish with transferred arc torch operated with argon as plasma gas, which resulted to hysteresis of current-voltage characteristics of the torch during the variation of arc current [8].

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Some Results of High Power Atmospheric Pressure RF Torches Development

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The authors report results of a three year project resulted in development of a product line of high power (over 30 kW), high efficient due to reverse vortex plasma stabilization (total efficiency from grid to a plasma plum enthalpy over 65%), atmospheric pressure, low maintenance (lifetime over 1,000 running hours), multi-purpose patented (US Patents 7955567,



Fig.1. Hybrid torch samples

7452513, and patent application 12756303) plasma torch with virtually unlimited lifetime and remote ignition. These torches will be mainly applied for coal, petro-coke, waste, and hydrocarbons gasification; bio mass pyrolysis; synthesis of new materials; production of nano- powders, nano-tubes, fullerenes; etching; coating; melting; treatment of hazardous liquids, coal ash, and fly ash; contaminated soil recovery; hypersonic flight simulation; bio weaponry, ammunition, and drugs destruction; possible combining with the plasma chemical reactors.

Reverse vortex flow inside the plasma chamber provides significant advantages for different materials treatment due to longer residence time and walls protection from the treated material deposition. It also practically eliminates a need in

the nozzle cooling.

Comparison of the hybrid plasma system efficiency with other plasma sources is provided in the table below.

TYPE OF PLASMA SYSTEM	POWER SUPPLY + WAVEGUIDE %	TORCH %	TOTAL EFFICIENCY %
ICP 1 st generation	60 - 65	70 - 75	42 - 48
DC	85 - 97	70 - 85	60 - 82
ICP - HYBRID 2 nd generation	85 - 90	80 - 95	68 - 86
MW	75 - 90	90 - 95	68 - 86

It shows that developed plasma systems could be more efficient than existing DC ones with limited lifetime, and provide similar scores as the MW systems, which have limited power and much more expensive. General view of the 50 kW, 150 kW and 300 kW samples could be seen in Fig.1. Torches operation on air and argon are shown in Fig. 2 and Fig. 3 accordingly.

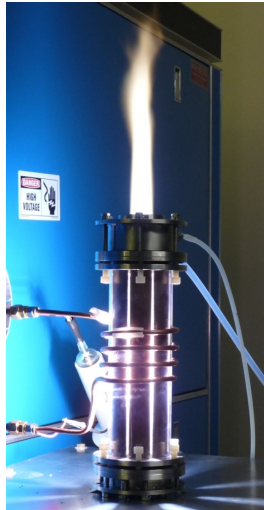


Fig.2. RF torch operating on air

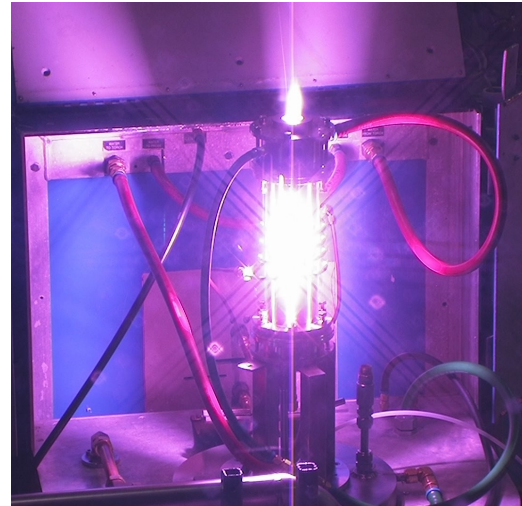


Fig.3. RF torch operating on argon

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Ionization and Energy Deposition in Pulsed Nanosecond Discharges in the Filamentary Regime at Different Pressures and Temperatures

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High voltage nanosecond duration discharges can be used in a repetitive manner to create a sustained pool of short lived excited species and ions and longer-lived radicals in a gas. The suitability of pulsed nanosecond discharges, both in high over-voltage conditions, [1], [7], and at lower over-voltages, [4], [5], as a means of creating a non-equilibrium plasma has already been shown. However, further insight can be useful to fully exploit their capabilities.

In particular, the Repetitive Pulsed Nanosecond Discharge (RPND) technique is very promising for ignition and flame stabilization due to its low power consumption (~ 10 W), in certain regimes, high energy deposition (~ 1 mJ) and its capability to provide a pool of radicals. [5] observed three different regimes at atmospheric pressure: a corona-like regime (C), a diffuse-like regime (D) and a filamentary-like regime (F), in order of increasing applied voltage. Visually, the C-regime is a localized discharge that appears close to the anode, the D-regime bridges the gap and has a homogeneous appearance and the F-regime has the strongest emission. The regimes can also be distinguished by the relative importance of the conduction, I_{cond} , and displacement, I_{disp} , components of the current: C and D-regimes, $I_{\text{cond}} \ll I_{\text{disp}}$, whereas the F-regime, $I_{\text{cond}} \sim I_{\text{disp}}$.

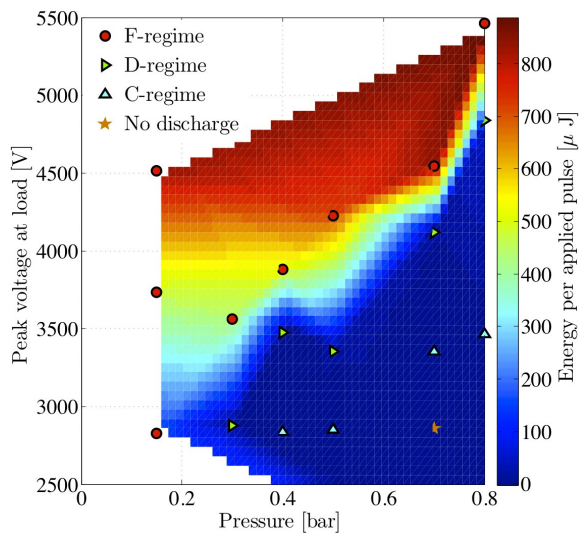


Fig. 1. Energy deposition as a function of peak voltage and pressure. Experiment in nitrogen, at 300 K and pulse repetition frequency 20 kHz

Of the different regimes, the F-regime is the most interesting from an ignition point of view as it provides the highest energy deposition and chemical activity. Its applicability to flame stabilization and ignition has been shown, amongst others, by [2] who reported an extension of the blow out limit of $\sim 10\%$ in methane/air lean mixtures or by [6] who measured significant reductions in ignition delay time in stoichiometric and lean propane/air mixtures.

For ignition studies, parameters of interest to describe these discharges are energy deposition in the gas (that needs to be compatible with minimum ignition energy requirements) and electron number density (indicator of the chemical activity that can be triggered through electron impact reactions). The present experimental study aims at evaluating these two parameters using the RPND technique in the F-regime as a function of applied voltage and reduced electric field.

Experiments have been carried out in air and nitrogen, with a flow residence time of ~ 0.3 ms, pressures ranging from 0.15-1 bar and temperatures 300-700 K. Repetitive nanosecond pulses of ~ 20 ns duration, peak voltage 3-10 kV and pulse repetition frequency 3-30 kHz were applied in a point-to-point electrode system with 5 mm between tips. Measurements include time-resolved

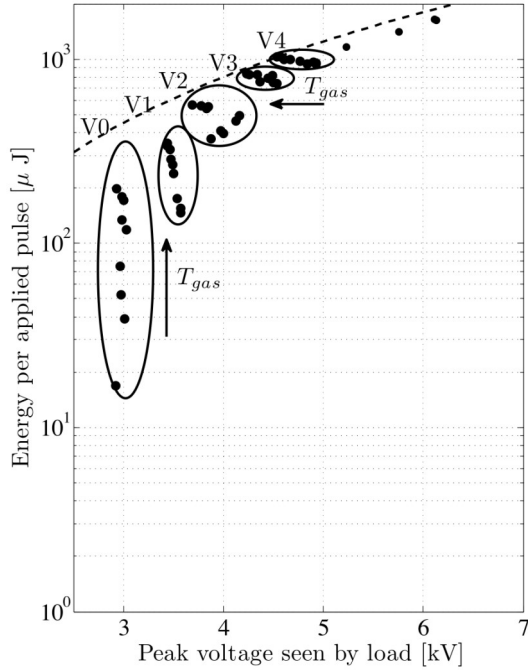


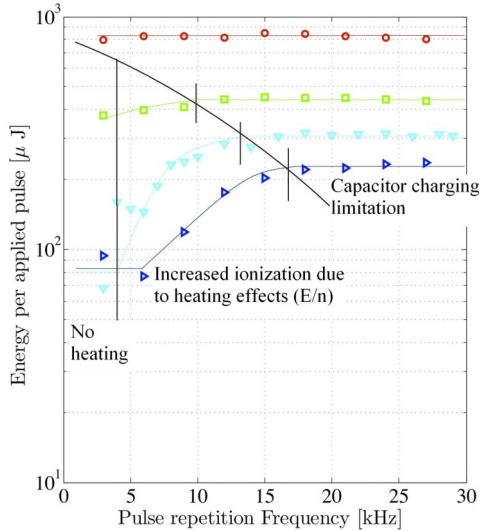
Fig. 2. Energy deposition in air at 0.15 bar and 3 kHz for different applied voltages. Points inside bubbles correspond to same applied voltage and temperatures 300-700 K. Dashed line is estimated maximum energy

voltage and current waveforms and temperature estimations using optical emission spectroscopy [3].

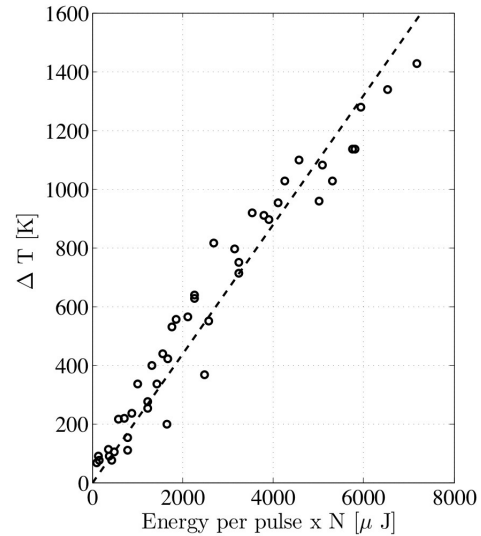
A study at different pressures revealed that the same regimes observed at atmospheric pressure could be obtained in sub-atmospheric conditions at lower applied voltages (Fig. 1).

The effect of the reduced electric field and applied voltage in the energy delivery to the gas in the F-regime was evaluated by varying the gas temperature at fixed applied voltages (Fig. 2). For the lower energy discharges, energy deposition was found to be strongly dependent on reduced electric field. As the applied voltage increases, energy deposition becomes approximately constant, for fixed applied voltage, although further ionization is taking place ($n_e \sim 10^{15} \text{ cm}^{-3}$).

Energy accumulation in the discharge gap was seen to be dependent on applied voltage, whereas energy delivery to the gas depends on reduced electric field until a certain threshold is reached. If enough ionization is achieved, most of the energy accumulated will be delivered to the gas, if not part of this energy will be reflected back.



(a) Energy deposition as a function of pulse repetition frequency (blue ~ 3 kV, cyan ~ 3.1 kV, green ~ 3.5 kV, red ~ 4.1 kV)



(b) Temperature increase as a function of cumulative energy deposition (N = number of pulses that affect the same gas volume)

Fig. 3. Energy deposition and temperature increase (from spectroscopy measurements) for a sweep of voltages [3-4.5 kV] and frequencies [3-30 kHz], air at 0.15 bar and room temperature

Hence, energy deposition in the gas is limited by applied voltage but further ionization can be obtained by increasing gas temperature, for example using cumulative gas heating through an increased pulse repetition frequency (Fig. 3). Also, in the limit in which energy delivery depends on applied voltage, energy deposition becomes less susceptible to electrode erosion or deviations from the nominal conditions.

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Supersonic Ignition System Utilizing Gliding Arc Plasma

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The current work presents the initial test results of a Gliding Arc Supersonic Igniter model designed for operating within high speed flow ambient (above Mach 1). This work has been motivated by Brazilian 14-X program where a hypersonic aircraft and a scramjet engine (which will provide propulsion to the vehicle) are currently being developed in IEAv – Instituto de Estudos Avançados – located in São José dos Campos – SP. The first aircraft flight is intended to be accomplished within the year of 2013.

A scramjet engine is essentially a ramjet where the air flow remains supersonic, requiring a special ignition system for starting the combustion reaction and to keep it stable during flight. A system using gliding arc plasma technology is currently being developed and the model will become the basis for the development of a final model to be installed in the aircraft's engine.

Initial tests have been accomplished within IEAv laboratory installations, where two ambient situations have been considered: vacuum (0.3 mbar) and atmospheric pressure (1.1 bar) – Those are the possible situations where the ignition system may be started during future experimentations with the engine model. Pure and dry air pressurized at 5 bar and 10 bar was used as the igniter's working fluid and a 10 kV rms power supply provided the required electrical energy.

Results observed for experimentation in vacuum ambient show that the breakdown voltage level is very low if compared the levels in atmospheric pressure ambient. Also, breakdown tension levels for air pressurized at 5 bar and 10 bar were observed to be very close (750 V). For atmospheric pressure ambient tests, the breakdown voltage levels had a noticeable difference – 7.5 kV for 5 bar pressurized air and 10 kV for 10 bar pressurized air. This increase in the breakdown voltage level is due to the fact that higher pressure levels outside the igniter imposes a lower flow speed inside the device, thus increasing its internal working pressure and the breakdown voltage level.

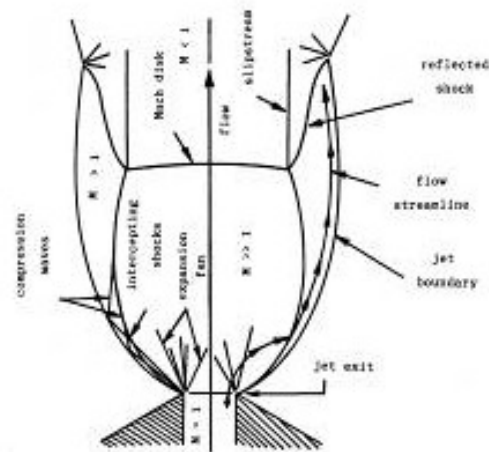
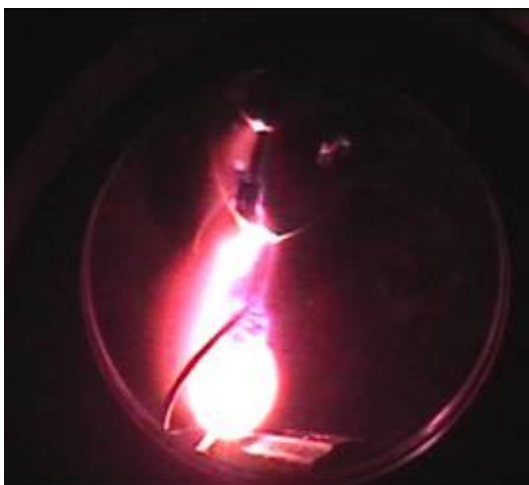


Fig. 1 . Vacuum test: 10 bar working fluid pressure and 0.3 mbar ambient pressure

The igniter's exhaust jet behavior is also completely different when the two situations are compared, as predicted by aerodynamics theory. A much wider jet boundary can be observed for vacuum ambient and the diamond structures formed by expansion waves in the jet are not observed like in atmospheric pressure ambient.

Future tests using hydrogen as igniter's working fluid (fuel to be used by scramjet engine) with the device properly installed in the engine model will be accomplished soon. Those tests, as well as the tests presented in this work, will provide the data needed for designing a final igniter model and a proper power supply which needs to be small and low in weight.

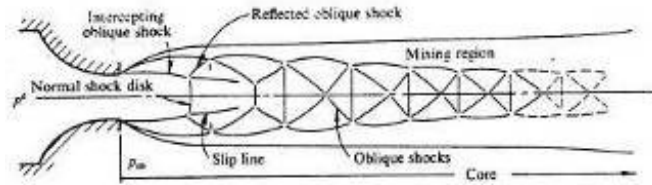


Fig. 2 . Atmospheric ambient test: 10 bar working fluid pressure and 1 bar ambient pressure



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Development of the Convective Cooling System for the Gas Turbine Plasma Assisted Combustor

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The modern market of gas turbine equipment sets high requirements for efficiency, reliability and ecological compatibility of engines. Many of these requirements are realized by the plasma effect [1-5] on the working process in combustion chambers with lean fuel-air mixtures.

For achievement of the effective parameters developers have to raise the temperature of gases after the combustion chamber which directly leads to an increase of thermal load on the combustor's flame tubes. An effective cooling system is a must attribute for a reliable operation of the gas turbine engine.

There are three types of cooling systems in combustion chamber: film, convective and convective-film. Especially effective is a convective type system in the conditions of cooling air lack. The efficiency of such systems application is well-proven by the leading organizations in the turbine building area, such as Siemens, Mitsubishi, Rolls-Roys, etc.

However, the questions arising during such systems design have not been solved up to the end. One of them is the determination of the heat transfer coefficient from combustion products to the tube wall, which would take into account the convective and radiative heat transfer.

Proposed by the authors' method allows to produce thermal calculation of the convective cooling system on the basis of the data obtained during the numerical 3D-modeling of processes in combustion chambers.

As an example, we replace a traditional film cooling system by a convective one in a serial flame tube of the combustion chamber of 25 MW gas turbine engine produced by "Zorya"- "Mashproekt" (Mikolayiv, Ukraine) [6].

First, pre-calculation of the total holes area for the convective cooling system was done. Source data are the following values:

- the temperature of the cooling air (759 K) assumed by the results of experimental measurements;
- cooling air flow rate (0.34 kg/s) was equal to 10.2 % of the total air flow through the flame tube;
- the values of the total pressure in the intertube space of the combustion chamber (1.61 MPa) and of the total pressure on the inner side of the flame tube wall (1.54 MPa) obtained as a result of numerical modeling of the working process in the initial combustor variant [7].

Second, the calculation of the heat transfer coefficient from combustion products to the tube wall were made on the techniques outlined in [8, 9] taking into consideration the radiative and convective heat transfer. The received dependence of the heat transfer coefficient from the wall temperature for

the hottest area is shown in Fig. 1. The source data, such as temperature and the flow rate of the flame tube inner wall, as well as the combustion products composition in the cross-sections were obtained by preliminary numerical three-dimensional modeling of processes inside the combustor.

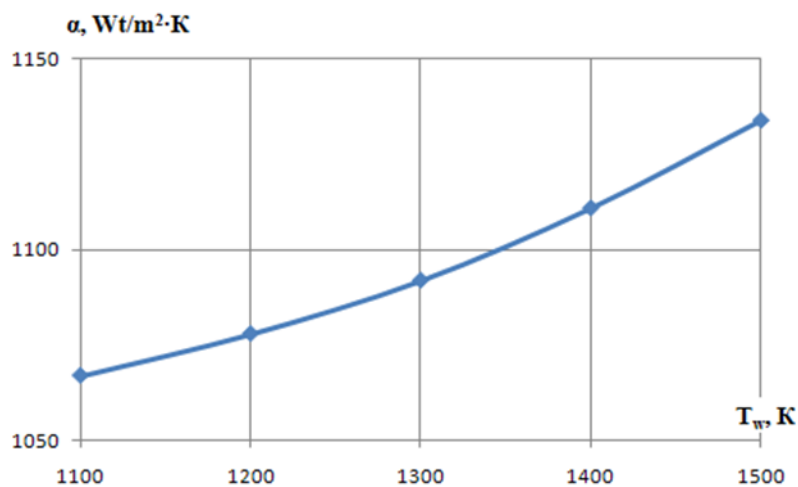


Fig. 1. Dependence of the heat transfer coefficient from the wall temperature for the hottest area of the flame tube

The alloy BЖ159 with working temperature of 1523 K was chosen as the material of the flame tube. On the inner wall it is covered by thermo barrier coating, which thickness considered of 500 microns. The coating is a zirconium dioxide ZrO_2 , stabilized by yttrium oxide Y_2O_5 .

The final hydraulic and thermal calculations of the convective cooling system were performed by methods of numerical simulation in the full-size model of the modified combustion chamber.

The results of calculation of the wall temperature for the hottest part of the flame tube are given in the Fig. 2.

