10th International Conference on Plasma Assisted Technologies (ICPAT-10)

07-09 March, 2016

Cancun, Mexico

International Plasma Technology Center

www.plasmacombustion.org

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WATER TREATMENT

PLASMA MINERALOGY

COAL, BIO-MASS, AND WASTE INTO ENERGY PROCESSING

Synopsis

ICPAT-10 will have ten consecutive sessions: (1) plasma generation, diagnostics, and modeling; (2) plasma ignition and flame control, fuel reformation and activation; (3) plasma treatment for coatings and surface modification; (4) new plasma effects and prospective applications; (5) water treatment; (6) plasma mineralogy; (7) business forum; and (8) coal, bio-mass, and waste into energy processing.

ICPAT-10 is expected to have over 30 oral presentations (30 minutes in duration, including questions and answers), and several poster presentations.

ICPAT-10 will be held 7–9 March, 2016 in Iberostar Hotel, meeting room Isla 5-6, Blvd. Kukulcan Km 17 Zona Hotelera, Cancun, Quintana Roo, Mexico, CP: 77500. Tel (front desk): 52-998 881 8000.

ICPAT-10 is sponsored by: Applied Plasma Technologies, LLC (APT) and International Plasma Technology Center (IPTC), both USA.

During the conference, 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. ICPAT-10 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.

ICPAT-10 has two new sessions – power sources and water treatment. This reflects our transition. From the conference presentations and associated discussions, it is clear that many attendees desire that the conference grow into a broader venue that is, expanding the sessions to cover more areas for the application of plasma technologies. ICPAT 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 ICPAT to include other plasma technology applications and will do this in future. 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 ICPAT – namely an emphasis on the scientific chain from ideas and fundamentals to practical applications.

ICPAT – 10
Tentative Agenda

8.30 – 9.00	Registration: Iberostar Hotel, meeting room Isla 5-6, Blvd. Kukulcan Km 17 Zona Hotelera, Cancun, Quintana Roo, Mexico, CP: 77500 Tel, (front desk): 52-998 881 8000
9.00 – 9.15	**ICPAT-10 Opening** Welcome remarks from *Dr. Igor Matveev,* ICPAT-10 Chair Applied Plasma Technologies, LLC Presentation of the PAC book volume 2, announcements
9.15 – 11.00	**PLASMA GENERATION, DIAGNOSTICS, AND MODELING** Chaired by *Professor Paolo Gessini* University of Brasilia, Brazil
9.15 – 9.45	**Progress in High Power ICP/RF Plasma for Gasification, New Materials Production, Tests** *Dr. Igor Matveev, Svetlana Matveyeva* (Applied Plasma Technologies, LLC, USA) *Dr. Sergey Zverev* (St.-Petersburg State Polytechnic University, Russia)
9.45 – 10.15	**Computational Study of Analyte Transport through an Inductively Coupled Plasma Torch** *Dr. M. Aghaei, A. Bogaerts* (Research group PLASMANT, University of Antwerp, Belgium)
10.15 – 10.45	**Ablative Pulsed Plasma Thrusters for High Delta-V, High Total Impulse Missions with Small Spacecraft** *Prof. Paolo Gessini, Lui T. C. Habl, Gabriela C. Possa* (University of Brasília, Brazil) *Stephen B. Gabriel* (University of Southampton, UK)
10.45 – 11.00	Round Table on Plasma Generation, Diagnostics, and Modeling
11.00 – 11.15	Coffee-break

11.15 – 16.00	**PLASMA IGNITION AND FLAME CONTROL** **FUEL REFORMATION AND ACTIVATION** Chaired by *Prof. Alexander Ustimenko* Research Institute of Experimental and Theoretical Physics of Kazakhstan National University, Kazakhstan Co-chair *Dr. Edbertho Leal-Quiros,* California State University Fresno, USA
11.15 – 11.45	**Prospective Solutions for Ignition and Flame Control in Gas Turbines: Plasma Igniters, Pilots, Plasma Fuel Nozzles** *Dr. Igor Matveev, Svetlana Matveyeva* (Applied Plasma Technologies, LLC, USA)
11.45 – 12.15	**Development of a Plasma Assisted Lean Premixed Fuel Injector for Gas Turbine Engines** *Felipe Gomez del Campo and Joseph Heebner* (FGC Plasma Solutions and Case Western Reserve University, USA)
12.15 – 14.00	Lunch
14.00 – 14.30	**Time-resolved Emission Measurement of Laser-induced Breakdown in Hydrocarbon Fuel Mixtures** *Kazunobu Kobayashi and Hiroki Tanaka* (Energy Technology Laboratories, Osaka Gas Co., Ltd., Japan) *Moon Soo Bak* (Sungkyunkwan University, Republic of Korea) *Campbell Carter* (Air Force Research Laboratory, Wright-Patterson Air Force Base, USA) *Hyungrok Do* (Seoul National University, Republic of Korea)
14.30 – 15.00	**Plasma-Aided Processing of Solid Fuel Organic and Mineral Mass** *V.E. Messerle* (Combustion Problems Institute, Kazakhstan; Institute of Thermophysics of SB RAS, Russia) *A.L. Mosse* (A.V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus, Belarus) *A.B. Ustimenko* (Research Institute of Experimental and Theoretical Physics of Kazakhstan National University, Kazakhstan)
15.00 – 15.30	**Small Scale Gas to Liquids (SS GTL)** *Dr. Igor Matveev* (Applied Plasma Technologies, LLC, USA) *Prof. Serhiy Serbin, Prof. Nikolay Washchilenko* (National University of Shipbuilding, Ukraine)
15.30 – 16.00	Round Table on Plasma Ignition and Flame Control, Fuel Activation and Reformation

16.00 – 16.15	Break

16.15 – 17.45	**PLASMA TREATMENT FOR COATINGS AND SURFACE MODIFICATION**
	Chaired by *Dr. Rajan Bamola* Surface Modifications, Inc., USA
	Co-chair *Dr. G. Capote* National University of Colombia, Colombia

16.15 – 16.45	**Plasma Modification for the Deposition of Hard and Adherent Diamond-like Carbon Coatings using an Active Screen as an Additional Cathode**
	Dr. G. Capote (National University of Colombia, Colombia)
	V.J. Trava-Airoldi (Institute for Space Research, Sao Jose dos Campos, Brazil)

16.45 – 17.15	**Anti-Fogging Properties of Nanostructured Polymer Surface by PECVD**
	Sun Mi Yoon (Korea Institute of Science and Technology, Korea University, Korea)
	Gunha Lee (Seoul National University of Science and Technology, Korea)
	Sahn Nahm (Korea University, Korea)
	Myoung-Woon Moon (Korea Institute of Science and Technology, Korea)

17.15 – 17.45	Round Table on Plasma Treatment for Coatings and Surface Modification

19.00 – 21.00	Welcome party (at Isla 1-2 ballroom)

Tuesday, 8 March

9.00 – 11.00	**NEW PLASMA EFFECTS AND PROSPECTIVE APPLICATIONS**
	Chaired by *Professor Gerardo Diaz* University of California Merced , USA

9.00 – 9.30	**Protection of Cellulose-Based Cultural Heritage Objects by Plasma Decontamination and Coating**
	E.G. Ioanid ("Petru Poni" Institute of Macromolecular Chemistry of Iasi, Romania)
	D. Rusu ("Moldova" National Museum Complex, Romania)
	S. Dunca and C. Tanase ("Alexandru Ioan Cuza" University of Iasi, Romania)
	V. Frunză and G. Savin (S.C. Romcatel Impex Research Design S.A. of Iasi, Romania)

9.30 – 10.00	**Plasma Treatment of Dentin Surfaces for Improving Adhesive/Dentin Interface Bonding**
	Xiaoqing Dong and Qingsong Yu (University of Missouri, USA)
	Meng Chen (Nanova, Inc., USA)
	Yong Wang (Center for Research on Interfacial Structure & Properties, School of Dentistry, University of Missouri-Kansas City, USA)
10.00 – 10.30	**A Study on Electrode-less Plasma Light Source Using GaN Transistor**
	Kiho Lee, ChoelJun Kim, Samuel Cho (RFHIC Corporation, Anyang, South Korea)
10.30 – 11.00	Round Table on New Plasma Effects and Applications
11.00 – 11.15	Coffee-break
11.15 – 14.30	**WATER TREATMENT**
	Chaired by *Dr. Isaiah Blankson* NASA Glenn Research Center; USA
11.15 – 11.45	**Water Purification by High-Voltage Nanosecond Plasma: New Developments**
	Dr. Isaiah M. Blankson (NASA Glenn Research Center, USA)
	Dr. John E. Foster (University of Michigan, USA)
11.45 – 12.15	**Liquid Processing by RF Field**
	Dr. George Paskalov (Plasma Microsystems, LLC, USA)
12.15 – 12.45	**Plasma System for Liquid Fertilizer Production From Air and Water**
	Dr. Igor Matveev (Applied Plasma Technologies, LLC, USA)
Poster	**Degradation of the Dye NA52 Present in Water Using a DC Plasma at Atmospheric Pressure**
	G. F. Salazar, C. Torres, J. Vergara, E. Montiel (Universidad Autónoma del Estado de Morelos, México)
	P. G. Reyes, A. Gómez (Universidad Autónoma del Estado de México, México)
	H. Martínez (Instituto de Ciencias Físicas, Universidad Nacional Autónoma de México, México)

Poster	**Horizontal Water Well Cleaning by Underwater Pulsed Spark Discharges** *K.J. Chung, Y.S. Hwang, G.C. Park* (Seoul National University, South Korea) *C.Y. Kim* (Sun & Sea Co. Ltd., South Korea)
12.45 – 14.00	Lunch
14.00 – 14.30	Round Table on Water Treatment

PLASMA MINERALOGY

Chair *Dr. George Paskalov*
Plasma Microsystems, LLC, USA

14.30 – 15.00	**RF Plasma Ore Processing: Development and Commercial Applications** *Dr. George Paskalov* (Plasma Microsystems, LLC, USA)
15.00 – 15.30	**Preliminary Estimations of Ore Processing Efficiency** *Dr. Igor Matveev* (Applied Plasma Technologies, LLC, USA) *Dr. Sergei Zverev* (St.-Petersburg Polytechnic University, Russia)
15.30 – 16.00	Round Table on Plasma Mineralogy

BUSINESS FORUM

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

16.00 – 16.30	**Five Top List Plasma Technologies for Immediate Development and Marketing** *Dr. Igor Matveev* (Applied Plasma Technologies, LLC, USA)
16.30 – 17.00	Discussions on commercialization of plasma technologies. Establishing international research groups. Site and time selection for ICPAT-11.