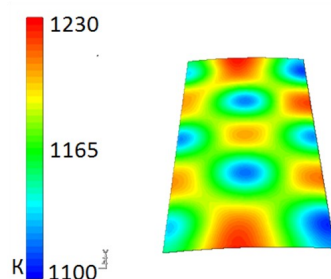


Fig. 2. Alloy temperature field on the inner surface of the flame tube

It is evident that the maximum temperature of the tube with ceramic coating is below the operating alloy temperature which proves the efficiency of the proposed cooling system.

As the result the new scheme allows to reduce relative cooling air mass flow rate from 11.4 % to 10.2 %.

This technique allows to define not only the averaged temperature level on the walls surfaces of the flame tubes, but allows to get its distribution inside the alloy. On that basis it is possible to optimize geometrical parameters of convection cooling systems not only for the combustion chambers of gas turbines but for the other high temperature units such as inductive plasma torches, gasification chambers etc.

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Kateryna S. Serbina was born on April 25, 1985 in Mykolayiv, Ukraine. She is a young scientist in the field of the techno-economical analysis of new ecologically clean technologies in various spheres of human activity, including plasma-chemical technologies. She is an author of 2 papers and conference proceedings in this field. Since 2007, she has been working in Energetic and Machine-Building Research Institute of the National University of Shipbuilding as a research engineer.



Dr. Igor Matveev

Ultra Lean Burn Combustion via Nanosecond Discharge Plasma Ignition

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The use of non-equilibrium plasma ignition was investigated in a 5.3 L, V-8, gasoline engine equipped truck. The plasma power supply used produced high Voltage rise times of < 3 nanoseconds with a total duration of < 54 nanoseconds. Voltage peaks were > 41 KV, effective pulse energy was 35 mJ. The fuel-air ratio and ignition timing were modified using a commercially available flash re-programmer. Testing showed that fuel mixtures could be leaned between 8 and 12% below that of the stock mixtures and timing could be retarded as much as 5 degrees using nanosecond discharge ignition vs. spark ignition. The spark plug configuration had a dramatic effect on engine fuel mixture and ignition timing settings. Fine wire anode spark plugs provided little change between plasma and spark ignition while large diameter anode spark plugs showed the best improvement using plasma ignition. Our laboratory tests showed more streamers present when the anode size was increased. Other investigators have shown that a coaxial anode-cathode configuration provides the greatest number of streamers in laboratory tests with streamer head electron energy > 10 eV. It is proposed that an engine worthy coaxial electrode configured spark plug be paired with nanosecond discharge plasma ignition in order to achieve ultra lean burn combustion.



Lonnie Lenarduzzi graduated from the Pittsburgh Institute of Aeronautics in 1977 with an Aeronautical Engineering degree, Airframe and Power plant License and aircraft Pilot License and went on to work for the US Department of Energy while attending California State University, Long Beach. In 1989 he started his own business providing high voltage equipment to government and private laboratories worldwide.

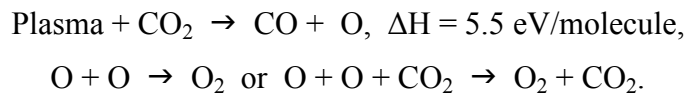
Efficient Conversion of CO₂ to CO by Novel Plasma Method

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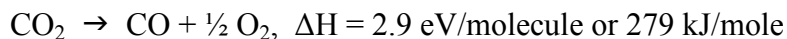
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The control of carbon-dioxide (CO₂), an important greenhouse gas, has become a major environmental issue in the last two decades. CO₂ has been shown by international experts to be a major contributor to global warming/global climate change. Researchers have become aware that CO₂ is actually a valuable commodity, provided that uses can be found for it. Among these are beverage carbonation or the conversion of CO₂ to carbon-monoxide (CO) which is a major component of synthesis fuel gas (CO + H₂). The first major use, unfortunately, requires the source of CO₂ to be near a bottling facility to avoid large transport costs.

Plasmas have been investigated as a means to convert CO₂ to CO via the reactions



The overall thermodynamics of the conversion of CO₂ into CO is represented by



(taken as the 100% thermodynamic-limit conversion efficiency).

Indarto *et al.* [1] have shown a fractional conversion of CO₂ into CO of about 18% and a conversion efficiency (relative to the overall thermodynamic efficiency of 279 kJ/mole) of about 17% in a gliding arc plasma operated at a plasma specific energy of about 15.4 kJ/L. These results were obtained with CO₂/N₂/O₂ mixtures and not pure CO₂. Nunnally *et al.* [2] have recently published an efficiency figure in the range of 18-43% and a CO₂ fractional conversion of 2-9% in an atmospheric-pressure reverse vortex gliding arc plasma operated over a range of 0.43-3.44 kJ/L specific energy, with a pure CO₂ feed. We have conducted plasma-based experiments on the decomposition of pure CO₂ in a novel, near-atmospheric-pressure (3/4 atm),

novel plasmatron-like reactor and have obtained a CO₂-CO conversion efficiency of approximately 30% at a plasma specific energy of 0.8 kJ/L and a conversion fraction of ~ 2%. Unfortunately, because Los Alamos Laboratory intellectual property concerns, we cannot give further details of the plasma reactor.

Our initial results were obtained using an AC HV power supply operating at about 3.5 kV reactor voltage (E/N ~ 18 Td) and about 1 kHz

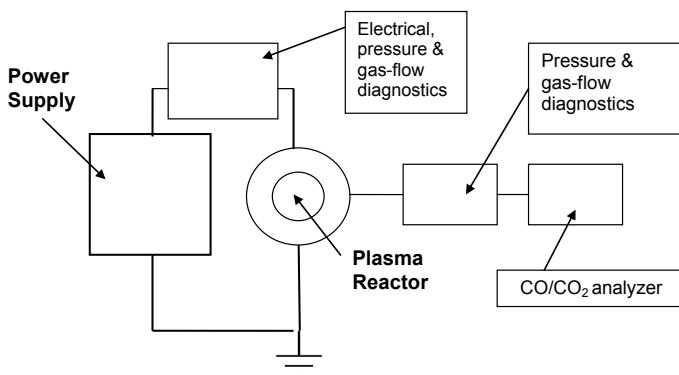


Fig. 1. Block diagram of experimental setup

frequency. In this IWEPEC presentation, we will show results comparing the AC-powered reactor to the case using a power supply developed by Korolev *et al* under a US Department of Energy-funded project on biofuel and municipal solid waste combustion.

Figure 1 shows a block diagram of our experimental setup.

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Louis A. Rosocha was born in February 1950 in Harrison, AR (USA). He received the BS degree in physics from the University of Arkansas (Fayetteville) in 1972 and the MS and PhD degrees in physics (with a minor in chemistry) from the University of Wisconsin (Madison) in 1975 and 1979, respectively.

From 1978-1981, he was at the National Research Group of Madison, WI, developing pulsed ultraviolet lasers, fast pulsed- power switchgear, and modeling commercial ozone generators for water treatment. From October 1981 – January 2008, he was a technical staff member and manager at the Los Alamos National Laboratory (LANL). After an early retirement from LANL in 2008, Dr. Rosocha became an independent consultant, focusing his R&D interests on CO₂ sequestration/global warming, national energy security, and water/air pollution abatement.

Dr. Rosocha is currently a member of the American Physical Society, the IEEE, and Phi Beta Kappa. He was formerly a member of the International Ozone Association. Dr. Rosocha received two Distinguished Performance Awards during his tenure at LANL, is the author of over one hundred publications in books, refereed journals and conference proceedings, and has five patents to his credit.



Yongho Kim (M'03) received the B.S., M.S., and Ph.D. degrees in nuclear engineering from Seoul National University, Seoul, Korea, in 1994, 1996, and 2002, respectively. Since 2003, he has been with the Plasma Physics Group, Los Alamos National Laboratory, Los Alamos, NM. His current research interests include plasma etching with atmospheric-pressure RF plasma jet, DBD plasma-assisted combustion, and microwave plasma-assisted fuel reformation.



Yury D. Korolev was born in the USSR on February 18, 1945. He received the M.S. and Ph.D. degrees from Tomsk State University, Tomsk, Russia, in 1967 and 1973, respectively, and the D.Sc. degree in physics from the Institute of High Current Electronics, Russian Academy of Science, Tomsk, in 1985.

Since 1977, he has been with the Institute of High Current Electronics, where he is currently the Head of the Low-Temperature Plasma Laboratory. He is also currently a Professor with Tomsk State University and with Tomsk Polytechnic University. His current research interests include fundamentals of a gas discharge and applications of high- and low-pressure discharges.

Methane Oxidation in a Plasma Torch of Nonsteady State Plasmatron

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Paper [1] describes the plasma-assisted combustion system intended to generate a torch flame with a high power density per unit area. In the system, a kind of hybrid concept is proposed. A primary unit for combustion sustaining is a low-current nonsteady-state plasmatron with a low level of electric power [2, 3]. The plasmatron activates an air/hydrocarbon mixture and sustains the oxidation processes in the plasma torch [1, 4]. In turn, the heat power of the torch sustains the main burning process in the torch flame. This paper is mainly concentrated on investigation of the primary unit of the combustion system, i.e. on the regimes of plasmatron operation and on methane oxidation in the plasma torch of plasmatron.

Schematic of experimental arrangement is presented in Fig. 1.

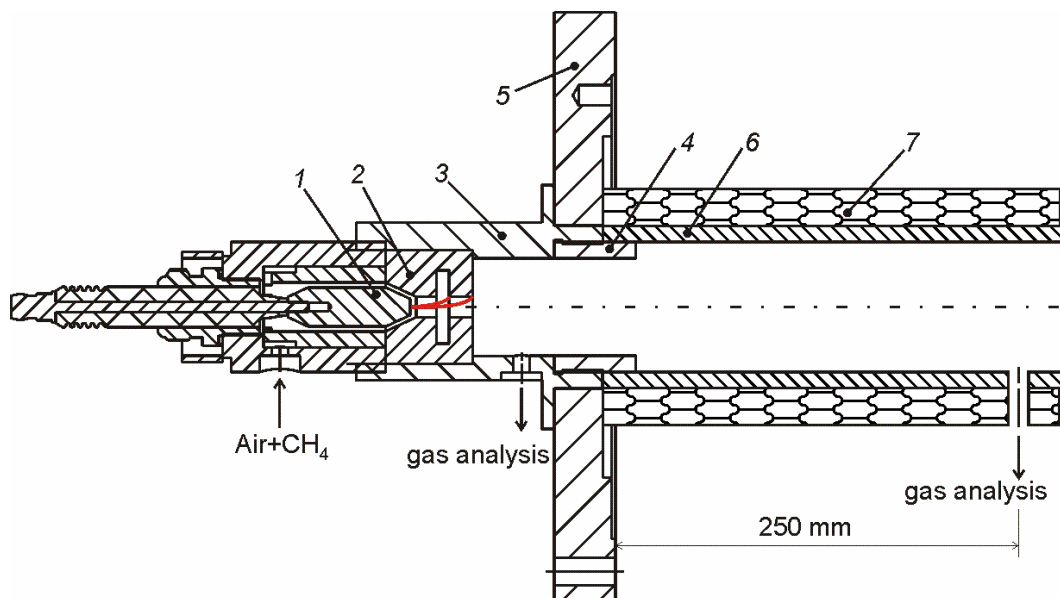


Fig. 1. Plasmatron with the heat-insulated combustion chamber and method for measurement the flue gas composition.

*1 – inner electrode of plasmatron; 2 – grounded outer electrode of the plasmatron;
5 – flange of the main combustion chamber; 6 – heat-insulated plasmatron combustion chamber; 7 – thermal insulation of the plasmatron combustion chamber*

The plasmatron unit is inserted in the combustion chamber 6 with a thermal insulation 7. To enhance reliability and reproducibility of the measurements, we have modernized the plasmatron

design. The inner surface of plasmatron nozzle has the ring-shaped groove. With such a design, the discharge burns mainly in the glow mode with the diffuse channels but without distinctively expressed spark channels. The glow plasma column is attached to the positions to the right of the groove as Fig. 1 shows. As a whole, the plasmatron and chamber design provides a stable burning of the air-fuel mixtures. The flue gas for chemical analysis is extracted by two probe tubes. Probe 1 is located at a distance $x = 2.5$ cm from plasmatron exit and probe 2 is located at a distance $x = 30$ cm.

The main component in the fuel is methane, and the excess air coefficient for air-fuel is determined by the relation:

$$\alpha = 0.0643 \frac{G(\text{air})}{G(\text{fuel})}, \quad (1)$$

where G is the gas expenditure in g/s.

Typical experimental conditions can be understood from the table below. In this table, the following notation is used: $G(\text{air})$ is the air expenditure; $G(\text{fuel})$ is the fuel expenditure; v_0 is the gas flow velocity in x direction at the plasmatron exit; t_{30} is the time interval during which the gas travels a distance $x = 30$ cm; Q_B is the heat power which would be generated in the plasma torch in the case of complete methane oxidation.

$G(\text{air})$, g/s	$G(\text{fuel})$, g/s	v_0 , m/s	t_{30} , ms	Q_B , kW
0.35	2.25×10^{-2}	14	≥ 20	1.26
0.45	2.90×10^{-2}	18	≥ 16	1.62
0.55	3.53×10^{-2}	22	≥ 13	1.98

Fig. 2 shows the contents of CH_4 and O_2 in flue gas versus the excess air coefficient α .

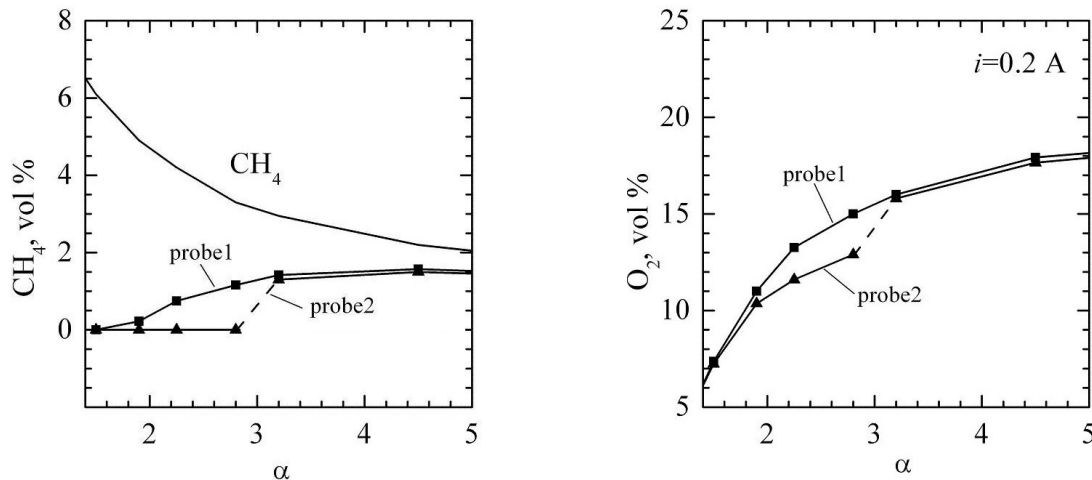


Fig. 2. Contents of CH_4 and O_2 in flue gas versus α for different distances x from the plasmatron nozzle

$G(\text{air}) = 0.35$ g/s; $i = 0.2$ A. Average power dissipated in discharge $Q_d = (150 - 160)$ W.
Curve CH_4 is the content of methane in an absence of discharge in plasmatron

It is seen that when the discharge is available in plasmatron, some decomposition of the fuel occurs even for rather high α values. However, there is some critical value of excess air coefficient ($\alpha_{cr} \approx 3.2$). This value can be treated as a lower flammable limit. When a relative content of air in the air-fuel mixture exceeds $\alpha_{cr} \approx 3.2$, the self-oxidation process in chamber 6 is not able to be sustained. A volume content of CH_4 and O_2 in the flue gas remains the same both for a distance $x = 2.5$ cm and for a distance $x = 30$ cm. For $\alpha < \alpha_{cr}$, a content of CH_4 , recorded by the probe 2, sharply decreases which serves as the evidence of starting the fuel burning process in chamber 6. With decreasing the discharge current, α_{cr} decreases as well.

Discharge in plasmatron generates a rather large amount of NO_x (Fig. 3). However, when methane is added in the plasmatron entrance, a content of NO decreases. In general, it is associated with the fact that due to fuel burning process, oxygen is expended not for NO formation but for methane oxidation.

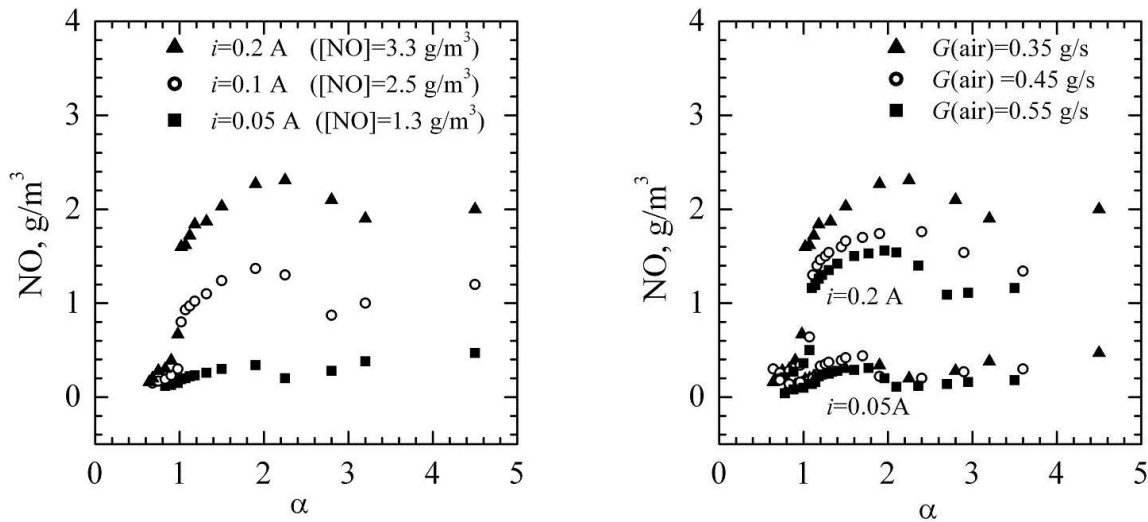


Fig. 3. Content of NO in flue gas versus α for different discharge currents and different gas flow expenditures.

Content of NO for $\alpha = \infty$ is shown in parenthesis. $x = 30$ cm

One of the remarkable facts is that the main fraction of NO is generated in the gas-discharge plasma. Hence, the regimes of discharge operation should influence to NO content. Such an influence is demonstrated in Fig. 3. It is seen that at a current $i = 0.05$ A, the NO content is essentially decreased as compared to a current $i = 0.2$ A.

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Kinetics and Plasma Chemistry of Nanosecond Pulse Discharges and Fast Ionization Wave Discharges

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The paper gives an overview of applications of nanosecond pulse discharges for low-temperature plasma-assisted combustion [1-4] and for flow control, both in subsonic and supersonic flows [5-7]. Diffuse, volume-filling, low-temperature nanosecond pulse discharges efficiently generate excited species and radicals in fuel-air mixtures, producing ignition and flame stabilization in high-speed flows and at low equivalence ratios. On the other hand, surface nanosecond pulse discharges in Dielectric Barrier Discharge (DBD) plasma actuators result in rapid energy thermalization and localized heating, thus generating strong compression waves and producing high amplitude, high bandwidth forcing of airflow. The latter effect is entirely different from Electrohydrodynamic (EHD) interaction in surface DBD plasma actuators powered by AC waveforms.

A specific nanosecond pulse discharge configuration, Fast Ionization Wave (FIW) discharge generated by alternating polarity pulses and propagating in a rectangular geometry plasma waveguide, is analyzed experimentally and theoretically [8,9]. Positive and negative polarity FIW discharge propagation is studied in helium, nitrogen, and air. Ionization wave speed and time-resolved electric field distributions in the discharge are measured using a calibrated capacitive probe. The wave speed and the electric field distribution in the wave front predicted by kinetic modeling calculations are in good agreement with the experimental results. An accurate self-similar analytic solution for parameter distributions in the wave front and behind the wave provides insight into wave propagation dynamics and energy coupling mechanisms.

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Development of Synthesis Gas Afterburner Based on Injector Type Plasma Assisted Combustion System

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We propose new effective synthesis gas afterburner technology based on the special injector type plasma assisted combustion system, allowing to supply fuel gas without overpressure from the pyrolysis system into the afterburner.