Wednesday, 9 March

9.00 – 14.00

COAL, BIO-MASS, AND WASTE INTO ENERGY PROCESSING

Chaired by *Prof. Vladimir Messerle*
Combustion Problems Institute, Kazakhstan

Prof. Alexander Ustimenko
Research Institute of Experimental and Theoretical Physics of
Kazakhstan National University, Kazakhstan

9.00 – 9.30	**Carbon Containing Waste Plasma Processing** *V.E. Messerle* (Combustion Problems Institute, Kazakhstan; Institute of Thermophysics of SB RAS, Russia) *A.L. Mosse* (A.V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus, Belarus) *A.B. Ustimenko* (Research Institute of Experimental and Theoretical Physics of Kazakhstan National University, Kazakhstan)
9.30 – 10.00	**Plasma Processing of Organic Materials** *E. Leal-Quiros* (California State University Fresno, USA) *G. Diaz* (University Of California Merced, USA)
10.00 – 10.30	**Sewage Sludge-to-Power** *Dr. Igor Matveev* (Applied Plasma Technologies, LLC, USA) *Prof. Serhiy Serbin, Prof. Nikolay Washchilenko* (National University of Shipbuilding, Ukraine)
10.30 – 11.00	**Inertiation of Sludge Produced During Treatment of Landfill Leachate by Thermal Plasma** *A.L.V. Cubas, M.M. Machado, A.R.A. Dutra, E.H.S. Moecke* (University of Southern Santa Catarina State (Unisul), Brazil)
11.00 – 11.15	Coffee-break
11.15 – 11.45	**Mercury Removal From Solid Waste by Reactive Plasma and Thermal Disorption Processes** *G. Petraconi* (Technological Institute of Aeronautics, Brazil) *A.C. Cruz* (Recaltech: Plasma Technology, Brazil) *A.R. Coutinho* (Piracicaba Methodist University, Brazil) *A. Petraconi* (Mogi das Cruzes University, Brazil)
11.45 – 12.15	**Current Status and Prospects of Waste-to-Energy Process Using Plasma Technology in China** *Jun Li and Kou Liu* (China TIANYING Inc., China)
12.15 – 14.00	Lunch
14.00 – 14.30	Round Table on Coal, Bio-mass, and Waste into Energy Processing
14.30 – 16.00	**DISCUSSIONS, NEGOTIATIONS** Conference Closing

PLASMA GENERATION, DIAGNOSTICS, AND MODELING

Progress in High Power ICP/RF Plasma for Gasification, New Materials Production, and Tests

Igor Matveev, Svetlana Matveyeva
Applied Plasma Technologies, LLC, USA

Dr. Sergey Zverev
St.-Petersburg State Polytechnic University, Russia

To investigate some promising plasma assisted processes at the elevated pressures Applied Plasma Technologies, LLC has developed an inductively coupled (ICP) or radio frequency (RF) plasma system APT-60 with input power up to 60 kW and APT-100 with input power 100 kW.

Configuration of developed RF systems is depicted in Fig. 1. General view of APT-60 at the customer site during start-up and commissioning is shown in Fig. 2.
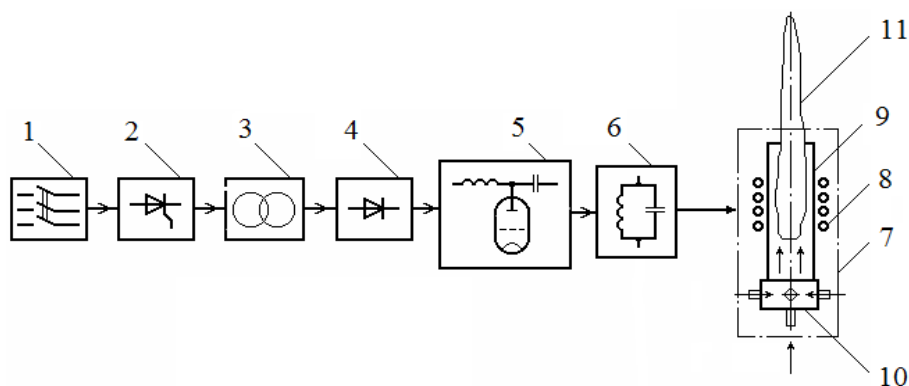

Fig. 1. ICP Plasma System Configuration:

1 – main switch; 2 – SCR or thyristor phase regulator; 3 – high voltage step-up transformer; 4 – rectifier; 5 – vacuum tube; 6 – matching network; 7 – torch; 8 – inductor; 9 – discharge chamber; 10 – swirler; 11 – plasma plume

Fig. 3 provides comparison of heat losses for 25–55 kW power, pressures at the torch output 1 to 5 bar for only argon as a plasma gas with flow from 30 l/min to 120 l/min, and for the cases of direct vortex plasma stabilization. For parameters coding we suggest the follows format P_xxx_yyy_zzz , were xxx – is the plasma system part name, yyy – is input power in kW, zzz – pressure at the torch output in bar.

One can see strong dependence of heat losses on power. Higher power – higher losses. The tendency remains the same at the elevated pressures. Very important parameter is gas flow. It's growth from 30 l/min to 120 l/min leads to the entire plasma system performance improvement from 46% for 25 kW input power mode to 51% for the 55 kW input power mode.

The comparison of energy parameters for the case of 5 bar pressure, 55 kW input power, and direct vortex argon plasma stabilization is provided in Fig. 4. It could be seen that depending on power, efficiency of plasma generation could decrease on 15% and 6% for 25 kW and 55 kW power modes in comparison to 1 bar pressure operation.

Fig. 2. From left to right: general view of experimental setup, vertically positioned torch in operation, plasma torch integrated with a powder feeding nozzle
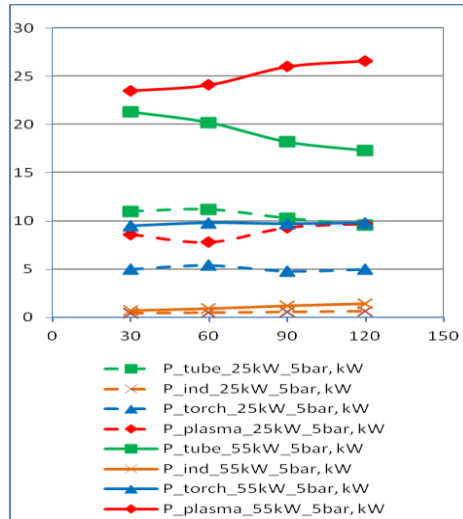

Fig. 3. Dependences of heat losse on power (25 kW and 55 kW) and gas flow for direct vortex argon plasma stabilization
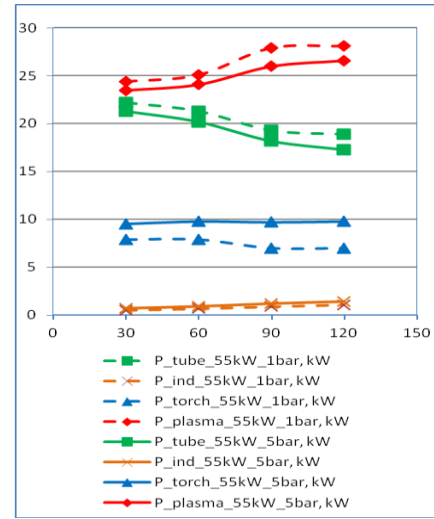
Fig. 4. Dependences of heat losses on pressure and gas flow for direct vortex argon plasma stabilization at 55 kW input power mode

Dependences of the heat losses when operating on argon/nitrogen blends from 1:2 to 1:5 volumetric ratios and nitrogen flows from 60 l/min to 150 l/min in case of its feeding through the direct vortex swirler are provided in Fig. 5. All the tests have been performed within the 1 bar to 5 bar pressure range keeping the input power at the level of 55 kW. It could be seen that the heat flux into the torch wall follows the pressure growth with simultaneous significant decrease of losses in the vacuum tube. As a result, total plasma system efficiency remains almost at the same level of 50% within the investigated plasma gas flow rate.

The pure nitrogen operation modes have been investigated as well. The main results are presented in Fig. 7 for the power level of 40 kW, pressures from 1 bar to 5 bar, nitrogen flow 50 l/min, and direct vortex gas feeding. These are the world's first experimental data for the RF

nitrogen plasma at the elevated pressures. One can see the tendency of heat flux increase through the torch wall and that's why importance of the reverse vortex application to keep torch efficiency and lifetime on the proper level becomes obvious. At the same time we have observed very low losses in the vacuum tube.
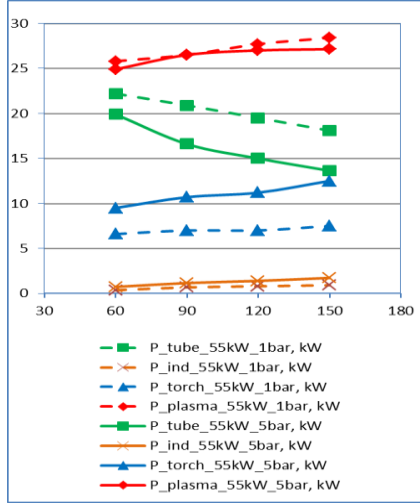
Fig. 5. Dependences of heat losses on gas flow and pressure at 55 kW power level for the case of direct vortex plasma stabilization and blends of argon and nitrogen

Fig. 6. The effect of un-mixed argon (top) and nitrogen (bottom) plasma layers existence in the RF torch with reverse vortex flow
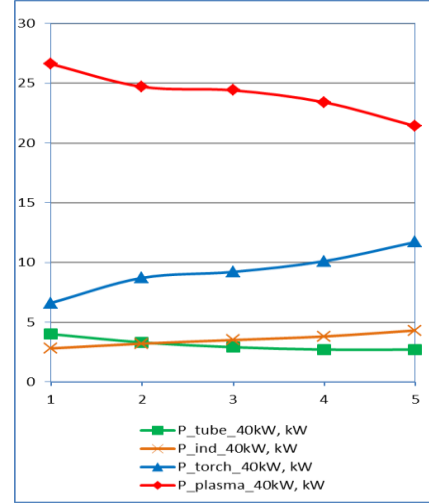
Fig. 7. Dependences of heat losses on pressure for the cases of pure nitrogen with constant gas flow 50 l/min at 40 kW power level and direct vortex plasma stabilization

Comparison of the plasma generation efficiency for different gases (Ar and N_2) and pressures (1 to 5 bar) shows its decrease from 0.45 to 0.4 for Ar and from 0.67 to 0.54 for pure N_2.

APT-100 was developed for the new aerospace material tests. Its main parameters are presented in Fig. 8, appearance in Fig. 9.
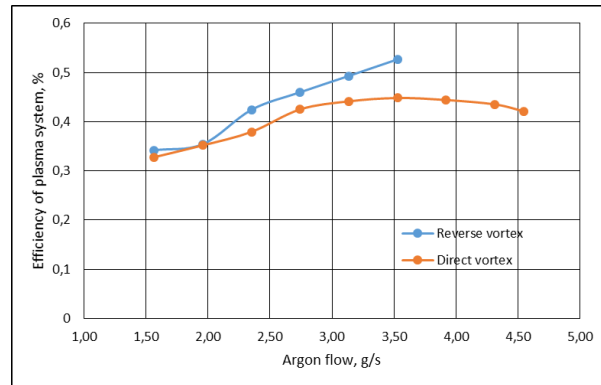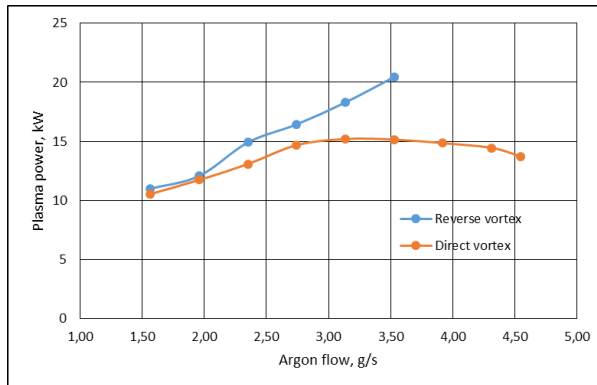
Fig. 8. Dependences of argon plasma power (left) and plasma generation efficiency (right) on gas flow

Fig. 9. Two-modular APT-100 (left) and its metal-ceramic torch in operation on air

Igor Matveev

Sergei G. Zverev, *Ph.D., Associate Professor of Peter the Great Polytechnic University (St-Petersburg Polytechnic University), Russia. Dr. Zverev teaches special courses and serves as a project manager for Plasma Technology Laboratory.*

Computational Study of Analyte Transport through an Inductively Coupled Plasma Torch

Dr. M. Aghaei, A. Bogaerts
Research group PLASMANT, University of Antwerp, Belgium

Introduction

Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is one of the most popular methods for determining trace elements and isotopes in a wide-variety of samples [1]. In an ICP, a plasma is created by applying electric power to a gas, which flows through a so-called "torch". The torch is surrounded by a coil through which radiofrequency current is flowing. This induces an

electromagnetic field in the gas, causing the gas atoms to break up into positive ions and electrons. In this way, an inductively coupled plasma is created. The ICP is maintained because the electrons are heated by the electromagnetic field, which causes further ionization of the gas atoms. The sample to be analyzed is introduced, mostly as droplets, with a central gas (mostly helium or argon), and will be subject to desolvation, vaporization, ionization and excitation in the plasma. The ions formed in this way can then be analyzed in a mass spectrometer, yielding ICP-MS.

A model for an atmospheric pressure ICP, operating at typical analytical chemistry conditions including ionization and viscosity terms, was presented in [2]. The model was subsequently modified by connecting the ICP torch to a mass spectrometer interface cone [3]. In [4] the sample introduction is modeled and added to the ICP-MS model. We discussed the transport of copper droplets trough ICP torch up to evaporation stage. In the current work, we will present our most recent results which include ionization of elemental samples. Copper droplets are taken as a case study and inserted from the central inlet and tracked through the ICP torch.

Computational model

The 2D axisymmetric ICP-MS model is based on solving partial differential equations for the gas flow dynamics (i.e., the Navier-Stokes equations) coupled with the energy conservation and Maxwell equations. It is built within the commercial computational fluid dynamics (CFD) program FLUENT (ANSYS). The power coupling into the ICP is a source term in the energy conservation equation, whereas the emitted radiation is treated as a loss term. Some self-written codes were added in order to calculate the electromagnetic fields (based on the Maxwell equations), the amount of ionization (by solving the Saha-Eggert equation, assuming local thermal equilibrium, LTE), as well as the material parameters, i.e., electrical conductivity, viscosity, heat capacity, thermal conductivity and diffusion coefficients as a function of the actual gas composition and plasma temperature. A validation of this model by experiments was provided in [5]. Typical calculation results from the model include the gas flow behavior, as well as the plasma temperature and electron density profiles [3–8].

The sample introduction is modeled with the so-called "discrete phase model". The trajectory of each droplet is calculated by integrating the force balance (i.e. Newton equation) acting on the particles. Besides their transport throughout the torch, the particles in liquid phase will undergo heating, vaporization and finally ionization. For the elemental droplets, a heat and mass balance equation is applied which relates the particle temperature to the convective and diffusive heat transfer, and calculates the mass transfer to the vapor phase by means of a vaporization rate based on thermodynamic relations. The heat lost or gained by the particle as it traverses each computational cell will also appear as a source or sink of heat in the subsequent calculation of the continuous phase energy equation. From the ionization degree and the (mass and charge) conservation equations, the number densities of electrons and of the atoms and ions of the sample material can be calculated.

Results and discussions

Copper droplets are inserted from the central inlet with a 2 mm width and tracked through the torch up to the sampler position. By means of our model, we are able to track the particles to determine their position, their phase (liquid, vapor or ionized), velocity and temperature both in ICP torch and at sampler orifice. The general results of the particle injection are shown in Fig. 1. The copper droplet flow rate is 100 ngs^{-1} and the droplets size is 1 μm. In Fig. 1(*a*) the Ar streamlines are shown in the background to clarify the path lines which the copper droplets can
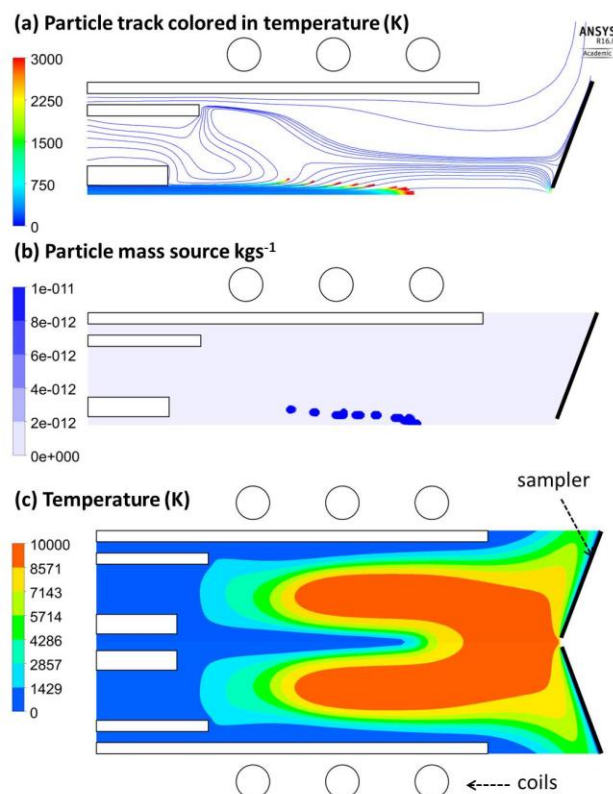
Fig. 1. Effect of copper droplet introduction into the ICP torch: copper droplet tracking colored by temperature, with the Ar pathlines illustrated for the sake of clarity (a), the mass transfer rate of copper to the gas phase (b), and the Ar flow temperature after copper droplet introduction (c)

follow. The injected droplet path line is then colored in temperature. It is seen that the droplets are gradually heated up till they reach the evaporation temperature. As soon as they are evaporated, they disappear from the droplet path lines and from then on we are able to trace them in the gas phase domain. Fig. 1(*b*) shows the mass transfer rate of copper droplets to the gas phase.