For developed afterburner the principle of the working process is the following. Air from a centrifugal blower or a compressor through an inlet duct enters into a receiver, where air is divided on the several streams. The first stream enters into an injector. Synthesis gas (or fuel gas) enters through a fitting pipe, injects by an injector, partially mixed with air in a mixer and enters into a flame tube. The second airflow enters into a vortex generator (swirler) and as a swirling flow enters into a flame tube, forming a vortex type combustion zone. The third airflow enters into a flame tube through a number of holes. The fourth airflow enters into a gap for the combustor wall cooling and after passing through an external vortex generator mixes with the combustion products for reaching necessary exit afterburner temperature.

For synthesis gas afterburner modeling following input data has been taken into consideration:

- synthesis gas mass flow rate 25 g/s with temperature ≤ 700 K;
- the lower calorific value of dry synthesis gas - around 18,300 kJ/kg (varies depending on waste composition in the pyrolysis system);
- air temperature 350 K;
- air overpressure at the inlet is changed from 1 kPa up to 25 kPa. Given range of the air overpressure is selected taking into consideration that the fuel gas consumption, as well as the synthesis gas composition from the pyrolysis system can vary and are not defined exactly by the customer.
- synthesis gas (fuel gas) overpressure at the input 0 Pa.

Three dimensional CFD-calculations using complex ANSYS Fluent were performed for the analysis of the basic geometrical parameters influence on the afterburner characteristics.

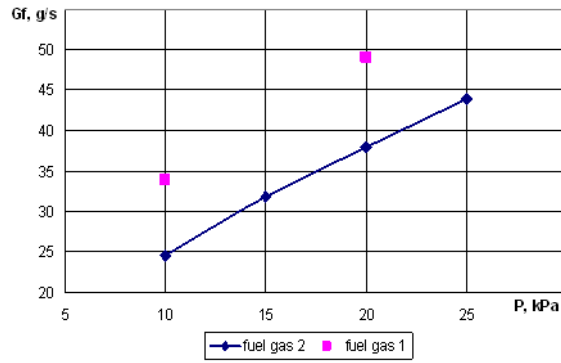
Simulations were conducted for two fuel gas compositions:

1) fuel gas 1: 40% C_3H_8 and 60% CO_2 (by volume), density under normal conditions 1.99 kg/m^3 , with a low calorific value 18,270 kJ/kg;

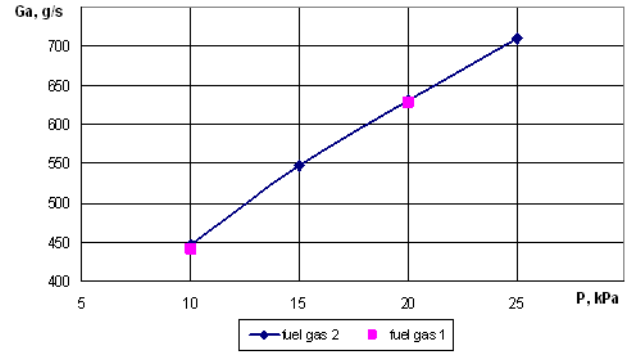
2) fuel gas 2 (is more closer to a synthesis gas composition): 1% CH_4 , 48% CO and 51% H_2 (by volume), density under normal conditions 0.65 kg/m^3 , with a low calorific value 18,363 kJ/kg.

Simulations of the afterburner working processes on two types of fuel gas are caused by the necessity to use fuel gas 1 for laboratory tests, and synthesis gas (similar to fuel gas 2) for real operation with the pyrolysis system.

In Fig. 1 dependences of the air flow rate and fuel gases consumption from air overpressure at the afterburner input are presented. These dependences show approximately linear character of parameter changing.



(a)



(b)

Fig. 1. Dependencies of mass air flow rate (a) and fuel gas consumption (b) from air overpressure in the afterburner input

Contours of temperatures and velocities along the afterburner cross-sections for fuel gas 2 at air overpressure 10 kPa in the inlet are shown in Fig. 2 and Fig. 3.

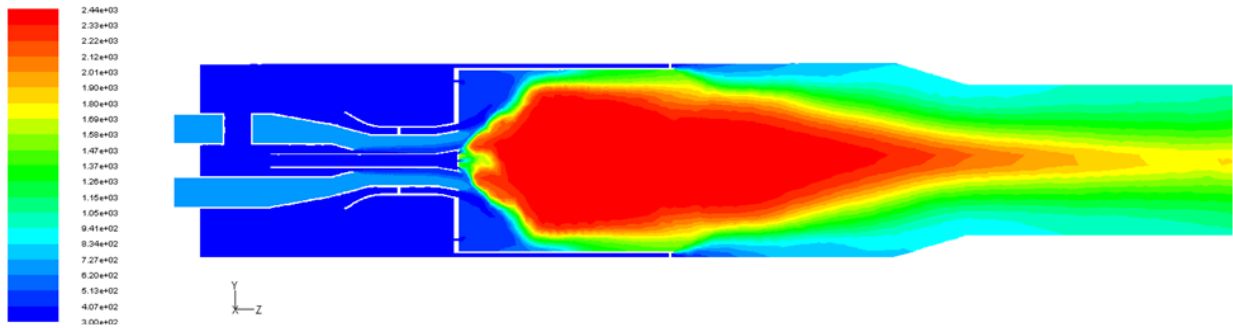


Fig. 2. Temperature field contour, K, in the longitudinal section

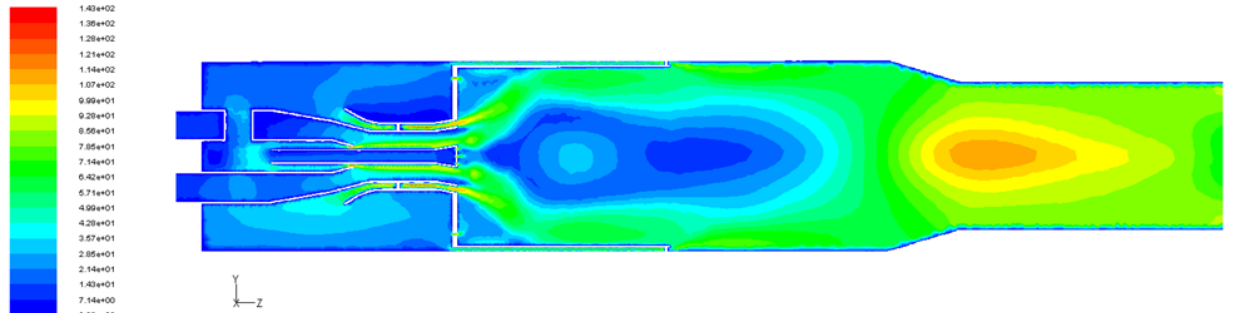


Fig. 3. Velocity magnitude contour, m/c, in the longitudinal section

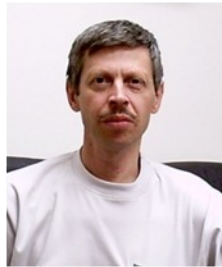
To ensure synthesis gas (or fuel gas) ignition during start ups and stable afterburner work within all operation modes, a plasma-assisted system is required to be mounted around the front afterburner device. There are two ways the plasma may impact on burning processes [1-4]. The first one is the thermal heating when a small volume of the mixture is brought to a high enough temperature to allow for a self sustaining reaction and hence, propagation of the flame. The second way is a production of “active particles” - radicals that increase speed of chain reactions, the generation of ion chains, in which goes the redistribution of the accumulated energy.

The results of numerical experiments testify:

- afterburner with the injecting device ensure stable and effective conditions for the synthesis gas processing with zero over pressure, provide specified consumption of the fuel gas with variable composition;
- the design concept and the basic overall dimensions of the afterburner with the injecting device are determined, allowing burning out of both real synthesis gas from the pyrolysis system and model mixtures $C_3H_8-CO_2$ at laboratory conditions;
- to ensure proper synthesis gas or fuel gas ignition and flame control during start ups and adjustments, flame outs at any transition and operation modes, a plasma-assisted combustion system should be designed and mounted around the afterburner front section;
- as synthesis gas composition and regularities of its consumption are changed in time and not defined reliably, laboratory tests of proposed afterburner are required with the purpose of finally geometrical and mode parameters selection and adjustment of injection system.

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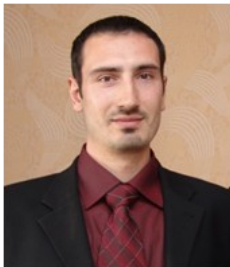
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His research interests are mathematical modeling of fluid flow and mixing, plasma processes modeling, the techniques of intensifying the processes of hydrocarbon-fuels ignition, combustion and the formation of harmful substances in power engineering.

Gasification of Pyrolytic Oil from Scrap Tires by Thermal Plasma

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Introduction

Sustainable development in transport includes proper handling of used tires. The amount of waste tires in EU, USA and Japan only is around 6 million tones per year and will increase in the future [1]. One of the treatment methods is pyrolysis of rubber from waste tires. The pyrolytic products (solid char, liquid pyrolytic oil and synthetic gas) are of poor quality and therefore investigations on upgrading of these products are taking place

In this paper we have studied the possibilities of pyrolytic oil upgrading in steam thermal plasma generated in dc hybrid torch with gas and water stabilization of the arc. The composition of the plasma, i.e. mixture of hydrogen and oxygen with small amount of argon, is very favorable for gasification as plasma does not dilute the syngas. In our experiments water, carbon dioxide and oxygen have been used as oxidizing media for partial oxidation of surplus of carbon in the oil to carbon monoxide.

Experimental system

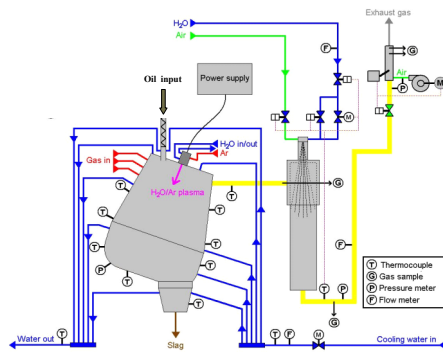


Fig.1. Scheme of gasification reactor

into the quenching chamber where their temperature is reduced to 300 °C. The gas then flows into the combustion chamber at the output of the system.

Plasma torch with hybrid gas/water stabilization of arc [3] was attached at the top of the reactor. The torch generates an oxygen-hydrogen plasma jet with small amount of argon. The operational parameters of plasma torch are given in Table 1. The high enthalpy and temperature of the plasma is advantageous

The plasma gasification reactor (Fig.1) was designed for operation up to 1700°C wall temperature [2]. The reactor has ceramic lining with the inner volume of 0.206 m³. The pyrolytic oil from a pump was fed into water cooled feeding nozzle 0.5 mm in diameter. Oxygen and carbon dioxide were supplied directly into the reactor through gas inputs, liquid water was injected into the same nozzle as oil. The output of gas is positioned close to the plasma input and thus outgoing gas passes high temperature region with high level of UV radiation. Gaseous reaction products are fed

Table 1. Operation parameters of plasma torch

Arc current, A	400
Arc power, kW	110
Steam plasma flow rate, g/s	0.3
Argon plasma flow rate, slm	7
Torch efficiency, %	59
Mean plasma enthalpy, MJ/kg	129
Bulk plasma temperature, K	14 200

for high reaction temperature and efficient utilisation of plasma enthalpy for gasification. The flow rates of oxidizing gases were controlled by thermal mass flow controllers (Brooks Instrument). The stream of pyrolytic oil crossed the plasma jet about 30 cm downstream of the torch nozzle. The composition of the syngas was measured online by mass spectrometer Omnistar (Pfeiffer Vacuum). The selected gases for monitoring were hydrogen, carbon monoxide, carbon dioxide, methane, oxygen, and argon.

Results and Discussion

From the analysis of elemental composition of pyrolytic oil follows its approximate molecular formula C_5H_8O .

The oxidizing media, liquid water, oxygen or carbon dioxide were fed into the reaktor in stoichiometric ratio to oxidize the surplus of carbon to carbon monoxide. Experiments were carried out at torch current 400 A and input power 110 kW. Some typical results are in Table 2 for different conditions. T_r is average temperature of inner reactor wall, T_g temperature of syngas at the output before quenching. The flow rates of input media are shown with measured syngas composition, calculated low heating value LHV and ratio of carbon content in syngas C_{out} to total carbon content in oil and input gases C_{in} (efficiency of carbon gasification).

Table 2. Reactor operating parameters, input media flow rates, syngas composition, and low heating value as well as carbon gasification efficiency

No.	T_r , °C	T_g , °C	Oil, kg/h	H_2O , kg/h	CO_2 , slm	O_2 , slm	H_2 , v.%	CO , v.%	CO_2 , v.%	CH_4 , v.%	O_2 , v.%	C_{out}/C_{in}	LHV , MJ/Nm ³
2	1072	876	8.8	10.6	0	0	57.7	32.7	4.1	4.9	0.7	0.67	12.1
5	1194	1042	10.6	0	0	92	47.9	47.0	2.9	2.0	0.0	0.87	11.8
8	1057	958	10.6	0	182	92	19.0	53.2	25.4	1.8	0.2	0.80	9.4
10	1056	991	10.6	0	182	0	26.9	53.2	16.4	1.9	0.3	0.58	10.7

Efficiency of carbon gasification varied between 0.58 and 0.67 for gasification with water, for gasification with CO_2 it was slightly lower, around 0.58. The highest efficiency of gasification 0.87 was obtained for oxygen, for the mixture of CO_2 and O_2 the efficiency was around 0.80. The heating value of syngas is quite high due to high content of hydrogen and carbon monoxide.

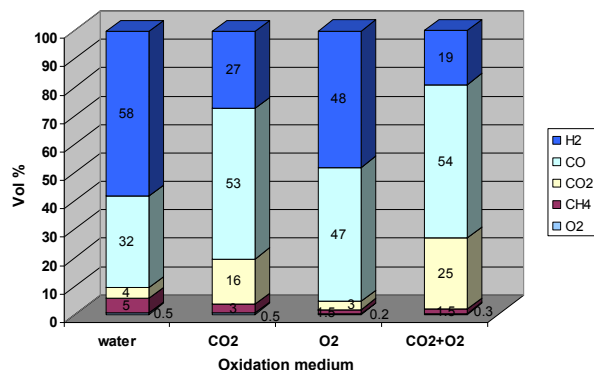


Fig. 2. Composition of syngas for various oxidizing media

Fig. 2 shows overview of averaged syngas composition for different oxidizing media, water, carbon dioxide, oxygen and mixture of CO_2 and O_2 .

The highest content of H_2 in syngas was in the case of oxidation with water, but part of the plasma enthalpy was lost for water dissociation.

On the other hand, the use of oxygen brings some extra energy for gasification.

The pyrolysis of scrap tires yields in solid carbon, pyrolytic oil and gas. The gasification of pyrolytic oil in thermal plasma can produce high quality syngas.

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Production of Synthesis Gas with Atmospheric Pressure Plasma Processing of Coffee Grounds (Borra de Café) and Other Organic Waste

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At the Sustainable Plasma Laboratory of University of California Merced, we have designed an experiment to process Coffee Grounds (Borra de Café) and other organic waste with atmospheric Pressure Plasma.

The plasma is generated using DC Discharge Current between the electrodes at atmospheric pressure. Contrary to conventional plasma torches that use very high kilovolts for the discharge, this device uses low voltage (maximum 400 V) and high current (maximum 150 A). The feeding system has been designed to vary the feeding speed of the fuel thereby changing the interaction time between the plasma with the coffee grounds. The Syngas produced is confined along a cylindrical mesh, and for this experiment, a series of thermocouples were located about 10 cm apart. The flux air to the compressor and the inlet temperature are monitored permanently. The Discharge Current and Voltage are monitored permanently during the experiment, as well. We present the results of the values of the temperature profile along the plasma flame and the Syngas generated in several runs. From the results we notice that the maximum temperature measured with the thermocouple is 1100 °C, at 10 cm from the plasma source, and temperature decreases with the separation distance from the source.



Edberto Leal-Quiros, PhD

Features of the Working Process in Three-Stage Plasma Coal Gasification System

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Coal is a promising raw material for energy and chemical products. Plasma technology can be used for treatment of low-grade coal into synthesis gas [1-3]. The process of plasma gasification is environmentally friendly. Due to the high temperatures in the reactor core, pitches, phenols and hydrocarbons are practically missing in the light-end products.

Coal gasification refers to a process that breaks down coal into its components, by subjecting it to high pressure and high temperature in addition to the use of water steam and oxygen. This leads to the production of synthesis gas consisting of carbon monoxide and hydrogen [3, 4]. Plasma water steam or oxygen coal gasification looks like the best solution for portable and small to media-scale coal processing facilities.

The purpose of this study is to find features of the working processes in three-stage plasma coal gasification system at atmospheric pressure using 3D mathematical modeling. The results will be used to design portable module with subsequent models verification with the experimental data.

For modeling of gasification processes a generalized method has been used, based on the numerical solution of the combined conservation and transport equations for turbulent system [1, 5, 6]. This method provides a procedure of the numerical integration of the 3D-differential equations that describe viscous gas flows: the equations for conservation of mass, momentum, and energy. Additional transport equations are also solved when the flow is turbulent. For aerodynamic prediction the RNG-based k - ϵ -turbulence model was used. For chemical reactions it is necessary to solve conservation equations for chemical species and to predict the local mass fraction of each species through the solution of convection-diffusion equation for the species.

At the preliminary phase 3D calculations of heat exchange in the inductive type plasma gasifier are conducted using the ANSYS Fluent computational program at total coal consumption of 16 g/s. The vertical design of plasma gasification system is considered.

The gasification system has two modules: a plasma pre-gasification module or a plasma muffle (the first and second stages) and a gasification module (the third stage). Plasma-process oxidizer (air, water steam or oxygen) is injected through the cylindrical duct. The part of the oxidizer (Ox 1 and Ox 2) is supplied tangentially (in reverse vortex case) into first and second stages of the pre-gasification module, providing the overrich mixture in the muffle (oxidant excess coefficient 0.2). The last part of the oxidizer (Ox 3) is fed through the special swirler. The total oxidant excess coefficient is 0.4.

The processes of coal gasification in three-stage plasma gasification system are investigated. Modeled coal has the following composition: C = 0.867347; H = 0.053288; S = 0.005669; O = 0.055556; N = 0.01814, diameter of the coal particles is 75 mkm, particle's temperature is 300 K, wall's temperature of first and second stages of the plasma gasifier is 873 K.

The computational grid of the plasma gasifier is shown in Fig. 1; numerical results are presented in Fig. 2.