Therefore, they are heated up and start to evaporate at earlier positions, while the droplets which follow the path lines with less expansion stay longer at the central axis and go longer through the central cooled channel. It should be realized that early evaporation and more expansion from the central axis may cause that some part of the sample ions does not reach the sampler. With the obtained data, any deviation from the central axes as well as any early/late evaporation along the torch are indicated which are caused by none optimal operating conditions. More specifically, we are going to present and compare the ion cloud maps of different operating conditions i.e. different applied power (600–1,600W) and carrier gas flow rate (0.6–1.6 L/min). By integrating the number density of ions passing through the sampler over orifice width and comparing to the entering material, we calculate the transport efficiency of different conditions and explain the whys behind it.

In conclusion, our model provides us the number of analytes that can enter the mass spectrometer, which is a hint to improve the analytical efficiency of ICP-MS.

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Maryam Aghaei, Iran, *1982.* *PhD in science, physics, University of Antwerp, Belgium, 2014. M.S in Science, photonics, Laser and Plasma Research Institute, Shahid Beheshti University, Tehran, Iran, 2008. B.S in physics, Tehran Polytechnic University, Iran, 2004. She found her interest in modeling physical phenomena and therefore she did computational work on gas dynamics of plasmas produced by laser ablation. As a result, a thermal model for nanosecond pulsed laser ablation of Cu was developed in Prof. S. H. Tavassoli's group in Tehran. Subsequently, she moved to Belgium and started her PhD in the PLASMANT group under the supervision of Prof. A. Bogaerts in Antwerp. She developed a computational model for an inductively coupled plasma (ICP) torch coupled to a mass spectrometer. Currently she works as a post-doc researcher in order to optimize the transport efficiency of injected material trough the ICP torch. Besides computational work, she wants to keep close to the real world of experimental labs, so she spent some research stays at ISAS in Dortmund, at Indiana University in Bloomington and at ETH in Zurich. Her works have led to publish 9 articles with over 80 citations.*
Dr. Aghaei was selected as a Young Analytical Scientists b y Journal of Analytical Atomic Spectrometry in 2014. She gave two invited talks at scientific conferences in USA and one in The Netherlands, as well as a keynote talk in China, and an invited web-seminar talk, organized by the journal Spectroscopy, USA. She recently received a national research grant from the prestigious Research Foundation Flanders (FWO) in Belgium.

Ablative Pulsed Plasma Thrusters for High Delta-V, High Total Impulse Missions with Small Spacecraft

Paolo Gessini, Lui T. C. Habl, Gabriela C. Possa
University of Brasília, Brazil

Stephen B. Gabriel
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Ablative Pulsed Plasma Thrusters (APPTs) were the first Electric Propulsion (EP) devices ever to be flown onboard an actual spacecraft, and continue to be used today in missions were simplicity, robustness and scalability to low power levels are dominant requirements. Therefore, they find a natural niche of application in small satellite missions, where mass, volume and onboard power are at a premium, in spite of their low overall efficiency and not fully understood physical operating principles.

Whereas APPTs have drawn renewed attention from the international space community after a long hiatus, this has been generally limited to low Delta-V, low total impulse missions. In this paper, we investigate the possibility of performing high Delta-V missions using APPTs onboard small spacecraft. The design of such missions is far from trivial, as the high specific impulse values that seem desirable to obtain a high payload ratio are generally obtained at the expense of impulse bit vs discharge energy (thrust to power ratio). This implies a high number of shots, which could strain the capacitor capabilities, or high values of discharge energy, which would increase capacitor weight and, due to power limitations onboard a small spacecraft, imply low firing frequencies and consequently increased mission times.

Thruster description and operation

Between the many EP devices conceived so far, the APPT is one of the most simple, reliable and trusted propulsion systems ever made. Using a solid polymer as propellant (usually Polytetrafluoroethylene – PTFE), it employs high voltage pulsed discharges to ablate, ionize and accelerate the propellant, thus producing thrust. Because of its simplicity, this was among the first types of electric thrusters to be developed and tested. In 1964 it became also the first EP system to actually be flown on a spacecraft, the Soviet probe Zond 2 [1].

The basic operation idea of the APPT, described in details by [2], is based on an electronic circuitry that stores energy in a capacitor bank and cyclically discharges it producing pulsed high voltage arcs on the surface of the propellant bar, causing its vaporization, dissociation and ionization. The resulting gas is accelerated partly by the Lorentz force and partly thermally, thus producing thrust. Despite their relatively low efficiency, APPTs have been employed because of their outstanding reliability. The absence of tanks, piping and moving parts in general makes them very little prone to malfunctioning and failure, while at the same time easy to scale down to low power levels. This caused a resurgence of interest in APPTs in the 1990s [3, 4] and has made them even more attractive in recent years, as increasingly smaller satellites, down to CubeSat size (10 cm × 10 cm × 10 cm), have been built and launched. Several problems, in particular carbonization and a large fraction of the mass being exhausted at essentially thermal speeds, thus lowering specific impulse and efficiency, remain unresolved, notwithstanding decades of experimental research and numerical/analytical modelling in various countries.

Works by many authors have reviewed and analyzed APPTs [1–8], proposing mechanisms of operation and correlations between geometry, operating parameters and performance characteristics, yielding formulas that can be used for design purposes. The main of the above-mentioned formulas relate I_{bit} with discharge energy E and I_{sp} with the ratio E/A, discharge energy per unit propellant area ("wetted area", the area exposed to the discharge). Such relations take the general form of power laws, with coefficients depending, in general, on the thruster configuration and, to some extent, on the range of discharge energy values. Impulse bit has been commonly assumed as proportional to discharge energy for a long time. The validity of this assumption has, however, been challenged in more recent papers [7–9], especially over wide energy ranges, and in particular at the very low end of the discharge energy spectrum, and the data reviews were updated with the collection of material from recent literature and yet unpublished data. For such low energies a general degradation of performance is observed, with values of the thrust/energy ratio sensibly lower than those observed at higher energy levels. This is especially true for breech-fed configurations, even if some experimental investigations seem rather to suggest a considerable data spread, with performance (impulse bit and specific impulse) strongly dependent on thruster design, and in particular on electrode geometry [8–12].

New correlations of experimental data are proposed and insights on APPT operation mechanisms are also sought from physical considerations. The aim is to develop a new set of formulas, useful for the design of high-efficiency APPT propulsion systems, which are going to find increasingly wider application in the growing market of small satellites [13–17].

Delta-V, total impulse and mass constraints

Delta-V and total impulse are the two main parameters used to characterize a given mission. If the specific impulse is sufficiently high, compared to the delta-V, propellant mass is low, negligible compared to the total spacecraft mass, which can then be assumed constant. Delta-V

and total impulse are, in such cases, proportional to each other. For example, with a delta-V of 8 km/s, corresponding to a low-thrust transfer from LEO (Low Earth Orbit) to LLO (Low Lunar Orbit), and a I_{sp} of 1,200 s, the difference between (5) and (6) is just below 30%. In order to bring such difference down to below 10%, we would have to operate with a I_{sp} of 4,000 s. While such values of $\Delta v/gI_{sp}$ could be easily achieved with a Gridded Ion Engine (GIE), this will not generally be the case for high-energy (a common shorthand for high delta-V, high total impulse) missions where APPTs are employed, unless new models of this thruster are developed, with sufficiently high values of specific impulse. The use of (5) is, therefore, generally preferable.

The feasibility of certain classes of high-energy missions, within the constraints of a small (<100 kg mass) spacecraft, is explored in the case of state-of-the-art and of near-to-medium-term projections for APPT technology.

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PLASMA IGNITION AND FLAME CONTROL FUEL REFORMATION AND ACTIVATION

Prospective Solutions for Ignition and Flame Control in Gas Turbines: Plasma Igniters, Pilots, Plasma Fuel Nozzles

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With the first known practical efforts in the early 60-s of the 20-th century the plasma assisted combustion (PAC) systems developers and investigators have engineered a list of technologies, which could be divided onto several groups, including the following:

• Plasma igniters;

• Plasma pilots and flame sustainers;

• Plasma fuel nozzles.

Plasma igniters are the most developed units for short-term operation (up to several minutes) mainly based on thermal DC torches, RF and MW initiators for sub- and supersonic flows [1, 2]. Over 1,200 plasma ignition systems developed by APT and its predecessor are in operation worldwide, including land-based gas turbines and furnaces. They normally replace spark plugs and have power consumption from 100W to 1 kW, plasma gas flow rate of up to 1 g/s and a lifetime up to 4,000 operating cycles. The main advantage of a plasma igniter in comparison to a conventional spark plug is in the much bigger plasma plume

Fig. 1. Plasma Igniter

volume and velocity. This allows deeper penetration of a highly reactive plasma plume into a combustion zone for more reliable ignition. One of the plasma igniters for industrial gas turbines in operation is demonstrated in Fig. 1. There are several known approaches for ignition in high-speed cross flows specifically for the aerospace propulsion systems and scramjets. Among the perspective solutions are radiofrequency (RF) and microwave (MW discharges, as far as non-thermal torches with a fuel feeding into the arc chamber. Developed by Applied Plasma Technologies (APT) the supersonic torch based on transient glow to spark discharge is shown in Fig. 2.

Fig. 2. Supersonic Plasma Igniter

Plasma pilots and flame sustainers are in the second group of the plasma devices with two main functions – ignition and continuous flame control. The market requirements of continuously operating in a high temperature environment with variable pressure pilots and flame holders have moved researches to development of nonthermal plasma sources with a significantly extended lifetime and less power consumption, pulse power devices, direct arc initiators, and MW initiators. Known plasma pilots operate within the average power range of up to 300–500 W, at pressure by 10–17 bar, and provide continuous operation by 1,000 running hours. One of the most prospective MW systems for ignition and flame control in a reverse vortex combustors has been developed by Moscow Radio Technical Institute and is presented in Fig. 3. Spatial arc is one of the recently patented by APT applications of a non-thermal

Fig. 3. Subcritical streamer MW discharge in a reverse vortex combustor
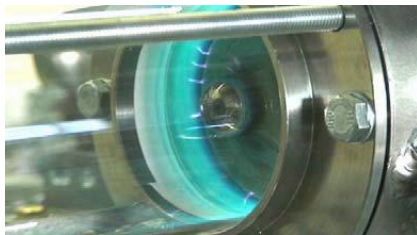

Fig. 4. Reverse vortex combustor with 10 W spatial arc

high voltage discharge in a form of orbiting inside a combustion chamber source of ignition and flame control. Employing the combustor walls as the electrodes, this arc with average power consumption from 10 W to 0.5 kW provides simple and energy efficient solution for gas fired furnaces and combustors particularly leanburned ones. A photo of one of the lab-scale combustor prototypes with low power spatial arc is provided in Fig. 4.