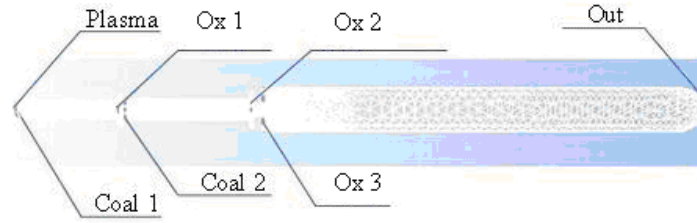


Fig. 1. Computational grid of the plasma gasifier

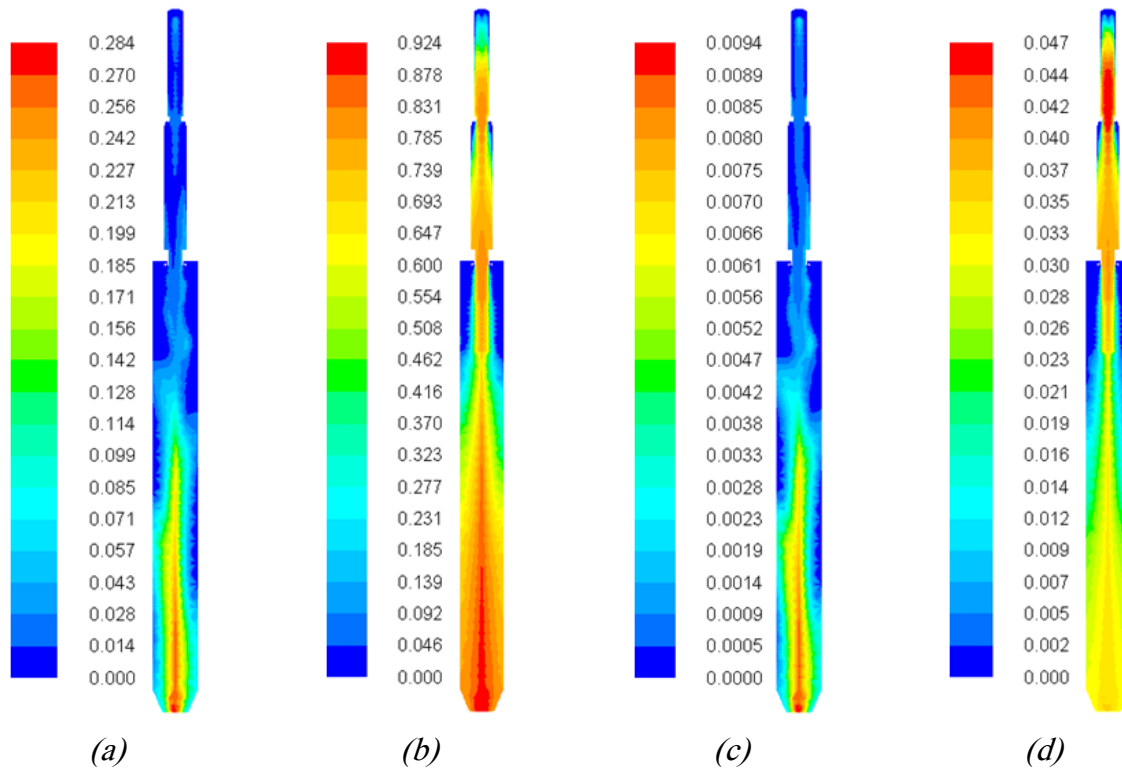


Fig. 2. Contours of CO mass fraction for air (a) and oxygen (b) gasification, and contours of H₂ mass fraction for air (c) and oxygen (d) gasification

The following average predicted parameters at the gasifier outlet are obtained (using air as carrying gas) for direct flow scheme: temperature = 1881.4 K; mole fraction of volatile = 0.12 %; mole fraction of O₂ = 0; mole fraction of CO₂ = 6.03 %; mole fraction of H₂O = 9.44 %; mole fraction of CO = 13.16 %; mole fraction of H₂ = 6.32 %. The rate of devolatilization is 100 %; the conversion of coal is 39.45 %.

The following average predicted parameters at the gasifier outlet are obtained (using oxygen as carrying gas) for direct flow scheme: temperature = 2030.1 K; mole fraction of volatile = 0.33 %; mole fraction of O₂ = 0; mole fraction of CO₂ = 2.66 %; mole fraction of H₂O = 4.88 %; mole fraction of CO = 59.39 %; mole fraction of H₂ = 31.76 %. The rate of devolatilization is 100 %; the conversion of coal is 89.84 %.

Analysis of obtained results showed the theoretical possibility of three-stage plasma coal gasification system modeling. Further improvements of computational procedures are linked with development of more detailed kinetic schemes of coal gasification with using water steam and oxygen as the carrying gas for more effective coal treatment.

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Thermochemical Assessment of Arc Plasma Gasification Efficiency for Brazilian Subbituminous Coal and Related Feedstock

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At recent years plasma gasification technologies are widely studied as high promising class for various coal based feedstocks, including low cost coal-water synthetic and wasted slurries [1, 2]. Prospects of last kind of feedstock is also due to the possibility of using new technology based on intensive grinding (up to particle sizes $\leq 1 \mu\text{m}$) of coal under coal fuel slurry preparation, which was designed by Compomash Co., Russia et al. [3]. For design of plasma gasifiers (PG) is necessary to determine the composition and transport properties of high

Table 1. Composition of the coal produced at industrial scale [4]

Ultimate analysis of coal, wt.%		Ash composition	
Moist. (total)	12.59	SiO ₂	65.7
VM	42.73	Al ₂ O ₃	27.9
FC	57.27	Fe ₂ O ₃	1.72
Ash	27.80	MnO	0.02
CV (MJ/kg)	22.46	MgO	0.34
C (db)	56.2	CaO	1.65
S (total, db)	0.57	Na ₂ O	0.10
H (db)	3.61	K ₂ O	0.96
N (db)	1.01	TiO ₂	0.89
O + Hal (db)	10.77	P ₂ O ₅	0.16
HGI (in relat. units)	57	H ₂ O–SO ₃	0.57
Cl	≤ 0.04 *		

Moist. - moisture content, *VM* - volatile matter,

FC - fixed carbon, *CV* - calorific value,

Hal - halogens, *HGI* - hardgrove (grindability) index,

d.b. - dry basis; * – on data [5] for Recreio mines

temperature medium in these under gasification. This paper presents the results of thermochemical assessment of PG potential efficiency with the focusing on Brazilian industrial scale coal feedstock (total output in 2008 was near of 11 Mt/yr), which belongs mainly to subbituminous class, and on the related feedstock, such as coal-water slurries. There are a few reports with chemical analysis in some details for Brazilian industrial coals [4-6]. The coal of Recreio mines (Rio Grande do Sul (RS)) [4] was used for our assessment because of most typical composition, which is near to others coals of Santa Catarina and RS states (see Table 1). It's important that to fulfill of gasification process a number of efficient plasma torches were last years developed, including of DC transferred electric arc torch (EAT) with water steam or air as plasma gas and power of 100-300 kW, which is currently adopted at ITA for experiments with coal feedstock.

Calculations of equilibrium thermodynamic parameters of high

temperature mixtures for the conditions of PG with EAT were carried out for variants with air as plasma gas as well as for steam one, and at using of 0.7 kg/kg mass concentration of coal in

the slurry. For this calculation of phase and chemical composition and properties at temperature range of 300–6000 K and pressure $P = 0.1$ MPa the program packages CHEMKIN (vers. 4.0) and TERRA (vers. 5.3) were used.

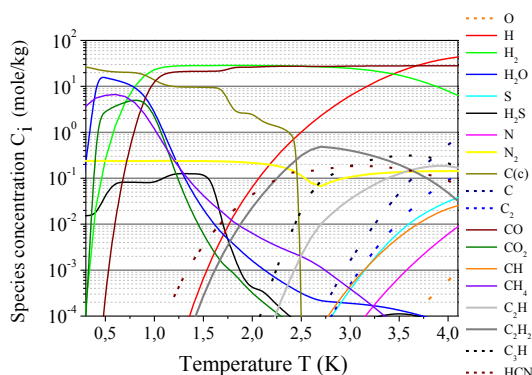


Fig. 1. Equilibrium composition for non-mineral part of system of “coal+steam gasifying agent” at mass ratio $G_C/G_{ST} = 4.0$

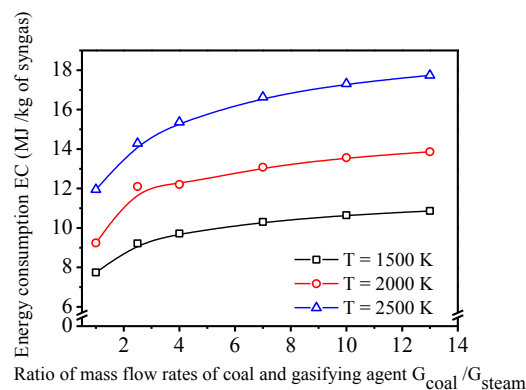


Fig. 2. Energy consumption for syngas under steam plasma gasification of coal vs. mass ratio of coal to gasifying agent G_C/G_{ST}

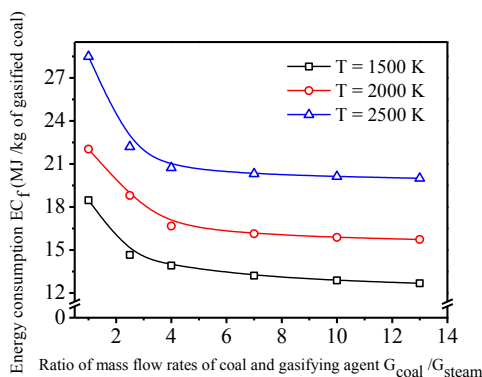


Fig. 3. Energy consumption for gasified part of feedstock under steam plasma gasification of coal vs. ratio of coal to gasifying agent

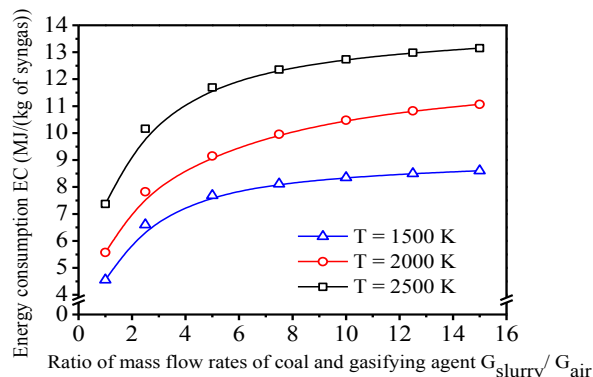


Fig. 4. Energy consumption for syngas under air plasma gasification of coal slurry vs. ratio of slurry to gasifying agent G_{SL}/G_{AIR}

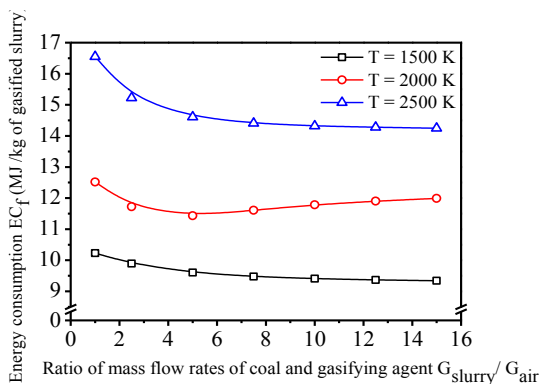


Fig. 5. Energy consumption for gasified part of feedstock under air plasma gasification of coal slurry vs. ratio of slurry to gasifying agent

Based on data calculated (see Fig. 1-5) it was determined that for reforming this coal feedstock (with quite high ash content) to syngas the energy consumption level of 10–12 MJ/(kg of syngas) is sufficient. For this it's enough to use regimes with ratio of mass flow rates of feedstock to gasifying agent $G_C/G_{ST} = 4.0$ (for coal case) and $G_{SL}/G_{AIR} = 10.0$ (for slurry case) at the $T = 2000$ K. Calorific value of 1 nm^3 of syngas is for these conditions (calculated on H_2 and CO concentrations) so high (for next fuel using) as 9.98 MJ for coal (at the gasification degree of 1.0), and as 9.64 MJ for slurry. Such beneficial component as solid SiC is also formed

in coal-steam systems with ratio of $G_C/G_{ST} \geq 4.0$ at 1800-2300 K with concentration of 1.5-2.5 mole/kg.

Then atoms and ions concentrations and transport parameters (electric conductivity σ and thermal conductivity λ) of high temperature media of C-H-O-N system in PG as well as air plasma with Cu and K impurities (products of EAP' electrode erosion and volatilization of coal ash), which affect on EAP voltage and as a result on the efficiency of PG, were determined for the ranges of $T = 4-40$ kK, using the simulating with the chemical model of weakly nonideal plasma in LTE [7] and based on system of ionization equilibrium Saha-Boltzmann' equations in a Debye' ring approximation.

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Ph.D. Student A. R. Marquesi



Prof. H. S. Maciel



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Effect of Gas Dynamic Mixing of Thermal Plasma Jets with Spray of Coal Slurry/Hydrocarbon-Based Feedstock on the Operation of Plasma Gasifier System

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Plasma gasification technologies for treatment of coal based feedstocks (including coal-water synthetic and wasted slurries (CWS)) and hydrocarbon-based liquids are widely studied technologies [1 - 3]. For design of plasma gasifiers (PG) with this liquid feedstock is necessary to calculate of parameters of thermal evolution of feedstock droplets under the mixing with plasma jet/flow. In this paper the method of semi-empirical calculation of these is presented. For PG a number of plasma torches can be used, including of DC transferred electric arc torch (EAT) with water steam or air as plasma gas and power of 100-300 kW, which is recently designed at ITA. Schematic of designed counter flow gasifier with electric arc plasma torch (as variant - transferred arc twin torch) and with pneumatic sprayer for coal slurry or hydrocarbon based liquid feeding presented on Fig.1. At the Fig.2 the schematic of evolution of feedstock'

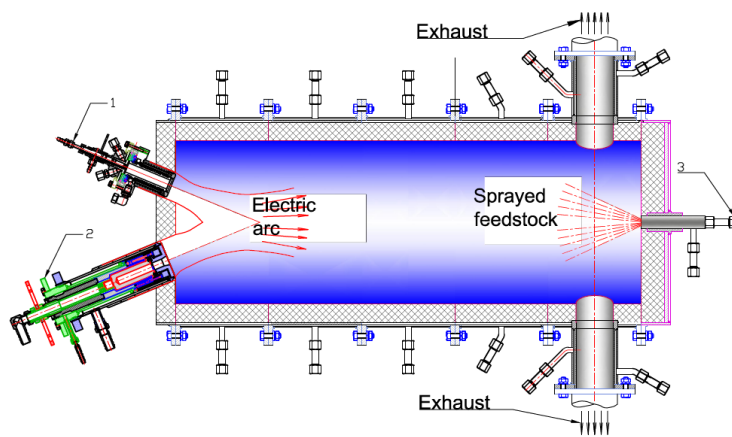


Fig. 1. Schematic of counter flow gasifier (reactor) with electric arc plasma torch (as variant - transferred arc twin torch) and with pneumatic sprayer for coal slurry or hydrocarbon based liquid feeding

droplets injected into plasma is shown, including of stage of secondary atomization (break-up) of droplets. For the experiments on determination of the effect of gas dynamic mixing of plasma jets with liquid feedstock on the droplets evolution the triple torch reactor [5] of parallel flow and counter flow kinds was also used. Under these experiments the mass average enthalpy of plasma flow at input to mixing zone was $H_{gpl}=5,9-14,0$ MJ/kg, i.e. equivalent to air temperature of $T_{gpl} = 3400-5800$ K. Parameters of feedstock spray were such high as droplet average diameter in the spray of 35-120 μm , and average velocity 10-60 m/s, surface tension of liquids was quite typical for the all class of feedstock and equal to 0.0402 N/m.

For the calculation of parameters of thermal evolution of feedstock droplet' phase sizes under the mixing with plasma jet/flow the set of equations (1-5) was used.

$$f_2(d_{p2}) = \int_a^b [f_1(d_{p1}) f_3(d_{p2}/d_{p1}) d(d_{p1})] / \left(\int_0^b \left[\int_a^b f_1(d_{p1}) f_3(d_{p2}/d_{p1}) d(d_{p1}) \right] d(d_{p2}) \right), \quad (1)$$

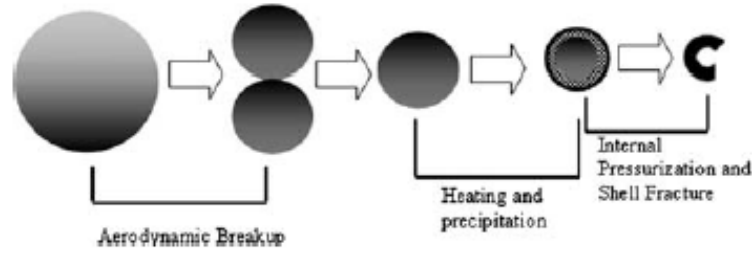


Fig. 2. Evolution of feedstock' droplets injected into plasma, including of stage of secondary atomization (break-up) of droplet

$$f_3(d_{p2}/d_{p1}) = k(2k_3(dp_2/dp_1) + k_2) \cdot \left(\exp[-k_3(dp_2/dp_1)^2 - k_2(dp_2/dp_1) - k_1] \right), \quad (2)$$

here constants $k = 1.037$, $k_1 = 0.036$, $k_2 = 0.092$, $k_3 = 10.899$;

$$\varphi_2(dp_2) = M_1\phi_1(dp_1) + (1 - M_1)f_2(dp_2) \quad (3)$$

$$\phi_1(dp_1) = (1/C_2) \cdot \left(\exp((dp_1 - C_1)/C_2) \cdot (\exp(-\exp((dp_1 - C_1)/C_2))) \right), \quad (4)$$

here constants $C_1 = 20$, $C_2 = 5.8$;

$$f(d_s) = (\varphi_2(d_s/K_0))/K_0, \quad (5)$$

here K_0 – constant, which depends from mass concentration of solid microparticles (i.e. coal ones for case of CWS) in the sprayed liquid feedstock γ_P .

Here in (1) $f_1(dp_1)$ - differential FRKR for primary atomization (Weibull' function with parameters $n = 2, 2-3, 4$ and $d_0 = 35-120$ mm); (2) - is a differential DSD products for secondary atomization of monodisperse droplets, calculated from the experimental data. The lower limit of integration in (1) ($a = 8-17$ μm , which corresponds to the of low size-fraction of primary droplets which mixed with plasma flow without secondary atomization $M_1 = 1-14\%$ by weight of the primary spray) was determined from the condition of the Kolmogorov- Levich to limit the size of droplets that are stable in locally isotropic turbulence gas flow.

$$d_{cr} = 2 \left(\sigma_p / (C_D \rho_p^{0.67} \rho_g^{0.33}) \right)^{0.6} \cdot (d_{p1}^{0.4} / (\omega_g - \omega_p)^{6/5}) \quad (6)$$

The calculation by this method showed that the parameters of empirical DSD for most cases are similar to solid powders obtained in counter PG (they have a criterion of homogeneity $h_{\text{gom}} = 2, 1-4, 5$), are in satisfactory agreement with the characteristics of current distribution (3), indicating that the prevalence of "quasi" fragmentation (atomization) of droplets in the plasma, as expected for gas-dynamic parameters estimation of the mixing zone. Based on data calculated (see example on Fig. 2 for the regime of counter flow plasma gasifier/reactor operated under such conditions as) it was determined DSDs for various regimes of plasma gasifiers operation. For the case of regime which corresponding to DSD of Fig.2 the parameter M_1 was equal 0.11 (i.e. 11 % wt. of low size-fraction of primary droplets which mixed with plasma flow without secondary atomization).

Also for the right conditions, and counter-PHR without postulating any mechanism for the

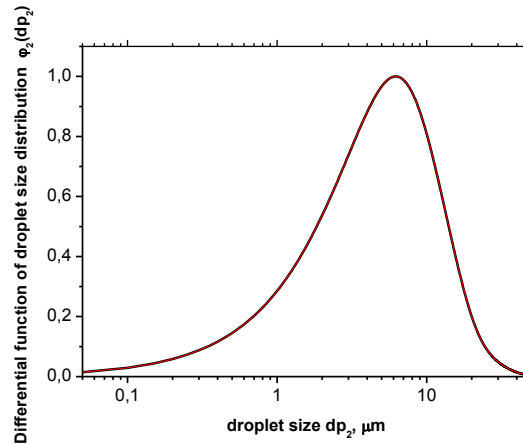


Fig. 3. Differential feedstock' droplet size distribution for the conditions of mixing zone of counter flow plasma gasifier with electric arc torchs and with coal slurry spray, which was calculated based on equations (1)-(4) with postulation of polydisperse gas dynamic secondary atomization (break-up) of droplets in accordance with approximation (2).

Homogeneity criterion $h_{gom} = 4.20$.

transformation of droplets were obtained by the generalized equation (6), (7), which relate the degree of polydispersity (expressed h_{gom}) discussed the variances (secondary droplet and the MF-powder) and the dimensionless mean droplet diameter them with gas-dynamic characteristics of the mixing zone, including Reynolds and Weber.

$$d_2 / d_1 = 0.149 \text{Re}_2^{0.27} (W_{gpl0} / W_{po})^{-0.38} \quad (7)$$

$$h_{gom} = 21.53 \text{Re}_2^{-0.68} We_2^{0.36} \quad (8)$$

Validity ranges of equations (7) and (8): $d_2/d_1 = 0.05-0.32$; $h_{gom} = 2.2-14.9$; $\text{Re}_2 = 0.8-28.4$; $W_{gpl0} / W_{po} = 1.1-30.2$.

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Plasma Coal Burner

Dr. Igor Matveev

Applied Plasma Technologies, LLC; McLean, USA

Applied Plasma Technologies, LLC (APT) works on development of a dual mode plasma coal burner, which flow diagram is provided in Fig.1.