Plasma fuel nozzle as a combination of plasma generator and fuel,atomizer with simultaneous fuel atomizing, ignition and flame control in one unit is the most complicated and advanced plasma assisted combustion solution. Several experimental nozzles for gaseous and liquid fuels with flexi-fuel operation and steam feeding are under development in APT.

Fig. 5. Appearance of a plasma fuel nozzle for gaseous fuel on the left and for liquid fuel on the right

The main advantages of these nozzles are: (a) dramatically increased ignition reliability; (b) much wider equivalence ratio or lambda range; (c) significant decrease in T4 (RIT) jump at the point of fuel ignition; (d) utilization as a pilot burner; (e) utilization for hydrogen enriched gas generation; (f) reduction of a combustion zone geometry; (g) reduction of the combustion chamber walls temperature; (h) increase of a combustion efficiency (COP); (i) achieving smokeless operation; (j) simultaneous burning of several fuels; (k) smooth regulation in a wider turn down ratio. Some samples are depicted in Fig. 5.

Development of a Plasma Assisted Lean Premixed Fuel Injector for Gas Turbine Engines

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It has been shown that the most effective way to decrease NOx emissions is to minimize the fuel to air ratio in the combustor. Both Lean Direct Injection (LDI) and Lean Premixed Prevaporized (LPP) combustion topologies have been shown to be effective in delivering these improvements [7] and [9] and are the likely choice for all next generation engine concepts. The challenge with incorporating lean combustion technologies in gas turbines is that lean flames have a propensity to become unstable close to the lean blow off limit and are prone to damaging combustion instabilities which cause over $1 billion US dollars in damages annually [8]. The requirement for ensuring both static and dynamic flame stability in gas turbines to avoid the aforementioned detrimental effects unstable flames poses a set of constraints on jet engine manufacturers [9]. These requirements are often competing and as such it is difficult for a single combustor concept to satisfy all of them simultaneously through the conventional pathways of aerodynamic stabilization.

This work presents the use of plasma to provide an additional stabilization pathway for these innovative combustor concepts (LDI and LPP) to enhance their operability and limit design tradeoffs. A gliding arc discharge topology was integrated into a realistic premixing gas turbine injector set in an optically accessible dump combustor. As the bulk flow velocity of air was increased while holding the methane flow rate constant and thus decreasing the equivalence ratio, different regimes of flame stabilization were observed, transitioning from an outer recirculation zone stabilized flame, to an inner shear layer flame, blow off and then stabilization by plasma. Using only 40 W of plasma, corresponding to 3.8% percent of the thermal power of the burner an enhancement in the lean blow off limit of 37% was obtained. It was also observed that increasing the power delivered to the plasma had a strong influence on determining the extension of stability limits. The character of the discharge was also shown to be very important, both corona and pulsed streamer type discharges were not very effective in providing ignition but once a flame was ignited they were effective in increasing stability even at discharge powers much less than 1% of the thermal power. Sequential images show the nature of plasma flame interactions below the lean flammability limit. Power to the plasma is increased in each frame resulting first in a streamer discharge, than a gliding arc which is strongly perturbed by swirling flow, here combustion is visible immediately downstream of the plasma, suggesting kinetic enhancement of the combustion reaction by the discharge. Flame stabilization in the inner shear

layer is observed when a discharge is formed between the center body and the high voltage electrode. It is theorized that this is because this configuration places the discharge in the closest proximity to the reaction zone of the flame and creates a pseudo-spatially uniform discharge due to the rotation of the arc thereby producing many active species proximal to the flame. Further tests will focus on different geometries and at elevated temperatures and pressures.

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His current research involves the application of plasma assisted combustion to solve marginal combustion challenges in gas turbine engines. This project originally started as a high school science fair and now, over four years later he has filed a patent and spun off this research into a company, FGC Plasma Solutions for which he serves as the CEO. Through this company he has raised over $130,000 of funding and is working to further develop the technology and commercialize it through a partnership with an engine OEM. He was recently honored by President Barack Obama at The White House as an emerging global entrepreneur and won best paper at the 2014 Society of Hispanic Professional Engineers for his paper on "A Novel Air Assisted Fuel Nozzle Incorporating Gliding Arc Plasma to Enhance Combustion in Lean, Premixed Flames." He has also been named to the "Who's Who to Watch in Technology" by Crain's Cleveland Business as well as one of México's six extraordinary young people by GQ Mexico.

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Time-resolved Emission Measurement of Laser-Induced Breakdown in Hydrocarbon Fuel Mixtures

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Laser induced breakdown spectroscopy (LIBS) has gained its attention as a diagnostic tool for chemical elemental analysis for solid, liquid and gaseous samples [1-3]. For the LIBS in gases, the quantification of species concentrations has been made based on atomic line-intensity ratios with use of relatively long time gates for the detection of the plasma emission. The technique has been successfully applied to measuring local equivalence ratios of flammable mixtures and concentrations of contaminants. However, few studies have focused on the effect of different gas species on the plasma properties, plasma kinetics, and resulting emission.

Fig. 1 shows a schematic diagram of the experimental setup. We have carried out measurements of spectrally and temporally resolved breakdown emission to characterize plasma properties such as plasma temperature and electron density. For this purpose, fuel-oxygen (O_2)-carbon dioxide (CO_2) mixtures with either helium (He) or nitrogen (N_2) balance are prepared while maintaining their atomic compositions. The fuels tested in this study are methane (CH_4), ethylene (C_2H_4), propane (C_3H_8), and butane (C_4H_{10}). The breakdown is produced in the mixtures ($CH_4/CO_2/O_2/He$, $C_2H_4/O_2/He$, $C_3H_8/CO_2/O_2/He$ and $C_4H_{10}/CO_2/O_2/He$ or $CH_4/CO_2/O_2/N_2$, $C_2H_4/O_2/N_2$, $C_3H_8/CO_2/O_2/N_2$ and $C_4H_{10}/CO_2/O_2/N_2$) at room conditions (P = 1 atm and T = 298 K) using the second harmonic of a Q-switched Nd:YAG laser (with pulse duration of 10 ns).
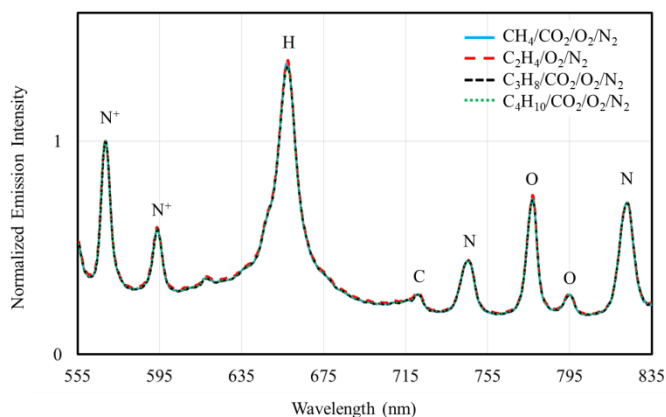

Fig. 2. Comparison between the plasma emission spectra measured in $CH_4/CO_2/O_2/N_2$, $C_2H_4/O_2/N_2$, $C_3H_8/CO_2/O_2/N_2$, and $C_4H_{10}/CO_2/O_2/N_2$ mixtures at 110 ns. The spectra are normalized by the intensity of the N^+ line (568 nm)

Fig. 2 shows the comparison between the emission spectra measured in $CH_4/CO_2/O_2/N_2$, $C_2H_4/O_2/N_2$, $C_3H_8/CO_2/O_2/N_2$ and $C_4H_{10}/CO_2/O_2/N_2$ mixtures with 110 ns time delay. After normalized to the N^+(568 nm) line-intensities, the spectra are almost identical regardless of their different gas species concentrations. The atomic line-intensities as well as the line widths and spectral baseline are closely matched. This detailed spectrum matching between the tested mixtures is obtained for all the other time delays as well until the emission intensities are fully

decayed. The temporal evolutions of these emission spectra are found to be independent of the different mixture compositions. This may be because the breakdown gases of the tested mixtures reach to a similar thermodynamic and physiochemical state after the breakdown while having a negligible effect of species diffusion from the surrounding on the excited state quenching, which is expected from short life time of breakdown emission compared to the timescales of species diffusion.

In this presentaion, the more detail results of fuel-O_2-CO_2 mixtures with either nitorgen and helium balance will be presented.

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Plasma-Aided Processing of Solid Fuel Organic and Mineral Mass

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Currently and in the foreseeable future (up to 2100), the global economy is oriented to the use of organic fuel, mostly, solid fuels, the share of which constitutes 40% in the generation of electric power. Therefore, the development of technologies for their effective and environmentally friendly application represents a priority problem nowadays. This work presents the results of thermodynamic and experimental investigations of plasma technology for processing of low-grade coals. The use of this technology for producing target products (synthesis gas, hydrogen, technical carbon, and valuable components of mineral mass of coals) meets the modern environmental and economic requirements applied to basic industrial sectors. The plasma technology of coal processing for the production of synthesis gas from the coal organic mass (COM) and valuable components from coal mineral mass (CMM) is highly promising. Its essence is heating the coal dust by reducing electric arc plasma to the complete gasification temperature, when the COM converts into synthesis gas, free from particles of ash, nitrogen oxides and sulfur. At the same time, oxides of the CMM are reduced by the carbon residue, producing valuable components, such as technical silicon, ferrosilicon, aluminum and carbon silicon, as well as microelements of rare metals, such as uranium, molybdenum, vanadium, titanium. Thermodynamic analysis of the process was made using a versatile computation program TERRA [1]. Calculations were carried out in the temperature range 300 -

4,000 K and a pressure of 0.1 MPa. Bituminous coal with the ash content of 40% and the heating value 16,632 kJ/kg was taken for the investigation. The gaseous phase of coal processing products includes, basically, a synthesis gas with a concentration of up to 99 vol.% at 1,500 K (Fig. 1). CMM components completely converts from the condensed phase into the gaseous phase at a temperature above 2,600 K (Fig. 2). At temperatures above 3,000 K, the gaseous phase includes, basically, Si, Al, Ca, Fe, Na, and compounds of SiO, SiH, AlH, and SiS. The latter compounds dissociate into relevant elements with increasing temperature.

Complex coal conversion for the production of synthesis gas from COM and valuable components from CMM was investigated using a versatile experimental plant the main element of which was plug and flow plasma reactor. The material and thermal balances helped to find the integral indicators for the process. Plasma-steam gasification of the low-grade coal with CMM processing gave the synthesis gas yield 95.2%, the carbon gasification 92.3%, and coal desulfurization 95.2%. The reduced material of the CMM was found in the slag in the form of ferrosilicon as well as silicon and iron carbides. The maximum reduction of the CMM oxides was observed in the slag from the walls of the plasma reactor in the areas with maximum temperatures, reaching 47%. The thusly produced synthesis gas can be used for synthesis of methanol, or as a high-calorific reducing gas instead of blast-furnace coke as well as power gas for thermal power plants. Reduced material of CMM can be used in metallurgy.
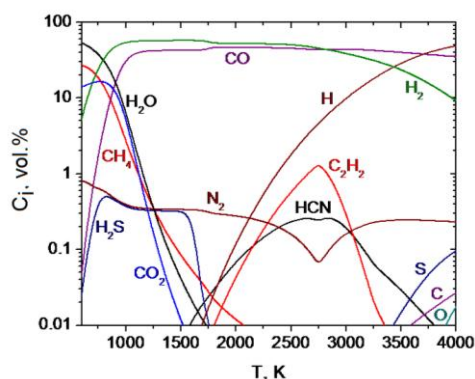

Fig. 1. Temperature dependence of the organic component concentration in the gaseous phase during comprehensive coal processing
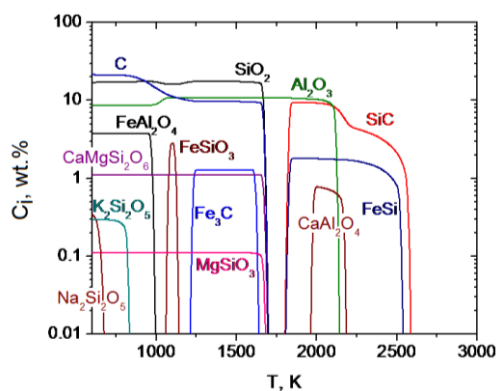

Fig. 2. Temperature dependence of the component concentrations in the condensed phase during comprehensive coal processing

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Small Scale Gas to Liquids (SS GTL)

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There is a significant worldwide demand for small-scale gas-to-liquids (GTL) modules with output capacity of up to 1,500 barrels per day for natural gas reformation, but the main limiting factor is their feasibility.

Practically all commercially available natural gas reforming technologies operate at high temperatures, high pressures, and employ a metal-based catalyst [1]. Our approach of a catalyst-free plasma assisted conversion of natural gas into high hydrogen yield syngas for small-scale GTL was discussed in detail [2].

We have searched for new solutions dealing with the Fisher-Tropsch (FT) and GTL processes and have found an alternative, which could significantly reduce capital and operating expenses for particularly small scale modules. This system is named Gas Turbine Integrated GTL [2, 3]. For the effective conversion of natural gas, the authors have proposed the employment of a recently-developed new generation of high power plasma torches.

The schematic flow diagram of the Gas Turbine Integrated GTL technological complex for natural gas processing into synthetic crude oil, using the air-methane reforming reactor with plasma assistance to produce synthesis gas with subsequent processing into the final product in the Fischer-Tropsch reactor has been developed by combining known and patented solutions of the industry experts (Fig. 1). The design with an output of 300 barrels of synthetic crude oil per day needs the following to operate: GT – gas turbine engine UGT2500 having the power of 2,500 kW and air consumption 14.55 kg/s on the input in terms of ISO is the source of air for a methane reforming reactor.

Processed natural gas in the amount of 3.22 MMSCFD is preheated in the heat exchanger GH and supplied into the reformer. Air is supplied into the reformer at the rate of 3.67 kg/s from the GTE compressor. The process in the reformer is initiated by a high-frequency plasma torch PT with 50 kW power, which uses air for plasma formation.

Sythetic gas with a temperature of 1,500 K produced in the reformer goes through the heat exchanger GH to the heat recovery steam generator HR2, where superheated steam is generated and supplied to the steam turbine ST. After cooling in the heat exchanger C2, synthetic gas

enters the scrubber Skr for water separation, pressure elevation in the compressor K, and further conversion in the Fischer-Tropsch reactor F-T.
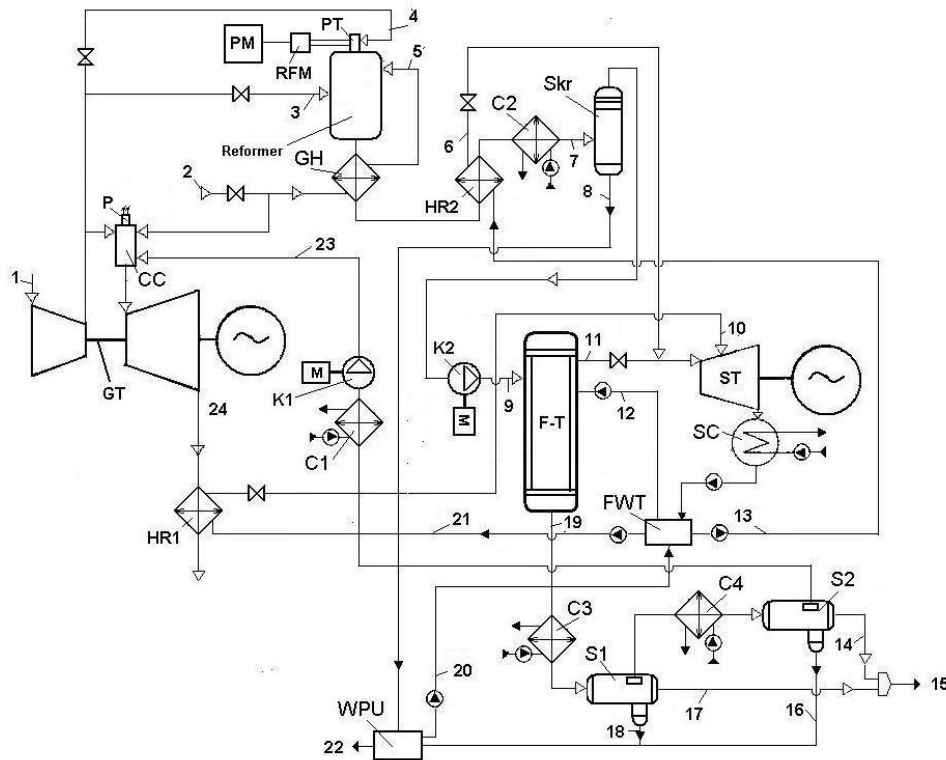

Fig. 8.35. Schematic flow diagram of the technological complex for natural gas processing into synthetic crude oil with power production

Units: PM – high-voltage module of the plasma torch power supply; RFM – high-frequency module; PT – high-frequency plasma torch; P – low-power arc plasma torch; GT – gas turbine engine (GTE); CC – combustion chamber (CC) of GTE; GH – natural gas preheater; K1 – compressor for the tail gas supply into CC of GTE; HR1 – heat recovery steam generator (HRSG) behind GTE; C1 – tail gas cooler; HR2 – synthesis gas HRSG after reformer; C2 – synthesis gas cooler; Skr – scrubber; F-T – Fischer-Tropsch reactor (FT reactor); K2 – synthesis gas supply compressor into the FT reactor; ST – steam turbine; SC – steam condenser; FWT – feeding water tank of the HRSG; WPU – water purification unit; C3 – FT reactor output product cooler; S1 – FT reactor heavy product separator; C4 –steam cooler and condenser of the FT reactor lightweight hydrocarbon product; S2 – FT reactor lightweight hydrocarbon product separator.

Working area flows: 1 – atmospheric air; 2 – natural gas; 3 – GTE compressor air; 4 – plasma generating air; 5 – preheated natural gas; 6 – overheated water steam behind HR2; 7 – synthesis gas in the input of the scrubber; 8 – scrubber water drainage; 9 – synthesis gas in the input of the FT reactor; 10 – overheated water steam behind HR1; 11 – overheated water steam in the output of the FT reactor; 12 – cooling water in the input of the FT reactor; 13 – feeding water supply into HR2; 14 – light hydrocarbon product in the output of S2; 15 – synthetic crude oil output; 16 – S2 water drainage; 17 – heavy hydrocarbon product in the output of S1; 18 – S1 water drainage; 19 – final product output from the FT reactor; 20 – treated water supply into FWT; 21 – feeding water supply into HR1; 22 – excess water discharge from the water purification system;23 – tail gas supply into CC of the GTE; 24 – GTE outlet on HR1.