Based on a recently developed and patented new generation of high power plasma torches with virtually unlimited lifetime (US Patents 7955567, 7452513, and patent application 12756303), the plasma burner will produce, depending on the operational mode, either (1) high temperature products of a plasma assisted clean coal combustion process for coal-boiler start up with elimination of the need for any supplemental fuel, and dramatic emissions reduction (NO_x reduction by a factor of 2 to 3), or (2) a high temperature mixture of coal dust and high hydrogen-yield syngas ($\text{CO} + \text{H}_2$) for continuous flame stabilization with significant boiler efficiency increase, and emissions reduction (SO_2 and Hg) due to optional sorbent injection and potential flue-gas cleanup by a secondary plasma stage.

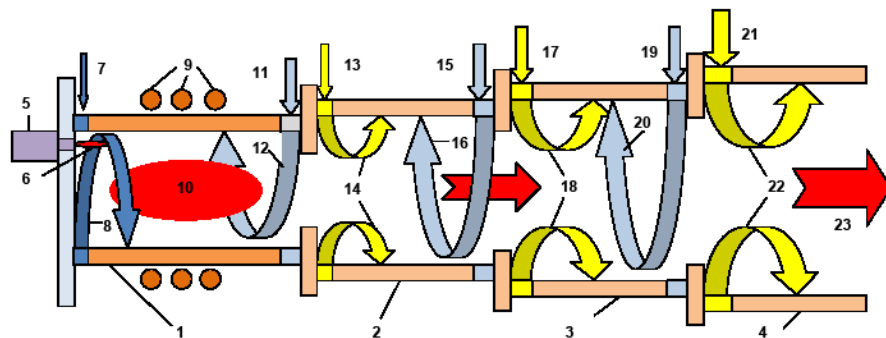


Fig. 1. Plasma assisted coal burner/gasifier scheme (US Patent 7,452,513 B2):
 1 – plasma generation module; 2,3,4 – stages of the combustion/ partial gasification module;
 5 – starting torch; 6 – starting torch plume; 7 – starting gas; 8 - starting gas vortex;
 9 – inductor; 10 – plasmoid; 11 – main plasma gas (air, oxygen, blends);
 12 – main gas reverse vortex, 13 – feedstock 1 fraction 1; 14 - feedstock 1 flow;
 15 - feedstock 2 (optionally water steam), 16 – feedstock 2 vortex; 17 – feedstock 1 fraction 2;
 18 – feedstock 1 flow; 19 – feedstock 2 fraction 2; 20 – feedstock 1 fraction 3;
 22 – feedstock 1 fraction 3 flow; 23 – high temperature exhaust gases/ products of coal dust
 partial gasification

Additionally, under a CO_2 sequestration option, captured CO_2 could be used as a feed gas for plasma generation, coal powder transport, gasification for pure hydrogen production, or CO production for syngas or other applications.

Our product will provide such unique and innovative features as:

- Employment of new-generation high power plasma torches with virtually unlimited lifetime, due to electrodeless design and high efficiency. Total plasma generation efficiency is over 70% and, in the case of steam coal gasification, can reach ~ 80-90%;
- Plasma coal combustion and partial gasification provides significant advantages in

comparison to the state-of-art approach of high temperature (3,000 – 4,000°C) processing, as well as high reactivity – which leads to simple and reliable process initiation, dramatic reduction of processing time, and corresponding decreases in volume and weight of the burner, and the possibility to use steam and oxygen as oxidants;

- Low electrical power consumption – 50 to 100 kW in plasma for 1.5 - 2.5 MW burner;
- Opportunity of sorbent injection for better mixing and more effective processing;
- Dramatic SO₂ and Hg emissions reduction due to different kinetics of high temperature oxidation and higher reactivity of ionized oxidants;
- Short response time – 10-15 minutes to initiate the burner;
- Presently-developed plasma torches can be scaled up from an achieved 300 kW power level to 1 MW per unit and use a variety of plasma-sustaining gases, including air, oxygen, CO, CO₂, water steam, and blends;
- Possible in-boiler syngas production and injection with volumetric hydrogen yield of 54-60%, depending on feedstock composition and oxidant; can also be used for hydrogen production and power generation.

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Dr. Igor Matveev

An Overview of Water Treatment by Plasmas – Advanced Oxidation/Reduction Technologies AO/RTs

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Applied Physics Consulting, Los Alamos, USA

This presentation will provide an overview of water treatment (viz., the destruction of contaminants/pollutants entrained in water) by the use of plasmas, in the context of Advanced Oxidation/Reduction Processes (AO/RTs) – which were historically developed to remove recalcitrant water pollutants. Recalcitrant pollutants are those which persist in the environment for long periods of time and are not easily removed by traditional water treatment methods like filtering, chlorination, or ozonation. Examples of such pollutants include halogenated (chlorinated, fluorinated) hydrocarbons, polychlorinated dibenzo-*p*-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), polychlorinated biphenyls, DDT, and others.

Advanced oxidation processes (AOPs) were defined by Glaze *et al* [1] in 1987 as “near ambient temperature and pressure water treatment processes which involve the generation of hydroxyl radicals in sufficient quantity to effect water purification”. Hydroxyl radicals (OH) which are generated in AOP technologies are very strong and non-selective oxidants. Once generated, the hydroxyl radicals can non-selectively attack organic compounds and are capable of degrading a wide range of resistant organic compounds to ultimate mineralization to CO₂ and H₂O.

AOPs employ reactive oxidizing agents such as hydrogen peroxide (H₂O₂) or ozone (O₃), with or without addition of catalysts or photolysis. These oxidation systems have been used to treat both individual organic and inorganic substances in water under laboratory conditions as well as real effluents from the different sources.

Since 1987, the field of AOPs has been expanded to include reductive agents, such as hydrogen atoms H and solvated/aqueous electrons e_{aq}, which are generated in plasmas in water and water irradiated by electron beams [2, 3] or gamma-rays. The AOP terminology has thus been evolved into Advanced Oxidation/Reduction Technologies (AO/RTs), including aqueous-based plasma treatment of pollutants and some minerals/solids.

The field of aqueous-based plasma water treatment has a history of about two decades, starting with so-called electrohydraulic discharges (EHDs) and corona-streamer discharges which were pioneered by Clements *et al* [4] in the 1980s and Sun *et al* [5], Sunka *et al* [6] and Joshi and Locke *et al* [7] in the 1990s. An excellent review of EHDs and non-equilibrium plasmas for water treatment is given in the publication by Locke *et al* [8]. Additional material on aqueous-phase electrical discharges for water treatment can be found in the more-recent publication of Shih and Locke [9]. Aqueous-phase electrical discharges have been powered by DC, pulsed DC, AC and RF sources – although we will not cite references here. Additional, more-recent work on plasma formation in water has dealt with discharges in gas bubbles entrained in water [10]. This technique appears promising for practical applications.

The foundation for the above investigations was set by studies of underwater arcs (usually produced by capacitive electrical discharges in water), which considered the plasma properties of such discharges. The earliest-reported, plasma-connected research on electrical discharges in water of which this author is aware is that contained in the 1960 publication by Martin [11].

However, for scholars and history-minded individuals, there is the 20th Century publication of 1932 by Carter and Campbell [12] that reports investigations on arc discharges in water, including descriptions of the chemical nature of the arc-produced byproducts. This publication was four years after Irving Langmuir coined the term “plasma” to describe the glow discharges like those in a Crookes tube of the late 19th Century.

Fig. 1 shows a typical circuit which characterizes many investigations of aqueous-phase plasmas. Here, a capacitor is charged to a high DC voltage (typically 5 – 25 kV, depending on electrode geometry) and switched into electrodes placed in water by a spark gap. The resulting electrical discharge is a pulse, whose properties depend on the water conductivity and the circuit parameters. Fig. 2 shows current and voltage waveforms for the case of plasma formation in a saline solution, as recently reported by Morgan and Rosocha [13].

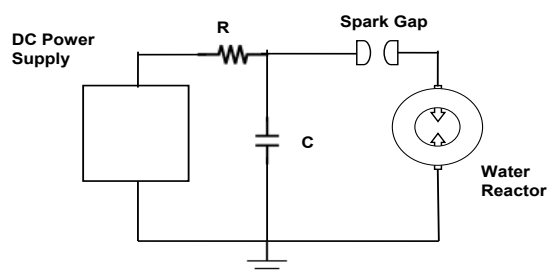


Fig. 1. Typical capacitive discharge circuit for HV electrical-discharge-created plasmas in aqueous solutions

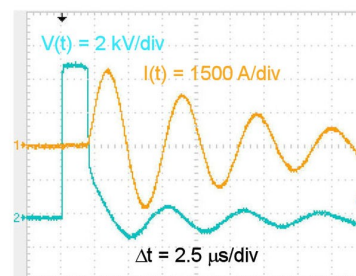


Fig. 2. Current and voltage waveforms for a pulsed HV electrical discharge in a saline solution. The current has been purposely displaced in time from the voltage for clarity of illustration

Table 1 lists plasma parameters for pulsed HV electrical discharges in water taken from the 1960 publication of Martin [11] and the more-recent 1986 publication of Radovanov *et al* [14].

Table 1. Plasma parameters for aqueous-phase electrical discharges. Top (Martin 1960), Bottom (Radovanov et al 1986)

V, kV	I, kA	E, J	T, K/eV	P, atm	[e], cm ⁻³	OH, cm ⁻³	H, cm ⁻³	O, cm ⁻³
25	85	1,800	29,900/2.6	10,000	2x10 ²¹	N/A	N/A	N/A
1.25-1.50	3-4	30-50	18,000/1.6	19.7	1.1x10 ¹⁸	2x10 ¹⁸	2x10 ¹⁹	7x10 ¹⁸

Concerning technology maturity and industrial applications, the field of plasma-based, AO/RTs is in its infancy. We know of no large-scale industrial installations of this technique, although the results of pilot-scale demonstrations have been published in the past two years. The major competition for plasma-based water treatment is water radiolysis, with the most promising systems being based on electron beams [15].

In 2009, Even-Izra *et al* [16] published the results of a pilot-scale demonstration of a pulsed corona-discharge plasma system for treating contaminated groundwater. The system employed a corona-initiated plasma above a volume of water to generate reactive species to degrade pollutants in the water. This does not represent aqueous-phase plasma treatment, but air-based

active-species formation which entails non-direct mixing of the reactive species with the treated water.

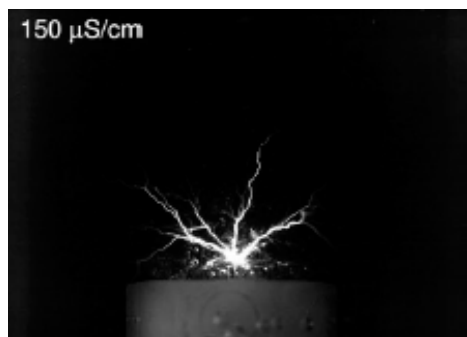


Fig. 3. Photo of pulsed streamer plasma in water taken at 500 fps. Note that high-volume fill is not obtained

based on a device patented in Japan [19]. The system has a flow rate of 69 L/min and a water dose of 3.3 kGy.

Typical, industrial-scale electron beam systems for drinking water and wastewater treatment (with recalcitrant pollutants such as benzene, toluene, and phenol) have a flow rate in the range of 300-600 L/min and a dose range of 0.25-8 kGy to meet water standards [15]. This points out the challenges facing plasma-based water treatment systems: the development of large-scale systems is required; direct water treatment, rather than the mixing of air-generated active species is more desirable; and large-volume active species generation is required. In direct active species generation, diffusion of active species out of electric discharge streamer channels is a limiting factor. The method of air-generated active species is limited by the mixing of the reactive species with the water, requiring the use of very thin water layers which results in cumbersome scalability. Electron beam systems are large bulk-volume treatment systems. To succeed with plasma-based water treatment, we must develop reactors that scale to large bulk-volume treatment. This will also require the development of novel power supplies and impedance matching techniques for powering plasma generation in the reactors.

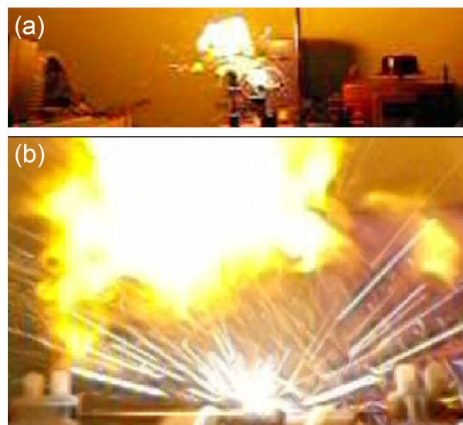


Fig. 4. Fireball from videos of open air salt water discharge (a) 1000 fps, (b) 420 fps

Aqueous-phase plasmas have mainly been explored in terms of water arcs (thermal plasmas) and pulsed corona discharges (non-thermal plasmas - NTPs). As is the case for air-based pollution control, NTPs are probably more effective and efficient in destroying entrained pollutants. Pulsed DC plasma sources are required for such systems. We believe that short-pulse (10s-100s ns) pulsed power modulators (like those used for decades in high average power, repetitively-pulsed lasers) are a promising option for NTP-based water treatment systems. Such

plasma-based processes will likely have an advantage over electron-beam processes in terms of capital equipment cost and radiation safety costs. This workshop and this session will explore power supply and plasma source technology.

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Dr. Rosocha is currently a member of the American Physical Society, the IEEE, and Phi Beta Kappa. He was formerly a member of the International Ozone Association. Dr. Rosocha received two Distinguished Performance Awards during his tenure at LANL, is the author of over one hundred publications in books, refereed journals and conference proceedings, and has five patents to his credit.

Non-equilibrium Plasma Applications for Water Purification Supporting Human Spaceflight and Terrestrial Point-of-Use: Organic Chemical Decomposition via HV Nanosecond Plasma Discharge

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One of the largest contributors to mass required to support long term human stays in space is water (e.g. resupply of the ISS). Also, manned, long duration space missions will require adequate water supplies. In cases where resupply options are limited, supplies can be sustained in part by recycling all water onboard. This work investigates the application of a fast, ns pulsed non-equilibrium discharge for the purpose of water purification with application to recycling systems as well as for terrestrial point-of-use applications in areas lacking water treatment infrastructure. A discharge apparatus was designed, tested and characterized as a function of input voltage and injected air-flow rate. Additionally diagnostics were installed which allowed for fast high voltage and current signals to be measured. The frequency spectrum of the current signal was also documented as a function of applied voltage. The evolution of the discharge as a function of voltage was mapped using a video camera. The effectiveness of the discharge on treating water was tested on simulated textile waste water effluent. Specifically, a DBD plasma jet excited by a repetitively pulsed ns pulse power modulator was used to decolorize a 1.4×10^{-4} M solution of Methylene Blue (MB). Time resolved decomposition of the MB in solution was assessed using spectrophotometry and high pressure liquid chromatography (HPLC). Spectrophotometry results were found to be in agreement with chromatography measurements. HPLC revealed the absence of appreciable intermediates suggesting high level mineralization. Acidification was also observed during processing. Samples from Rocky River, Ohio and Huron River, Michigan were also treated, and the analyses are ongoing.

Introduction

Conventional water treatment systems purify water through essentially two processes: filtration and disinfection [1]. In this regard, the conventional system is designed and optimized to address suspended particles and microbial contaminants. Such systems are not capable of addressing organic compounds present in the water. With increased industrialization and urbanization, water the contaminant levels of organic compounds in source water has been on the increase [1]. These contaminants include herbicides and pesticides intrusion into the water supply derived from runoff [1]. In addition, industrial toxins such as dyes, aromatic compounds, halogenated hydrocarbons, petroleum products and derivatives, as well as pharmaceuticals are all now detectable in the source water supplies [1]. These contaminants are not removed from source water when treated conventionally [1-2]. Though these contaminant levels are low, it is not clear of the health impact of the chemicals presence. Through the process of bioaccumulation, these toxins can build up in the body, particularly in fatty tissue leading to biomagnifications. In this manner, the food chain can be contaminated. An example of dangers of these processes may be found in the Great Lakes, which are currently contaminated with PCB [1].

One method of water remediation or decomposition of organic contaminants is the application of advanced oxidation processes (AOP) [1-6]. This method involves the introduction of species such as OH, atomic oxygen, ozone, peroxide, ultraviolet light and excited nitrogen into the liquid water. OH has nearly twice the oxidation potential than chlorine. Highly reactive radicals such as OH decompose organic compounds through a process known as mineralization. This process involves the oxidative reduction of contaminants to carbon dioxide and water vapor. Though these methods can be introduced into liquid water conventionally, it is the injection of these processes into liquid water via plasma injection that has attracted much attention in recent years [2-6]. Plasmas are desirable in that through the interaction of plasma with water, all of the aforementioned advanced oxidation components can actually be generated at once. The radicals are short-lived so the plasma method allows for AOP introduction on demand without appreciable residual effects. Plasma based injection of AOPs has potential advantages over conventional methods both in the area of decomposition rates, energy efficiency. Additionally, in principle, AOPs do not require consumables as conventional methods require - such as UV-Ozone methods. An active area of advanced oxidation techniques via a plasma discharge involves quantifying 1) conversion efficiency, 2) electrical efficiency, 3) throughput [2-4].

Experimental Setup

The underwater discharge apparatus utilized in this study is of similar geometry to that used in a previous low frequency, ac excited DBD discharge study [7]. The apparatus consists of a central electrode biased positively and a negatively biased coil electrode. As shown in the figure, the coil electrode is located near the tube end. A dielectric material such as quartz or alumina encloses the central electrode. In the present case quartz is used as the dielectric. The entire applicator is submerged underwater. In this manner, the discharge apparatus has the appearance of a dielectric barrier discharge with the water and the dielectric tube serving as the intervening insulator. The discharge apparatus was powered using a rapid rise time pulse generator. The generator is capable of producing pulses with a peak voltage up to 40 kV at a repetition rate of up to 100 kHz. For these experiments, the repetition rate was set at 9 kHz. The primary voltage pulse had a width of 20 ns and a rise time of approximately 2.5 ns. Gas was injected into the discharge apparatus using an air pump, which forced air through the gap between the central electrode and the inner surface of the quartz tube. An air pump supplied continuous gas flow up to 10 SCFH. The entire apparatus was mounted into a cylindrical vacuum chamber approximately 60 cm long and 40 cm in diameter. The enclosure was useful in minimizing electromagnetic interference produced at the source plasma as well as confining any process gases produced through the interaction between the plasma and the water or air. For all tests reported herein, the operating pressure was ambient at 1 ATM.

Results Summary

The DBD underwater plasma jet excited by a nanosecond pulsed power modulator revealed the presence of three discharge modes during operation. The modes included a corona glow, discrete microdischarge jets and streamers. Several illustrations of these modes, characterized by a background glow—corona in nature, the discrete jets, and streamers emanating from electrode tip were recorded. Because the various discharge modes possess unique electron temperature and density, radical production is multifaceted and likely highly nonuniform. The

discharge was used to decolorize an MB solution. Spectrophotometer measurements agreed well with the more precise liquid chromatography measurement of MB concentration. Both revealed similar exponential decay and decay constants. Plots of the degradation in molarity of diluted samples with time will be presented. Furthermore, the liquid chromatography did not indicate a significant presence of intermediates, suggesting that mineralization was indeed taking place in the solution. The discharge efficiency was found to vary as a function of time. The decomposition efficiency was highest at early times and essentially decayed via a power law. Decomposition efficiencies were higher than glow discharge and pulsed corona discharges reported in the literature. It was also found that the decomposition efficiency did not depend appreciably upon initial volume solutions for similar concentrations. A pathway to scaling up the discharge active volume through parallel operation (multiple source applicators) was investigated. Operation with two sources, powered in parallel, revealed stable operation and rapid MB decomposition rates. Distributed or parallel mode operation is likely the most logical method of improving process time regardless of excitation method. Results will be presented of the time variation in solution color as a function of treatment time using the dual applicator.

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From 1981 to 1988, he was an aerospace scientist at the General Electric Corporate Research Center (CRD), NY where he conducted research on hypervelocity plasma-armature projectile launchers and gas-dynamic circuit breakers. Dr. Blankson has two US patents including one on an MHD-controlled turbojet engine. He is an Associate fellow of the AIAA. Recently (2006), he was the recipient of the Presidential Rank Award of Meritorious Professional for sustained superior accomplishment.