The overall evaluation of the complex energy balance has been made. The main results are summarized in Table 1.

Table 1. Total GTL complex energy balance

Parameter	Value, kW
Electric power from heat recovery steam generator 3	4,355
Gas turbine electric power generation	1,995
Electric power from heat recovery steam generator 1	759
Electric power from heat recovery steam generator 2	1,783
Total electric power generation	8,892
Own needs for HR1&HR2	95
Electric motor power for tail gas compressor	310
Electric motor power for syngas compressor	287
Total power consumption for plasma torches	75
Total own needs	765
Net electric power production	8,127

Technological complex with 300 barrels/day of synthetic crude oil output capacity consumes about 2,850 kg/day of natural gas, and can produce more than 8,000 kW of net power. UGT2500 gas turbine could be applied as a source of air and for the tail gas combustion after some design improvements. Power consumption for the described GTL own needs is 8-9% of the total generated power. Combination of the gas turbine and steam turbine with advanced heat recovery at all stages allows additional to the main product generation of significant amount of electric power for sale.

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PLASMA TREATMENT FOR COATINGS AND SURFACE MODIFICATION

Plasma Modification for the Deposition of Hard and Adherent Diamond-like Carbon Coatings using an Active Screen as an Additional Cathode

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Plasma surface modification has been widely used to modify the surface properties of polymeric and metallic materials [1]. The active screen plasma nitriding (ASPN) method was reported as a technique used for the surface modification of materials, which avoided the drawbacks associated with plasma surface modification. ASPN has been applied to metals such as low-alloy steel, austenitic stainless steel, and surface modification of polymeric materials [2].
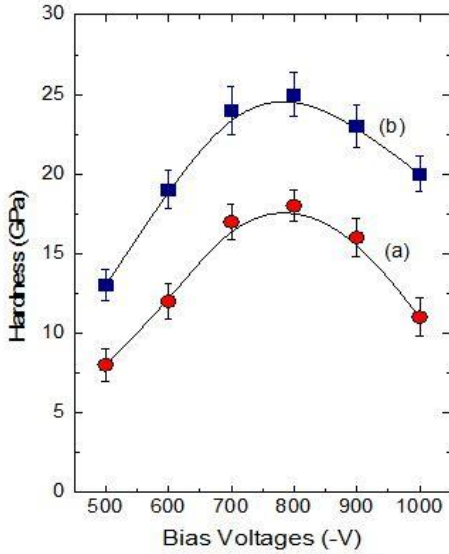
Fig. 1. Hardness values for the DLC coatings as a function of the bias voltages: (a) using a conventional DC-PECVD system and (b) employing an additional cathode

Although these surface treatment techniques increase the mechanical and tribological properties of the metal surfaces, for several industrial applications harder and more wear resistant surfaces are required. In order to improve surface properties, protective coatings have been used. Among them, the diamond-like carbon (DLC) coatings have attracted significant attention recently due to their low friction, high hardness and elastic modulus, chemical inertness, biocompatibility, and high degree of wear resistance [3].

The major disadvantage of hard DLC coatings, and therefore of their industrial applications, is the low adhesion of the coatings on metallic substrates, caused by high total compressive stress. In order to overcome the low adherence of the coatings on steel substrates, an amorphous silicon interlayer has been deposited as an interface using silane as a precursor gas [4]. This interlayer is obtained at low temperatures by using low-energy ion implantation, and it causes a continual change in the thermal expansion coefficient and helps to reduce stress in the films.

The depositions of hard and adherent DLC coatings onto AISI 304 stainless steel substrates employing modified asymmetrical bipolar pulsed-DC plasma enhanced chemical vapor deposition (PECVD) system, gas methane, and an active screen are reported in this work. A cathodic grid was designed to act as an additional cathode in order to accomplish plasma densification and to enhance the source of carbon atoms. The active screen and the cathode were subjected to the same bias voltage.

Table 1. Critical load values as a function of the bias voltages for DLC coatings deposited by conventional DC-PECVD method and using an additional cathode

Bias voltage (V)	Critical load (N) (conventional method)	Critical load (N) (additional cathode)
−500	15.1±1.1)	24.1±1.8
−600	14.8±1.0	24.7±1.7
−700	15.5±1.2	25.1±1.8
−800	16.0±1.3	25.4±1.6

The coatings were analyzed according to their microstructural, mechanical, and tribological properties as a function of the applied bias voltage during deposition process. The hardness values as a function of the bias voltages using a conventional DC-PECVD system (a) and employing the modified system with an additional cathode (b) are presented in Fig. 1. Important improvement in the hardness of the films was observed in the coatings that were deposited using the new system. On the other hand, the critical load values for both depositions system were reported in Table 1. More adherent coatings were also deposited when the additional cathode

was used. This system represented a step forward for thin DLC coating growth by using very lower pressure (about 1 Pa) in almost collision less regime and higher plasma density than the conventional PECVD system.

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Anti-Fogging Properties of Nanostructured Polymer Surface by PECVD

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Plasma treatments method is one of the representative methods for surface treatments. Recently, the plasma treatments are proposed and in spotlight as fabricating nanostructure with several advantages of eco-friendly, high throughput and low temperature processes. Also, many types of nanostructures can be made by plasma without any pre-patterning technique [1].

In this research, we suggest superhydrophilic polymer surface which was created by making nanostructures by PECVD (plasma enhanced chemical vapor deposition) to improve the the anti-fogging function.
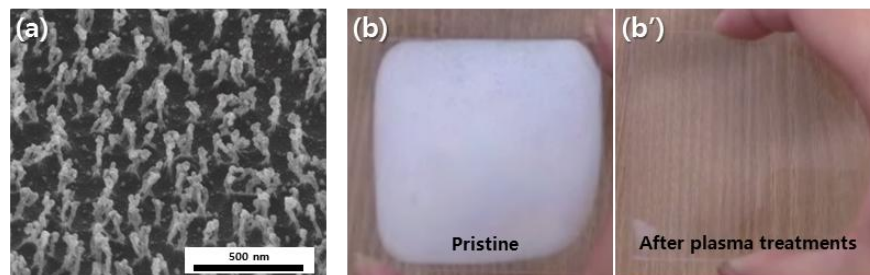
Fig. 1. (a) SEM image of O₂ plasma-etched polycarbonate surface;
(b) and (b') images of anti-fogging test

First, we made nanostructures on polycarbonate (PC) by the plasma treatment with O_2 gas. Fig. 1(*a*) shows the SEM image of nanostructured PC surface. Then, the treated surface was coated with hydrophilic material, SiOx. The superhydrophilic surface was examined by the static water contact angle and anti-fogging test on 80℃ water. The nanostructures helped to enhance the surface wettability. As Fig. 1(*b*) and (*b'*) show, the fog did not form on the plasma treated PC surfaces.

In addition, we made the diverse nanostructures on polymer surfaces for applications in various fields. The nanostructures on PC and polyurethane (PU) were made by PECVD with Ar, CF_4, O_2 and their mixture. We could make nanostructures on the polymer surfaces in various sizes and shapes by controlling different physical variables.

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NEW PLASMA EFFECTS AND PROSPECTIVE APPLICATIONS

Protection of Cellulose-Based Cultural Heritage Objects by Plasma Decontamination and Coating

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The study presents a complex equipment (Fig. 1, Patent application A/00533/2015) of radio frequency cold plasma (1.5 MHz), designed to be used for paper-based materials decontamination, cleaning and their consolidation by coating with compatible polymers for long term protection.

Microorganisms (bacteria, fungi) play an important role in the deterioration of cultural heritage on cellulose support [1]. During the normal metabolic processes these organisms secrete enzymes and organic acids, degrading the cellulose fibers and determining the paper embrittlement [2, 3].

Decontamination and cleaning is carried out in nitrogen plasma generated between two electrodes, one fixed (1) and other mobile (2), mounted inside the reactor (3), connected to a 1.5 MHz, 100W generator. The paper is electrostatically fixed on a transfer foil (polyethylenterephtalate foil) (5), placed on the mobile electrode. The pressure within the reaction chamber is adjusted to $(5$–$6)\cdot10^{-1}$ mbar. Depending on microbiological loading degree, the decontamination duration varies between 5 and 7 minutes.
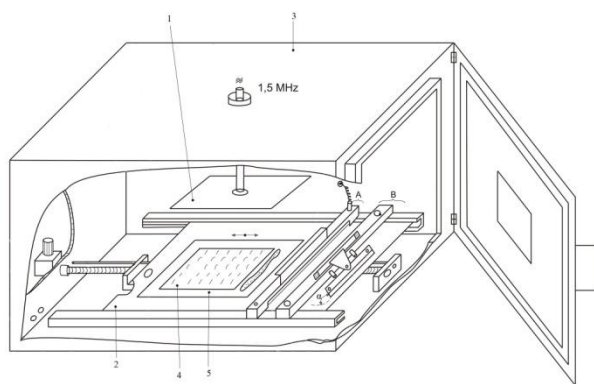
Fig. 1. Decontamination-coating equipment

The final stage consists in paper coating, which is carried out immediately after disinfection. The ensemble paper-transfer foil-mobile electrode is displaced towards the reactor exit, where the document is electrostatically fixed on the transfer foil by sliding the ensemble under the corotron. The polymer is deposited on the transfer foil in the corotron close proximity and the polymer displaying is made by translating the paper material under a rubber blade. The paper material is then dried in the reaction chamber (3), heated at a constant temperature of maximum 30 ^{o}C by a thermostatic resistance.

The preliminary microbiological tests made on representative samples collected from historical books reveal an inhibition of bacterial (Table 1) and fungal (Table 2) growth after maximum 7 minutes of treatment, depending on the initial infestation degree.

The surface analysis (FTIR, contact angle) confirm the presence of the polymer on the entire surface of the paper material and its uniform displaying.