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From 1998-2006, he serves as a Senior Scientist, NASA Glenn Research Center, in the Space Propulsion and Power Branch where he conducted research on ion thrusters. Dr. John Foster has spent over 20 years investigating plasma discharge and plasma source development. He previously investigated macro-particle acceleration driven by low current, high voltage cathode spots for potential applications ranging from micrometeoroid simulation to nanoparticle deposition/implantation. Current research includes electric

discharges and streamers in liquids through vapor phase channels produced by the streamer, or in gaseous bubbles. Recent work has specifically addressed the study of plasma discharges in liquid water, the ultimate goal being the development of point-of-use water treatment systems for places lacking such infrastructure. Dr. Foster is a member of the American Physical Society, and is the recipient of several NASA technical awards.

Water Treatment and Power Co-Generation Using Hydro-Thermal, Supercritical Water Produced by Pulsed Electric Discharges

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Recent experiments and analyses published by Morgan and Rosocha [1] have demonstrated the possibility of producing supercritical water at high temperatures and densities using a short pulse electric discharge in saline solutions. Such an experiment is depicted in Fig. 1. The electrical conductivity of the electrolyte is far greater at the liquid surface than is the bulk conductivity. A short pulse, high voltage and current surface discharge will then ablate liquid layers, much like laser ablation, driving the ablated fluid to high temperatures at pressures and densities above the saturation line, as is found with exploding wires in water. Fig. 2 shows an example of a computed trajectory in (p, T) – space. This calculation was performed in one-dimension using a self-similar solution to Euler’s hydrodynamic equation without energy dissipation. The time-scale is 10s – 100s of nanoseconds.

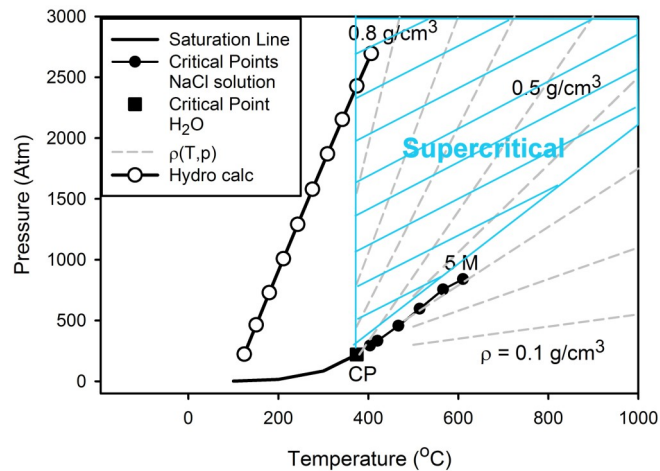
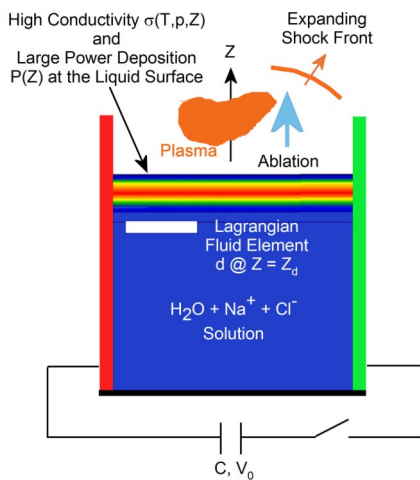


Fig. 1 , Depiction of the geometry of the experiment and fluid model

Fig. 2 . $p(T)$ from hydrodynamic surface discharge calculation along with the water saturation line, critical points for 0.5 – 5 M salt water solutions, and fluid density $\rho(T, p)$ contour

In our experiments we deposited 15 – 20 Joules of energy (~10 kV, ~500 A) into a thin layer of water in several microseconds and observed Mach 4 – 8 shock waves and transonic bulk fluid flow in our closed test vessel. The electrical energy deposited was too small to produce such shocks. Similar observations were made by several authors in experiments performed between 1985 and 2001. See Ref. 1 for the citations.

We have proposed in [1] that the exothermic ion chemistry in the ablated supercritical water releases enough energy on a short enough time-scale to produce a detonation front and propagating shock wave. We have since demonstrated the feasibility of this scenario via

thermodynamic and detonation – shock modeling [2]. Via speciation and enthalpy calculations we have shown in [2] that equilibrium thermodynamics predicts a sizable net exothermicity when taking a thin film of water from (1 atm, 25°C) to, say, (1,000 atm, 600°C). Whether this is operationally feasible depends upon the details of the microscopic physics and the macroscopic fluid dynamics and energy transport. The short pulse electric discharge is the most likely approach to the experimental parameter space where the thermodynamic possibilities might be realized.

Given that we can produce hydrothermal, supercritical water in a pulsed surface discharge on an electrolytic solution, we propose that the supercritical water may be useful for treatment of wastewater and, in addition, produce some amount of recoverable energy. Research on the use of supercritical water oxidation (SCWO) and so-called hydrothermal flames [3, 4] has been in progress for a couple of decades. The concept is based on the remarkable property of supercritical water that its dielectric constant ϵ_r , which is ~ 78 for water under normal conditions, can range from $\epsilon_r \simeq 20$ down to $\epsilon_r < 2$. The normal balance of $[\text{H}_3\text{O}^+] = [\text{OH}^-] = 10^{-14}$ is disrupted and water can become acidic having $\text{pH} \ll 7$; electrolytes become less soluble; gases become miscible; and organic compounds become soluble. In short, supercritical water behaves as an organic solvent [5, 6]. These properties make supercritical water potentially an ideal medium for oxidizing substances that, under normal conditions are not even soluble in water. Such experiments have been highly successful in breaking down and oxidizing urea [7], acetic acid, ammonia [8], nitrates/ nitrites, cellulose, oil/ grease [9], fecal matter [10, 11], and in incredible variety of substances. It has also been shown that significant fractions of the energy required to produce the supercritical water can be recovered from the exothermic enthalpies of reaction of the oxidation processes.

The difficulties encountered in an operational continuous flow system are mostly materials issues. In addition to pumping and flowing substances such as those listed above through tubular reactors at temperatures of 100s °C and pressures of 100s atm, the supercritical water is a very corrosive hot acid.

The previous two paragraphs have been a brief summary of the state of SCWO research to be found in the published literature to date. If our suppositions about the fluid properties of the ablated salt water in a short pulse surface discharge are correct, it may be feasible to use the supercritical water so produced in an SCWO wastewater treatment process with power co-production to recover much of the energy from external sources used in the process. The individual devices are small and relatively inexpensive to construct. It may be reasonable to pulse each one at 100s – 1000 Hz. Hence an SCWO processing system comprising many such reactors operating in parallel may be feasible.

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Power Supply for Discharges in Gas Flow

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Research and development associated with the plasma assisted combustion and the catalytic plasma conversion are a progressing field of activity [1]. In the recent papers [2, 3], the investigations of specific gas-discharge regimes in plasmatron for sustainment of combustion process have been presented. These regimes can be referred to as a kind of glow discharge at an average current of about (0.1 - 0.2) A with the random transitions from glow to sparks. The discharge manifests itself as an essentially nonsteady state load for dc power supply. Papers [2, 4] describe a version of power supply with a maximum output voltage up to 10 kV that had been intentionally developed for similar type of gas-discharge loads. The results of further work on improvement of the primary version are presented below.

The operating diagram for the novel power supply is shown in Fig. 1.

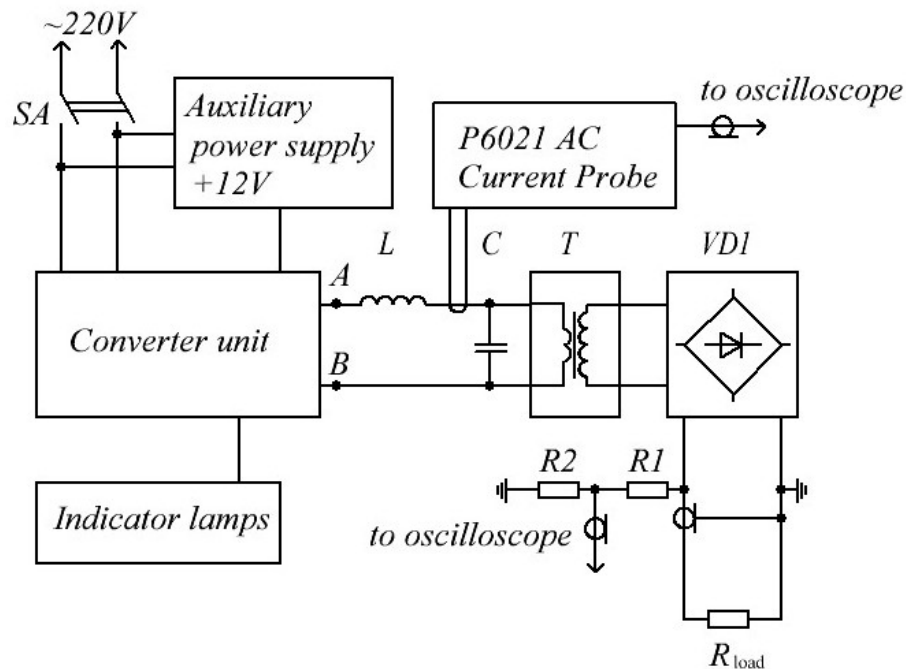


Fig. 1. Operating diagram for power supply with maximum output voltage up to 20 kV. Voltage of 20 kV at the secondary coil of pulsed transformer T is provided due to resonant charging of capacitance C via inductance L. Current Probe P6021 AC is used for measurements in the course of testing.

The main part that determines the principle of operation is the Converter unit. The alternating industrial voltage is rectified to a value of 310 V and after that is converted to a bipolar-pulsed voltage. The converting is provided by a half-bridge converter circuit. Then at the output of Converter unit (between the points *A* and *B*) we have the bipolar voltage pulses ± 155 V with a frequency of 50 kHz.

The bipolar voltage is applied to the primary coil of the pulsed transformer *T* with transformation ratio $k = 35$ via the resonant *LC* circuit. The increased voltage at the secondary coil of the transformer is rectified by the diodes *VDI* so that a pulsating current with a frequency of 100 kHz is delivered to a load.

The power supply is intended to deliver a current value of about 0.1 – 0.15 A in a wide range of variations of load resistance R_{load} . Then the voltage at the load V_{load} is determined by its resistance. The parameters of *LC* circuit are selected from the condition to provide approximately constant current in the load when the load resistance is varied from zero to 50 k Ω .

LC circuit operates by the following way. When R_{load} is close to zero (for example, a short circuit with arc discharge) then an influence of the capacitance *C* on the current in the load is negligibly small. The current is limited by the inductance *L* at a level of 0.1 – 0.15 A. Increasing in R_{load} results in the situation when the capacitance *C* starts affecting to the load current jointly with the inductance *L*. When the load resistance increases the voltage at the capacitance *C* increases as well. This leads to an increased voltage drop at the secondary coil of transformer. The tuning provides the condition that the output voltage of power supply with open circuit does not exceed 20 kV.

The voltage waveforms at the resistive loads jointly with the current waveforms in the primary coil of the pulsed transformer *T* are shown in Fig. 2 (method of current measurements is presented in Fig. 1).

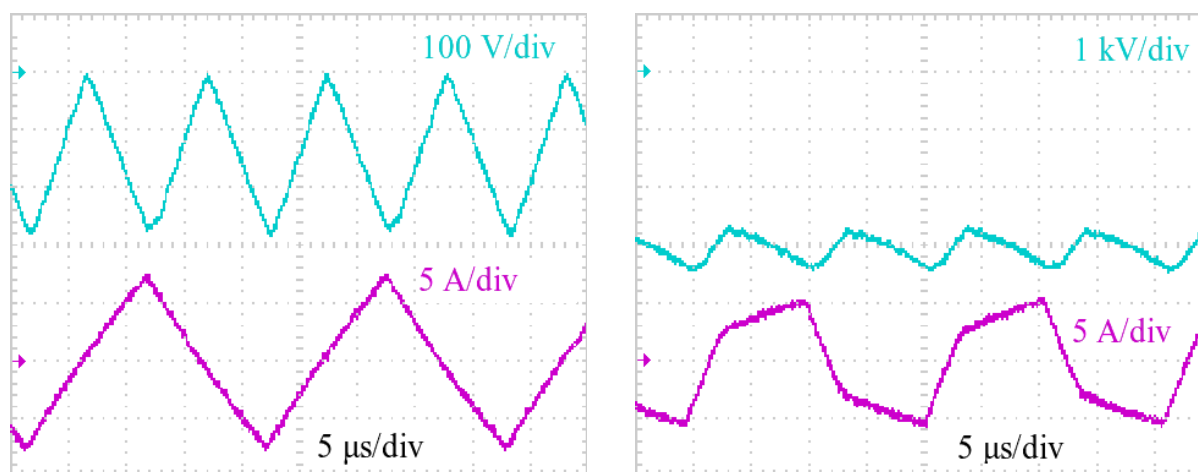


Fig. 2. Voltage at the resistive loads and current in the primary coil of the pulsed transformer *T*
a) $R_{\text{load}} = 1.25$ k Ω , b) $R_{\text{load}} = 35$ k Ω

It is seen that the current has a bipolar form with a frequency of 50 kHz. Then the output rectified voltage has a pulsating form with a frequency of 100 kHz. For a load $R_{\text{load}} = 1.25$ k Ω , amplitude voltage value $V_m = 280$ V, amplitude current value $i_m = 0.22$ A, and RMS load

current $i_{\text{load}} \approx 0.13$ A. When we increase the load resistance to $R_{\text{load}} = 35$ k Ω , amplitude voltage value is increased to 3.4 kV. In this conditions, RMS load current $i_{\text{load}} \approx 0.09$ A, and an average power dissipated in the load $Q \approx 280$ W. The testing show, that the regime with such a power still seems to be normal for power supply, i.e. the power supply is able to deliver into the loads a power at a level of (250 - 300) W.

An example of the voltage waveforms for the very first breakdown of a high-pressure plasmatron is shown in Fig. 3. The conditions correspond to the situation when the plasmatron is connected to the power supply by a high-voltage cable with a length of 2 m (cable capacitance is of 300 pF).

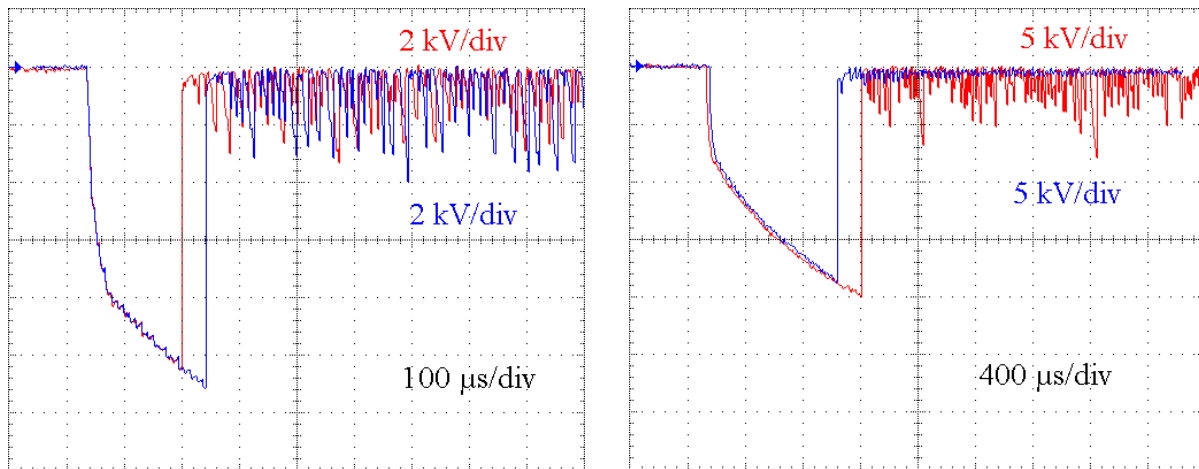


Fig. 3. Voltage waveforms for the very first breakdown at the electrodes of a high-pressure plasmatron. a) $p=4$ bar, b) $p=10$ bar

Figure 3a shows that the cable is charged to a voltage of about 11 kV for 100 ms. After that the breakdown occurs, the discharge in the gap appears, and the voltage sharply decreases. We can see that the breakdown voltage value fluctuates from pulse to pulse.

Evidently, that when a gas pressure in the gap is increased, the static breakdown voltage increases as well (Fig. 3b). For a pressure of 10 bar, the breakdown voltage corresponds to 20 kV. However, an average voltage at the plasmatron electrode in the course of discharge operation is normally not exceed of 5 kV.

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Power Supplies for Non-Thermal Torches

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We present results of a three year strategic partnership in development, production, and marketing of the power sources for non-thermal plasma torches. Over 20 samples with fixed output (50-500 mA), regulative output (50 mA to 1 A), and for feeding from one to six torches by independent channels were developed, tested, and shipped to customers in the US, Canada, Belgium, Israel, and New Zealand. Depending on application, breakdown voltage can vary from 10 kV to 30 kV. The power supply list includes as an option a water proof, shock resistant, and sealed performances. Fig.1 demonstrates front panel of the regulative output power supply in operation. Fig. 2 and Fig. 3 show shell fish at the moment of treatment by non-thermal plasma and after treatment.



Fig. 1. Regulative output power supply for research purposes



Fig. 2. Non-thermal torch for mussel opening



Fig. 3. Opened by non-thermal plasma mussel

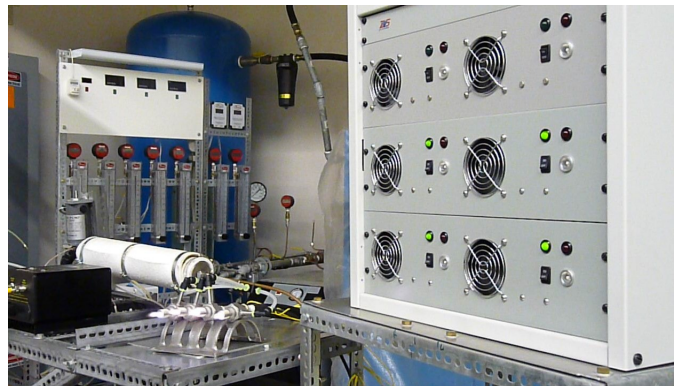


Fig. 4. 6-channel power supply in operation

An Overview of Recent Innovations in Power Sources for Advanced Plasma Processes

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There is no solution which already satisfied every engineer. There is no process engineer which would be satisfied with all the features offered by any of the power supply available on the market. HUETTINGER Electronic together with its mother company TRUMPF has a clear mission. It is to be always innovative and offer the highest quality products. Does this mission fulfill the dream of every process engineer? The author presents only selected innovations introduced by HUETTINGER in last 2 years which are available in standard solutions. The answer for question naturally stays open and should be answered by the reader.

There are many different challenges in front of power supplies engineers. There is no special investigation needed to list such features like reliability, controllable break downs, accuracy and repeatability, efficiency, footprint and packaging, interface flexibility, communication interface speed and flexibility, price equivalent to value achieved ending at selected and more detailed requirements forced by process itself like arc management which assure no arc influence on the process, no hysteresis phenomena in reactive processes, process stability independent on system configuration (like cable length or even cable quality or features) and many others.

Most of the generators currently offered by HUETTINGER contain all above listed features and selected has been presented.

How to detect and react on the arc phenomena in order to do not influence the process?

The short as possible arc detection time is crucial for the arc management process but not necessary the most critical. The fastest the arc is detected and the shortest break time occur the smaller the arc related power losses exist and finally the probability of secondary arc occurrence is very low [1]. Simplifying the sentence, the time during which the power is delivered to the arc should be limited to zero (does not taking into account the processes when the arc energy is required by tendency).

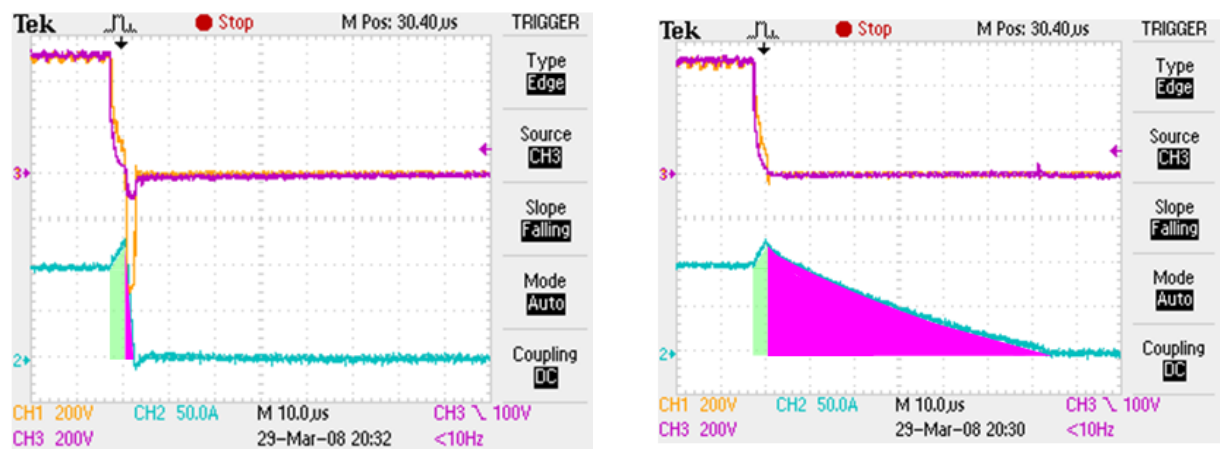


Fig. 1. An example of arc energy limitation with the CompensateLine innovation

The cable length compensation features commercially called CompensatLine assure the lowest energy currently commercially available and gives a process ability to return to stable operation in microseconds. Also the energy delivered to the arc is limited to below 0.3 mJ and is independent on cable length. An example of arc energy limitation at 50 kW operation where the stored energy in the cable and delivered to the arc is reduced by the factor of 13 with the total energy of 10 mJ is presented in Fig 1.

How to supply the reactive processes in the way the hysteresis does not exist

HIPIMS (High Power Impulse Magnetron Sputtering) [2, 3] produces high ionization percentages in the sputter flux; these can be used for film densification, surface modification, trench filling and other applications. Layers produced with HIPIMS show superior properties in many applications. One of the unique feature of HIPIMS technology is lack of hysteresis loop [4] of reactive sputtering. In case of the DC technology the process does not allow to reach a high rate sputtering of the oxide. If HIPIMS is used for the same process then the target is kept metallic at significantly higher oxygen flows and most importantly Aluminum Oxide can be sputtered at much higher rates than for the DC case as presented in Fig. 2.

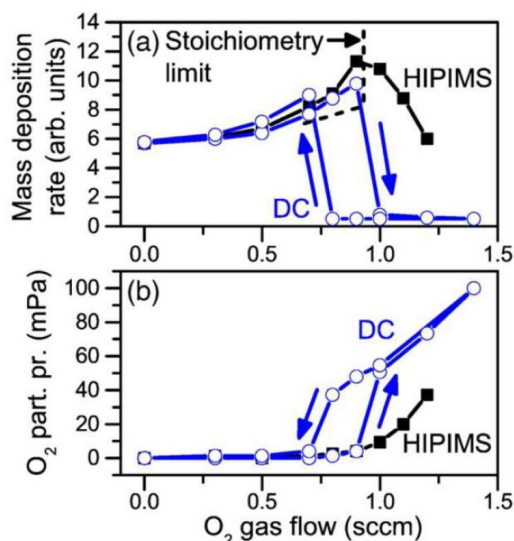


Fig. 2 Hysteresis-free reactive high power impulse magnetron sputtering [4]

How to assure same high accuracy and repeatability at all power levels

Continuous improvement and wish of the semiconductor market helped HUETTINGER's R&D engineers to design the generator with power accuracy $\pm 0,8$ W or $\pm 1\%$ and power repeatability ± 0.8 W or $\pm 0.8\%$. It has been achieved for the whole power range [5].

How to to minimize energy consumption and optimize the efficiency

It was always a goal for engineers to use the energy only for the designated purpose. Any waste should be minimized. This was achieved in both DC and RF generators recently introduced on the market. Just for example previously presented feature of the cable length compensation for the DC generator has ability to re-use the energy stored in the cable [6] (which was pulled backed from the cable in order to do not feed the arc). In case of RF generators a class D topology [5] has been implemented in order to convert the DC power into RF. This feature helped not only to reach the efficiencies higher than 80% (if compare to A/B $\sim 50\%$, E $\sim 60\%$,) but also reduces cooling requirements and finally decrease a temperature stress for internal components what finally significantly improve the reliability of the generator.

How to control breakdowns and assure very high MTBF

The measuring capabilities and finally sensing of every detailed behavior of the system becomes a must for current processes including processes inside of the generator. It is not only voltage and current to verify the process status but temperature in tens of measuring points. Actually it would not be surprise if the pressure became a measured parameter as well.

It has been recently introduced the software which can successfully work as a process oscilloscope (Fig. 3) and help an engineer to work with the system to optimize the usage and tune it into the process. The oscilloscope feature help also more advance electrical engineers to diagnose the status of the generator, especially power modules, and predict unexpected failures.

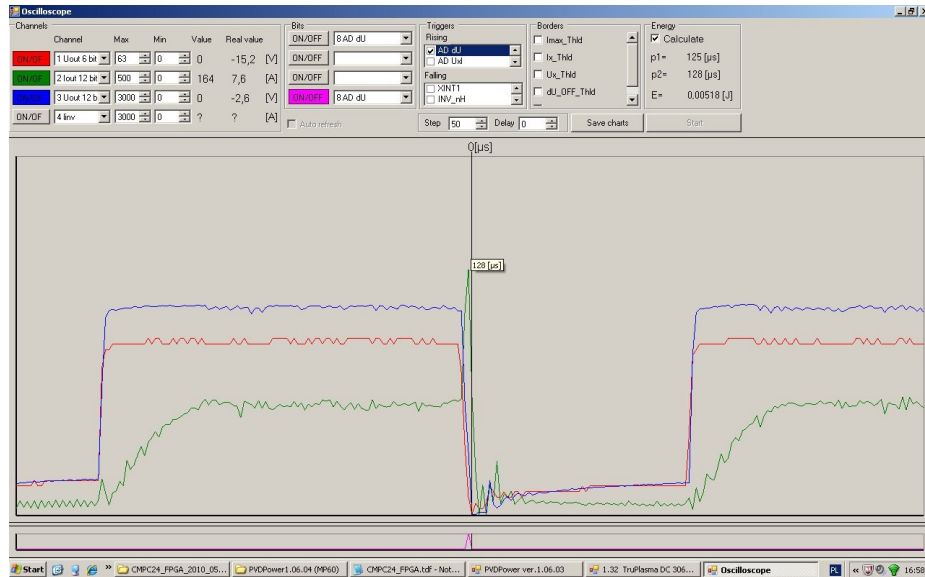


Fig. 3. Internal oscilloscope - Observation of output signals: arc energy calculation, output current, output voltage, and internal signals: driving signals, ADC signals, FPGA signals and microcontroller signals

How to get low footprint and packaging

Another dream for all of design engineer is to minimize the dimensions of the system and getting the same output at the same time. The recently presented by HUETTINGER Electronic results are very promising. Just for example a 12 kW RF 13.56 MHz generator a few years ago (still in sales) needs to be installed in a cabinet of size of average home refrigerator. Today the new 12 kW RF generator fit to standard 19" deep and 4U (equivalent to 7") high.



Fig.4. More power in less space – comparison of 10kW RF 13.56 MHz old design with 12 kW RF 13.56 MHz generator today

Several other improvements has been implemented, launched on the market and accepted by process engineers and system designers worldwide. Will it be enough to fulfill the dream of every process engineer? The answer naturally can only be one – No.

The assigned mission for HUETTINGER's engineer will not always be to work hard to introduce new innovations and offer the high quality products. It should be said "work hard and try to catch the endless imagination and creativity of the process engineers".

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Paweł Z. Grabowski, was born on March 18th, 1970 in Warsaw, He was graduated from the Warsaw University of Technology (Warsaw, Poland) in the Industrial Control and Power Electronics faculty. The Ph.D. Degree in Electro technology has received in 2000. He has an industrially implemented patent for frequency converters technology. From 1999 moved to industry working initially for Schneider Electric than after a few years for Advanced Converted (Poland) having pleasure to be co-builder of a fast growing company and introducing to the Plasma Market technology “on the edge”. As the result the company has become part HUETTINGER Electronic GmbH (TRUMPF Group) after acquisition in 2007. Since 2008 Paweł has been with HUETTINGER Electronic Inc. (USA) as President of this company.

Main Requirements to Prospective Power Supplies for High Power 1+ Bar Pressure RF Torches

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Specialists know that over 50 years of ICP plasma application unfortunately did not lead to development of the power supplies (PS), especially for plasma. All utilized in vacuum systems power sources are mainly modified welders and heaters both solid state and vacuum tube based. The main reason for such a situation is the absence of the market caused mainly by the absence of the atmospheric pressure torches, hard plasma initiation at atmospheric pressure, and low efficiency of existing power sources.

The situation has changed due to recently developed 1+ bar plasma torches with reverse vortex plasma stabilization for such emerging markets as coal, waste, and biomass gasification, nano-powders production, new and high purity materials sintering, high velocity plasma spraying, ash vitrification, precise metals recycling, and so forth.

To enable new RF plasma based technologies, a new generation of power sources should be developed within the next 1 to 3 years. We see a need in two types of high power PS both solid state and vacuum tube based – experimental and industrial. Experimental or laboratory samples should provide researchers with the opportunities to run multi-gas torches within a wide range of the plasma gas flow (0.5 to 5 g/s), plasma power (30 – 1,000 kW) and pressure in the plasma chamber or reactor (1-10 bar) and precisely measure main process parameters including coil voltage and current. These power supplies will have so named two-circuit schemes to allow wider regulations and more sustained operation. The industrial samples in major cases should be more likely remotely controlled one-circuit black boxes with power input, RF power output, coaxial cable (at least 3 meters length) to connect PS and torch, operate according to custom developed software, and sustain hard environmental conditions as temperature up to 60 °C, dust, etc.

We see in the first stage more practical and feasible development of the vacuum tube based sources with operating frequency 5-10 MHz, output by coaxial cable, and matching network coupled with a torch. Total power losses excluding coil should not exceed 30%, specific weight (kW of output power in coil per kg of weight) $\leq 3 - 5$ kg/kW, and specific volume ≤ 5 to 10 l/kW. The power supply should have integrated ignition gas supply and remote discharge initiation systems, provide independent regulative output power and voltage over 5-6 kV (RMS) to enable torch operation on such gases as Ar, air, O₂, CO₂, water steam, and different blends, and optionally integrated or detached closed loop water cooling system. Depending on the application and customer budget, PS should have optional plate power supply based on high voltage dry type transformer or solid state inverter. We also believe that the tube operation mode optimization and other critical components improvements could lead to the PS's efficiency (coil power to consumed one from the grid) increase to 69-75% and extended to 5,000 – 7,000 running hours maintenance period.

The second stage beginning will be defined by the progress in development of high frequency solid state units and will have the main objective of significant up to 85-87% increase of the power supply efficiency and maintenance cost reduction due to elimination of components with limited life time. At the moment, achieved level for high power (over 100 kW)

systems is 800 kHz. This is not enough for atmospheric pressure discharge initiation by retractable electrode. Using as an alternative solution as the hybrid plasma torches seems not practical and less feasible at the moment in comparison to the vacuum tube based systems.



Dr. Igor Matveev



Evgeniy Petrov was born in St.-Petersburg, Russia on August 13, 1959. He earned his Master of Science degree in high frequency electronics and technologies from Leningrad Electrotechnical Institute in 1982. From 1982 to 1992 he was an engineer, researcher, and senior researcher with the Scientific Research Institute of High Frequency of the Russian Academy of Sciences. Mr. Petrov was involved in development of atmospheric pressure up to 500 kW power RF plasma systems for variety of applications, including coating and nano powders production. From 1992 to 2000 was with PLASMAS, as a chief engineer, developing RF based technologies for seeds processing, wood drying, biomedical waste gasification, etc. Developed under his supervision was a wood drying plant with 1 MW power and 1.500 tons capacity and has been in operation since 1998. From 2000 to 2010 Mr. Petrov was a senior technologist with APIT, France focused on nano-powders production, waste pyrolysis, wood processing, drinks sterilization, etc. He has performed a number of projects for customers in Poland, Finland, Switzerland, China, and USA, is an author and co-author of over 20 patents, including 2 US Patents, and 3 Patents of France. From 2011 Mr. Petrov is with Applied Plasma Technologies, LLC as a senior engineer responsible in RF power supplies development and production.

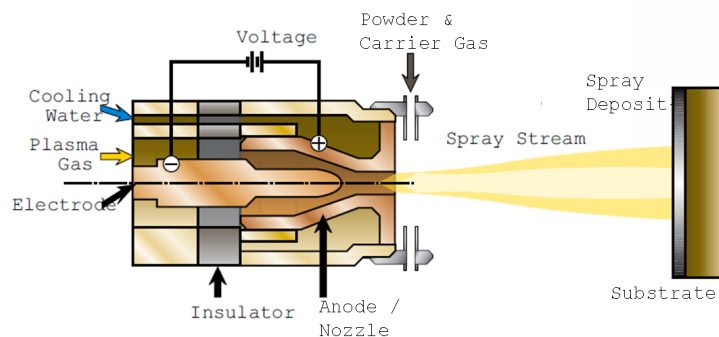
Current Status of Plasma Spray Coatings

*Dr. Rajan Bamola, Dr. Vasudevan Srinivasan
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The use of thermal spray and in particular plasma spray to form functional surfaces has reached maturity in many industries. This short review outlines the plasma spray process, commonly used torch design, the interaction between the plasma state and spray material and their influence in coating microstructure. A summary of common plasma spray feedstock material used in various industries and their uses is presented.

Plasma spray can be described as a process where plasma is used as a source to impart thermal and kinetic energy to finely divided particles of coating material, heating and accelerating them to temperatures and velocities where upon impact on specially prepared surface, particles impinge, cool and form a functional surface. Continual passes of the torch result in coating build-up.

DC single cathode torches are commonly utilized for industrial coating production. Typical water cooled gun is comprised of a thoriated tungsten cathode and an annular copper anode, which also acts as a nozzle for the directing the plasma flow. A primary gas such as argon or nitrogen is mixed with a secondary gas such as hydrogen or helium and ionized to form the plasma. This plasma is then forced out through the anode/nozzle where the coating material, in the form of powder, is injected into the stream. Plasma spray coatings have a characteristic lamellar structure as a consequence of particle flattening upon impact.



*Fig. 1. Schematic of typical DC Plasma Spray Process
(courtesy Sulzer Metco)*

Typical process stages of functional importance are identified in the schematic below. Coating properties are governed by their microstructure, which in-turn is influenced primarily by the plasma and the feedstock powder amongst other variable clusters.

Key plasma parameters such as enthalpy, energy density and its spatial distribution upon exiting the nozzle, and gas velocity influence the interaction between the plasma and the injected powder. Second level parameters influencing these primary parameters are the amount and type of gases, gun design and the power input, most of which can usually be controlled independent of each other.

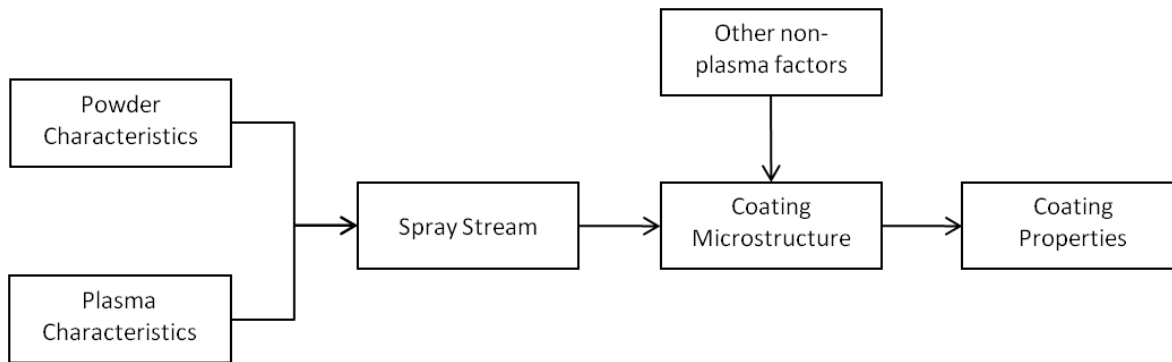


Fig. 2. Schematic of key variable clusters influencing the plasma spray process

The other key component in determining the coating microstructure/property/performance is the feedstock/powder characteristics and their injection into the plasma jet to form the spray stream. Powder characteristics such as their size distribution, density, thermal conductivity, specific heat, emissivity and reactivity (usually to oxygen) determine the property of the coating under consideration. The key dividing factor is the location and type of injection – axial (injected inside the gun axial to the plasma jet typically through an opening in the cathode) or radial (injected perpendicular to the plasma jet as shown in figure 1, usually external to the gun). Most reliable and widespread form of plasma spray incorporates radial external injection (as shown in Fig. 1). The most significant impact of particle injection comes in the form of spatial distribution of powder particles at the point of introduction into the plasma jet and downstream.

All aforementioned powder characteristics along with radial external injection lend itself to a very stochastic deposition process due to the trajectory and distribution of powder particles. Interaction of this stochastic distribution of particles with the property distributions of the plasma jet results in a complex as well as versatile spray stream that is as unique as the process parameters controlling it.

Despite the complexity of the spray stream, their importance has led teams of researchers to understand its behavior and control it to tailor the process to achieve the desired coating property and functionality. An array of ensemble and single particle sensors have been developed in the past few decades in an effort to understand the spray stream.

The steep plasma temperature and velocity gradients as well as powder size distribution, result in varying thermal and velocity histories for particles, which when combined with the rapid heating and cooling lead to microstructural variations in the coating. This is shown in Fig. 3.

Needless to say manipulation of the coating chemistry and microstructure determines the functionality of the surface. The final coating chemistry is a function of the starting powder, plasma-particle interactions and the gas-material reactions that occur as a result of exposure to the ambient environment.

Plasma spray is utilized in a broad range of industries. The predominant use of this technology being in aero and industrial turbines. Here, sprayed coatings are utilized as thermal barriers, oxidation and wear resistant surfaces. Typical materials are partially stabilized zirconias as thermal barriers, chrome and tungsten carbides with appropriate binders as wear

materials and a special class of material with an acronym MCRALY where M stands for nickel or cobalt, CR is chromium, Al is aluminum and Y is yttrium. Chemistries of these materials are formulated to yield optimum performance as oxidation and/or sulphidation resistant coatings. A further use of these materials is as bond layers for ceramics such as the thermal barriers. Current research is being conducted on new thermal barriers capable of up to 1300-1400 °C performance and environmentally resistance coatings for silicon ceramic composites.

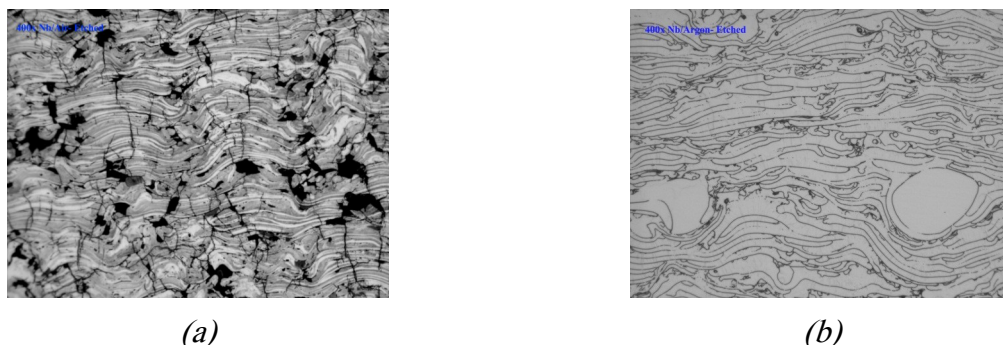


Fig. 3. Optical Cross-Sections of Niobium Plasma Spray in (a) air, (b) Inert Chamber

Plasma spray coatings are used on implants in the medical field. In these applications the biocompatibility of titanium and calcium phosphates (hydroxyapatite), is utilized to ensure osseointegration. Titanium is chamber sprayed under inert or light vacuum conditions to minimize gas-metal reactions which occur when spraying is conducted in air. Careful control of the titanium particle size is needed to realize a porous layer to allow good adherence of connective tissue during the healing process. Another application in the medical field is dielectric coatings (normally alumina) on knives for electro surgery. A passage of current cauterizes the wound, the alumina coatings prevent shorting of the cutting surfaces and restricting the current to the cutting surface.

Green energy applications are of increasing importance. Plasma spray is used in solid oxide fuel cell (SOFC) manufacturing to fabricate the cathode and electrolyte for cells. The cathode is a gas tight yttria stabilized zirconia layer whereas the cathode is a ternary oxide of lanthanum strontium and magnesium (LSM). Density, crack distribution and chemistry all need to be tightly controlled to enable successful performance. In thin film solar cell manufacturing sputter targets are used to deposit films with specific functions; electrical conduction, absorbance, transparency etc. Plasma sprayed targets up to 13mm in thickness can be used as the source material for these. Materials range from molybdenum, chromium, zinc- aluminum oxide, silver, copper, copper gallium indium and silicon aluminum. Depending on the performance required the manufacturing process can be conducted in air or inert conditions.

Table 1. Comparison of Properties of Air and Inert Environment Sprayed Molybdenum

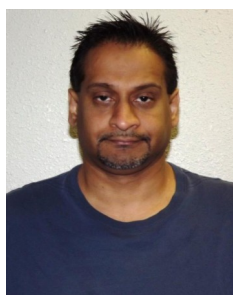
	Oxygen Content	Microhardness Hv ₁₀₀	Resistivity, μΩ/cm	Density (% of theoretical)
Mo in Air	4700	424	50	88
Mo in Inert Chamber	690	202	40.6	93

Table 1 lists the properties of plasma sprayed molybdenum targets conducted under air and inert gas showing how significantly properties can be affected by control of the spray environment.

Thin films deposited using these targets show significant differences on sputtering efficiency and deposit quality.

Hard coatings of tungsten carbide and chromium oxide are routinely sprayed on pump and valve components in the petrochemical industry. This is an important application since downtime in this industry is critical and can cost many tens of thousands of dollars per day. The technical demands of this industry are generally; material selection for chemical resistance, hardness, density and exceptional bond strength.

In summary, one can say that although plasma spray is an established rapid deposition technique for application of thick films, opportunities exist to further the application base by innovating torch design to allow for the fabrication of denser coatings, coatings in the submicron to 10 micron range, and coatings that do not have a lamellar structure since the lamellar interfaces create anisotropic properties distribution within the coating.



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Advantages of High Pressure RF Torches with Reverse Vortex Stabilization for Plasma Sprayed Coating and Powders Treatment

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Fast growing interest in high power atmospheric pressure RF torches for plasma sprayed coating and powders treatment is defined by their advantages – generation of pure plasma, low maintenance cost due to no need in the electrodes replacement, opportunity to apply almost any plasma gases, and particularly due to optional material feeding into the plasma chamber for direct treatment by plasma with longer residence time and more uniform material distribution in the plasma plume. Additional advantages are provided by utilized method of reverse vortex plasma stabilization, which is one of the key features of recently developed and patented by APT, LLC plasma torches.

Fig.1. below shows gas dynamic scheme of the torch with optional places for material feeding into the plasma chamber: (1) through the axial water cooled probe; (2) with secondary plasma gas through the bottom swirler; (3) with main plasma gas through the exit swirler; and (4) through channels in the area of exit nozzle.

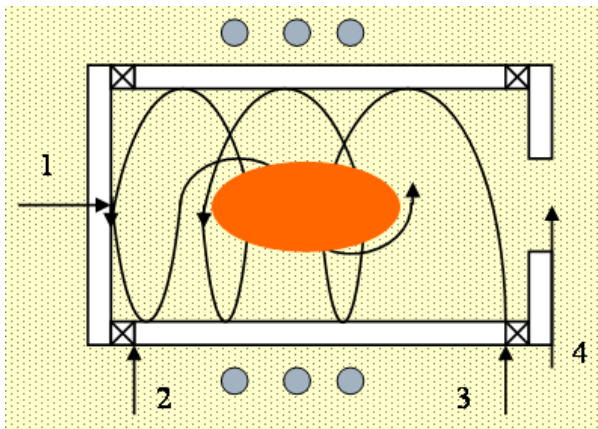


Fig.1. Reverse vortex ICP torch gas dynamic scheme with optional places for material feeding

For modeling of basic flow processes inside an inductively coupled (ICP) atmospheric pressure plasma torch a generalized method has been used, based on numerical solution of the combined conservation and transport equations for turbulent system. This method provides a procedure of the numerical integration of the 3D-differential equations that describe viscous gas flows: the equations for conservation of mass, momentum, and energy.

Application of the Maxwell's equations with fluid dynamic modules allows carry out the 3D investigation of different coil shapes, torch geometries and operating conditions. Additional transport equations are also solved when the flow is turbulent. For aerodynamic prediction the RNG-based k- ϵ -turbulence model was used.

During solid particles modeling discrete parcels are tracked through the computational domain by solving the Lagrangian equations. For steady state calculations, a parcel is tracked through its lifetime and this procedure is repeated for all the parcels. The local time step used for integrating the spray equations is estimated based on cell residence time and maximum allowable droplet temperature, velocity, and diameter change. Solid particle size distribution during injection is defined by fitting the size distribution data to the Rosin-Rammler equation.

For preliminary solid particles trajectories calculations inside the 50 kW ICP torch the following input data was chosen:

- reverse vortex argon injection;
- current density (real) $2.8 \times 10^7 \text{ A/m}^2$;
- field frequency 1.0 MHz;
- argon flow rate 3.0 g/s, temperature 300 K;
- reference pressure 10^5 N/m^2 ;
- injected material - aluminum alloy;
- aluminum alloy consumption 0.05 g/s, temperature 300 K.

Injected material characteristics were: density 2700 kg/m^3 , specific heat $880 \text{ J/(kg} \times \text{K)}$, thermal conductivity $190 \text{ W/(m} \times \text{K)}$, melting latent heat 390 kJ/kg , resistivity $0.0005 \text{ Ohm} \times \text{m}$. Size distribution - Rosin-Rammler, number of sizes 5, Sauter mean diameter 15 micron, minimum size fraction 0.1, maximum size fraction 0.9.

Used calculated grid and geometry of the torch are shown in Fig. 2.

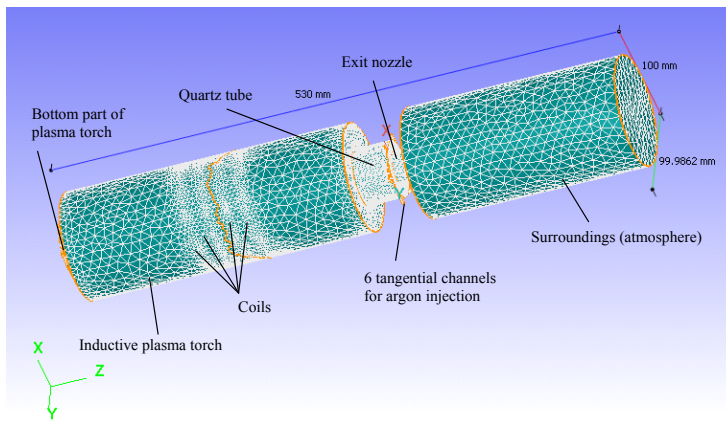


Fig. 2. ICP torch calculated grid

Three cases of aluminum powder injection were investigated:

Case A. Point injection at the center of exit plasma torch nozzle.

Case B. Point injection at the center of the plasma torch bottom plate.

Case C. Point injection at the area of main plasma gas (argon) feeding.

Contours of gas temperature, K (a), of inductive heating, W/m^3 (b), solid particles diameter, micron (c), and solid particles temperature, K (d) for center particles injection (Case B) are presented in Fig. 3

Case B is one of promising for solid particle injection, has some advantages in comparison with Cases A, C, but does not consider influence of solid particles on plasmoid, flow stability, and technical aspects.

Provided preliminary investigations demonstrate opportunities and advantages of the reverse vortex atmospheric pressure ICP torches for the field of material sciences and just one simplified approach for tracing particles, but do not consider extremely complicated processes of plasma and injected material interaction as a function of operating frequency, pressure, gas composition and flow, electrical and magnetic fields, and so forth, which should be a subject for further works.

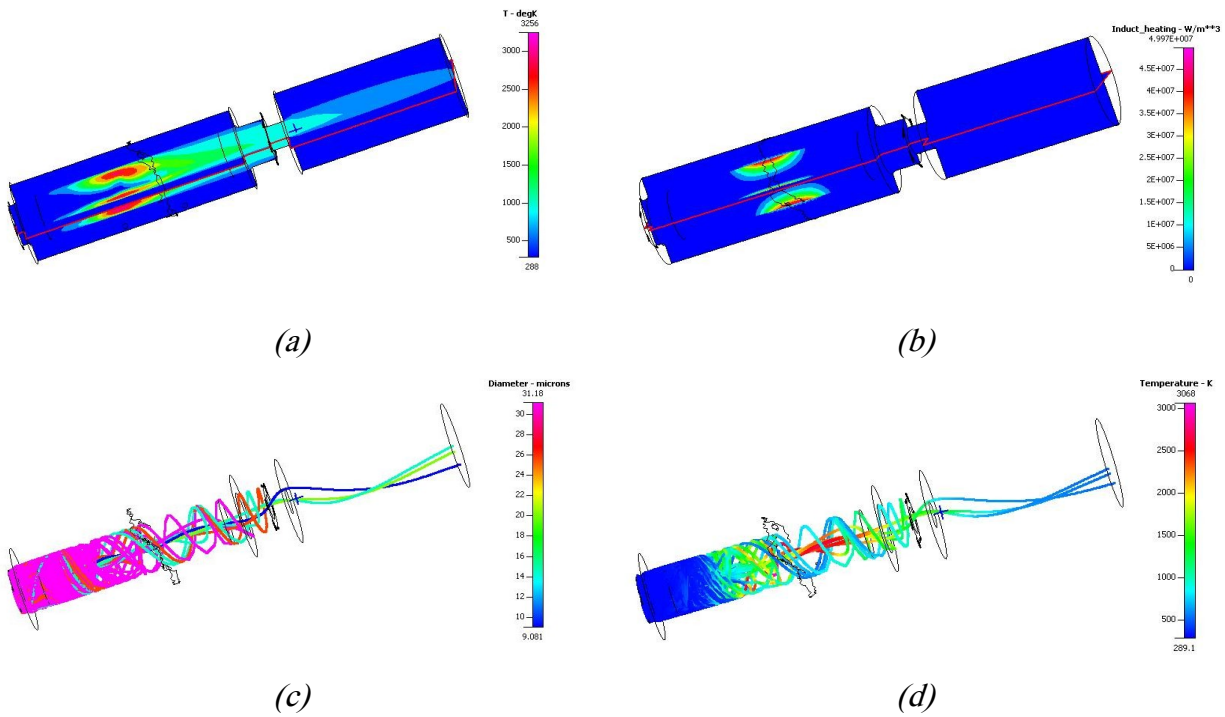


Fig. 3. Parameters distribution inside the ICP torch with central solid particles injection



Prof. Serhiy Serbin



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Matching Electric Power to Processing

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Introduction

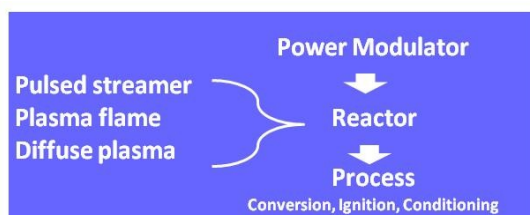


Fig. 1. Summary of research area

The challenge is electric power for smart processing. Attractive applications are chemistry, combustion and pollution control. Conventional chemistry is huge in energy consumption, hard to control and often slow or large. Combustion is another problem area where huge gain is possible. The main task of the technology is clear: couple the electric power effectively into the process. It must be effective, be efficient in energy, be efficient in feedstock, and be very safe. The interface between power and process is the crucial ingredient. A pulsed plasma is the ideal choice because it offers a controllable load to the electric circuit and a manageable source of chemical actors to the process. The power modulator is the source of electric power, the atmospheric plasma a convenient interface and the process is the final target. Two interfaces actually: power modulator to atmospheric plasma and the other one, the plasma to the process. Matching at the interfaces is a special focus area of research that needs dedicated attention.

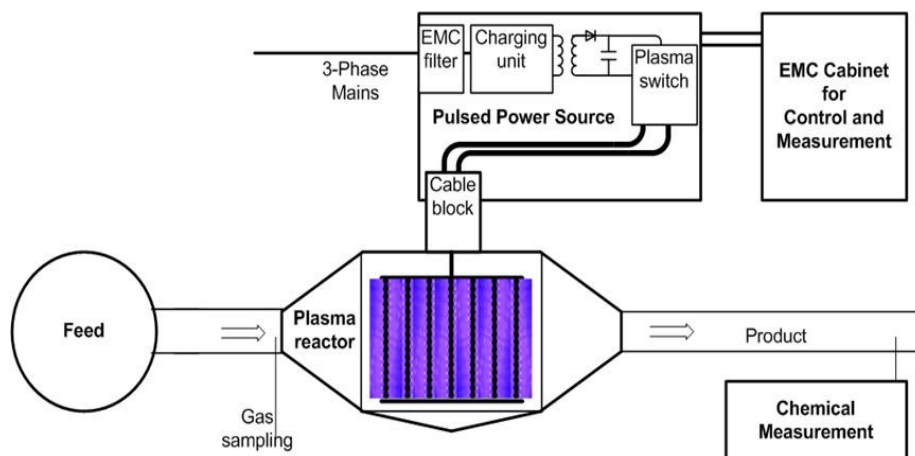


Fig. 2. Layout of a typical system

Pulsed power processing system

The plasma discharges are energized by repetitive pulsed power of high output voltage (up to 100 kV) and short pulse duration (tens of nanoseconds or less). The peak power applied to a reactor may reach levels of several tens of MW. For larger scale industrial applications peak power levels of hundreds of MW are needed and average powers of hundreds of kilowatt can be required in high volume applications. The resulting discharges occur as streamer channels in the reactor through which a gas and/or a liquid flows. The gas pressure often is near atmospheric.

The temperature range for applications in gas is very wide (at least up to 850 °C). Generally speaking, in order to generate intense streamer discharges while avoiding their evolution into spark breakdown, voltage pulses with short duration and electrode arrangements producing highly non-uniform electric fields are used.

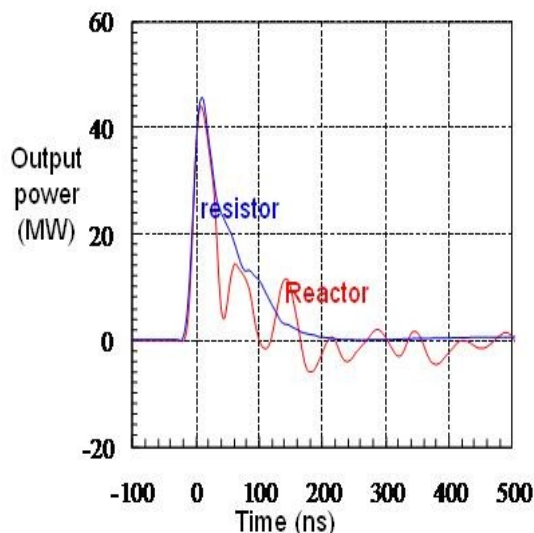


Fig. 3. Plasma and resistive load compared for matching quality

transmission line transformer and appears at the cable block as a 70 kV pulse with 15 ns rise time and approximately 100 ns length. This pulse is fed to the electrode structure in the plasma reactor. The cycles are repeated at a rate between 1 and 1000 pulses per second.

Interfacing

Matching electric power to plasma power, we are dealing with impedance matching. The output impedance of the power source has to match the load impedance that the plasma offers to the source. One very elegant solution is the transmission line transformer. Its advantages are: impedance control, voltage multiplication and DC path to ground. We have chosen this approach. In Fig. 3 we have an example of matching quality: here we used a transmission line transformer and a DC bias voltage added to the pulse voltage. The first measure improves the

Table 1. Classical actors replaced by smart activation

Temperature	Classical: All molecules are heated	Only tail of distribution is usefull
Catalytic surface	Layer near surface is heated	Catalyst lowers activation energy
Electric field	Only E-field is generated	Interacts directly with valence electrons
Electrons	Only electrons are accelerated	Tuned energy distribution

electrical matching and the second measure increases the conductivity of the plasma discharge to the value needed for correct matching.

The next step is matching to the process. The plasma itself is the main tool. Two parameters are plasma energy distribution and plasma spatial distribution. The usual activation of

Fig. 2. shows a typical system. The reactor depicted here is a duct with rectangular cross section, 1mx1m, and 1 m in length. It is subdivided into 8 parallel channels. In the center of the sub-ducts we have an electrode array of barbed strips. The power source shown here consists of a resonant charging unit, a high-voltage pulse transformer, a high-voltage capacitor bank, a fast switch, a transmission line transformer and a cable block. The basic operation is a cyclic process. For each cycle the resonant charging unit produces a pulse of 1 kV, 30 microseconds wide. Each cycle pulse, fed to the transformer, charges the high-voltage capacitor up to 35 kV. Each cycle the capacitor is fully discharged by the fast switch and its load. This load is a transmission line transformer. The basic action of this device is pulse formation, voltage doubling and impedance matching. So each pulse follows the

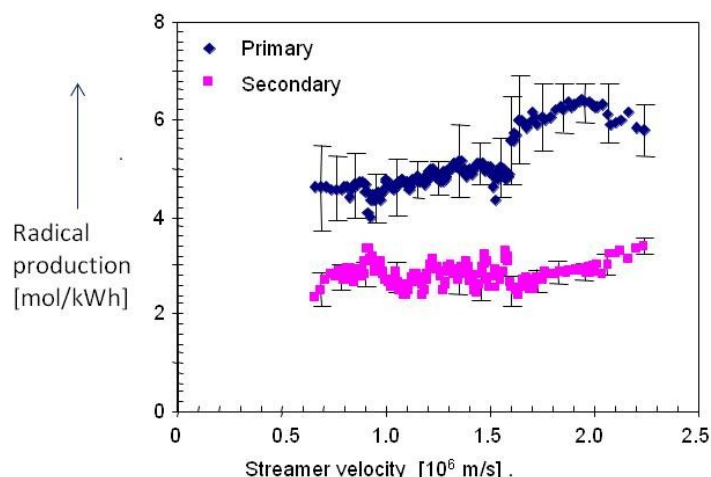


Fig.4. *O*-radical yield affected by plasma properties:
CDS, Cathode Directed Streamers

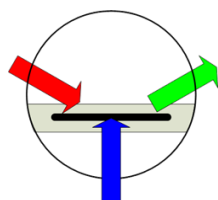


Fig.5. The concept of the
chemical transistor: Input
reactants, output products
and electrical ion

The second parameter, homogeneity, is not well investigated yet. Tools can be: adding turbulence and decreasing rise time of voltage pulse. An analytic result indicating what is possible is given in Fig. 6.

Finally we should check total system efficiency. That is the combination of both matching issues. It turns out that the best radical yield does not always coincide with the best impedance matching. Guidelines are given in Table 2. Abbreviations: ADS means anode directed streamer and CDS similar with cathode.

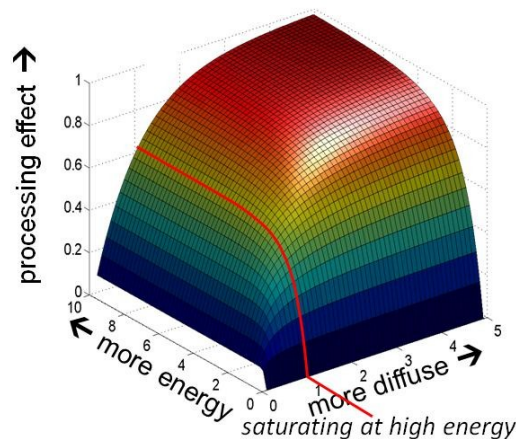


Fig.6. Outcome of analytic model: Effect of
homogeneity and energy density on processing

Table 2. Guidelines to optimize matching

Parameter	CDS	ADS
Pulse width	No effect	Increase
Rise rate	Increase	Increase
Total voltage	Increase	Increase
DC bias	Increase	Increase
Wire-plate distance	No effect	Decrease

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