Table 1. Inhibition of bacterial growth by nitrogen plasma treatment

Sample	Bacterial contamination	Micro-morphological types identified	Treatment type	Treatment time	Bacterial decontamination
1	+ + −	Gram + bacillus, isolated, sporulated (central spore, undeformed)	N$_2$ plasma	3 min	+ − −
2	+ + −	Gram + bacillus, isolated, unsporulated	N$_2$ plasma	5 min	−
3	+ + +	Gram + bacillus, isolated, sporulated (central spore, undeformed)	N$_2$ plasma	7 min	−

Table 2. Inhibition of fungal growth by nitrogen plasma treatment

Sample	Initial fungal contamination	Fungal species	Treatment type	Treatment time	Growth of fungal culture
1	+ + + +	Numerous colonies of *Penicillium* and *Aspergillus*	N$_2$ plasma	3 min	+ + +
2	+ + +	Numerous colonies of *Penicillium*	N$_2$ plasma	5 min	−
3	+ + +	Numerous colonies of *Penicillium*	N$_2$ plasma	7 min	−

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Plasma Treatment of Dentin Surfaces for Improving Adhesive/Dentin Interface Bonding

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Polymethacrylate-based dental composites have received widespread clinical acceptance as alternative restorative materials to dental amalgam amid concern regarding the potential health risks associated with mercury release. As supported by results from multiple clinical and laboratory studies, however, the current dental composite restorations suffer from much reduced longevity mainly due to interfacial failures of dental adhesives to the surrounding tooth structures, which cause recurrent caries and composite restoration failure [1, 2].

Materials and Methods

For each extracted unerupted human third molars with un-etched or etched dentin surface, one half of it was treated with non-thermal argon plasma brush, while the other half was shielded with glass slide and used as untreated control. After applied adhesive and composite according to manufacturer's instructions, the teeth were cut into micro-bar specimens with cross-sectional size

of 1mm×1mm for micro-tensile bonding strength (μTBS) test. Before the test, the micro-bar specimens were screened for possible interface defects using optical microscopy. After the test, the fractured surfaces were examined for failure location and interface quality assessment by using both optical microscopy and scanning electron microscopy (SEM).

Results and Discussion

Bonding strength data was analyzed using histograms and Welch's t-test based on unequal variances. μTBS test results showed that, with plasma treatment, the average adhesive/dentin bonding strength was significantly improved (Fig.1). For total etch adhesive, the bonding strength was increased over 30% as compared with the untreated controls. For self etch adhesive, the bonding strength was improved over 22% than the untreated controls. SEM examination of the adhesive/dentin interfaces did show thicker hybrid layer and longer resin tags were formed with plasma treated dentin.
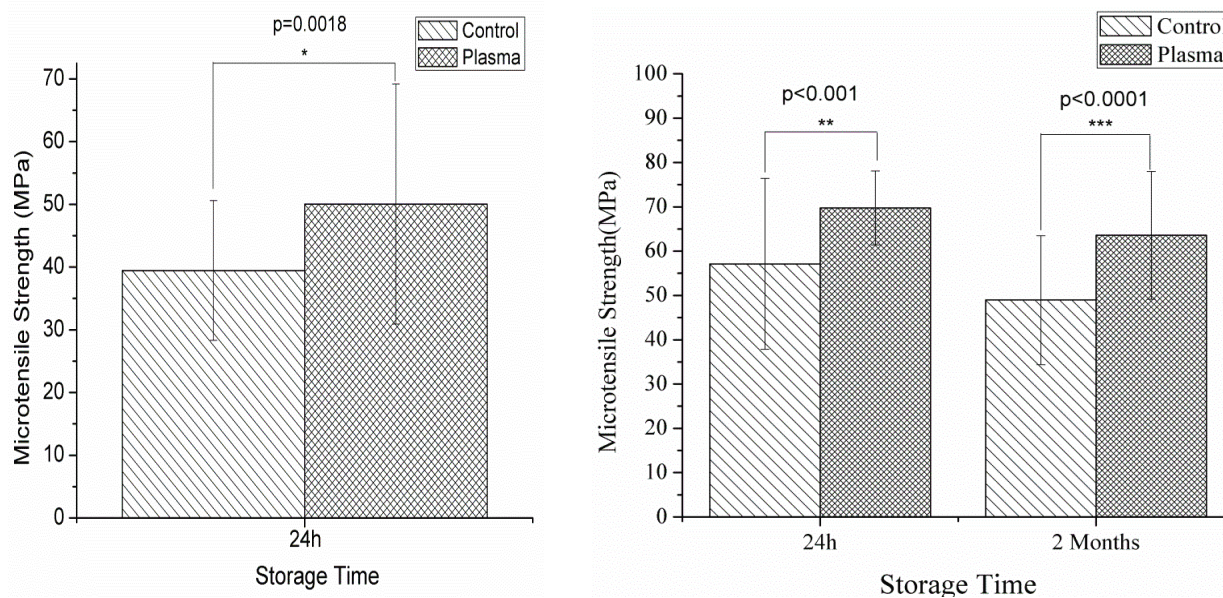

Fig. 1. Adhesive/dentin interface bonding strength for plasma treated specimens and their untreated controls. (Left) Total etch adhesive; (Right) Self etch adhesive

Conclusions

The experimental results from this study further demonstrate that, for both total etch and self etch adhesives, non-thermal argon plasma treatment of dentin surface was very effective in improving adhesive/dentin interface quality and bonding strength, which is crucial for increasing longevity of dental composite restorations.

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A Study on Electrode-less Plasma Light Source Using GaN Transistor

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The purpose of this study is to develop an electrode-less Plasma lighting system using solid state power amplifier based on GaN (Gallium Nitride) transistor technology for generating Plasma source instead of using conventional Magnetron technology.

SSPA (solid state power amplifier) can be operated ten times longer than the lifetime of Magnetron, starting immediately without warm-up time, and implemented on various frequencies. In addition, SSPA allows lighting system designer with more freedom of design through smaller form factor than Magnetron for the same output power level.

The Magnetron traditionally uses frequency band at 900 MHz and 2.45 GHz mostly, and operates with high voltage power supply which requires special caution and limits the peak power efficiency [3]. Table 1 shows general comparison of the characteristics between SSPA and Magnetron.

Table 1. Comparison between SSPA and Magnetron

Parameter	Unit	SSPA	Magnetron
Maintenance	-	Low	High
MTBF	hours	50,000	3,000
Start-up	-	Instan-taneous	Warm-up
Spares	-	Low	High

This study utilizes GaN HEMT (high electron mobility transistor) at the end stage of SSPA implemented with 3-stage amplification, and PLL (phase locked loop) circuit to generate CW (continuous wave) signal at 2.45 GHz.

Due to the physical properties of silicone LDMOS (laterally diffused metal oxide semiconductor) amplifier, it is hard to achieve good performance above 3GHz frequency. However, GaN shows excellent performance at higher frequency, so studies are being done in ISM band of 5.8GHz too [1].

Table 2 shows comparison of the characteristics between GaN transistor developed for this study and LDMOS used to generate Plasma source at 2.45 GHz frequency band released recently.

GaN transistor operate at higher bias voltage and higher current density than any other commercially available device, so which can make device with highest power density on the

same foot print. In addition, GaN SSPA is using DC power supply around 50V allowing to achieve high efficiency over 97%.

Table 3 shows the characteristics of 250W GaN SSPA module developed in this study.

Fig. 1 is the picture of quartz lamp turned on with the GaN SSPA module. The quartz bulb was lit up immediately with GaN SSPA in contrast with Magnetron taking more than ten seconds. [2]The change of color temperature was observed during dimming control by changing the light intensity through adjustment of microwave power level.

Pulsed RF signal generation and control method is under study to improve color temperature, and resolve uncontrollability of blue spectrum under low light output. Further development is on-going to optimize matching between SSPA and quartz bulb, and directly compare the lighting characteristics of Plasma source excited by GaN SSPA and Magnetron ultimately.

Table 2. Comparison of Performance between GaN Transistor and LDMOS (250W CW operation)

ITEM	Unit	GaN	LDMOS
Operating Frequency	MHz	2,450	2,450
Output Power Level	W	250	250
Drain-Source Voltage	V	50	28
Gain	dB	37	15

Table 3. Characteristics of 250W GaN SSPA Module

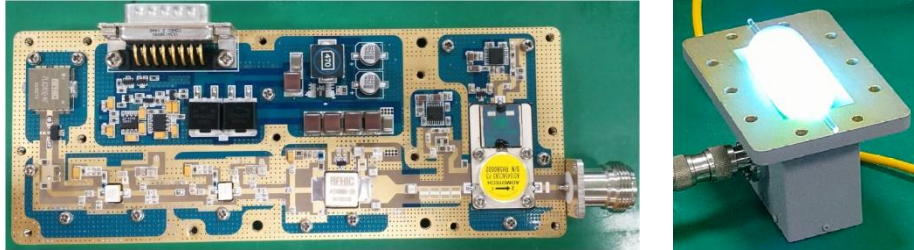| ITEM	UNIT	MIN	TYP	MAX
Operating Frequency	MHz	-	2450	-
Output Power Level	W	250	-	-
Drain Efficiency	%	65	-	-

Fig. 1. Electrode-less Plasma Light Turned on with GaN SSPA

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WATER TREATMENT

Water Purification by High-Voltage Nanosecond Plasma: New Developments

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Further results are presented in the application of fast, repetitive, nanosecond pulsed non-thermal plasma discharge for the purpose of water purification. The primary application is to space recycling systems during long-duration space missions, as well as to terrestrial point-of-

use applications especially in areas lacking water treatment infrastructure. The reactor consists of a DBD plasma jet excited by a repetitively pulsed ns pulse power modulator. In previous experiments, the reactor was used to decolorize a $1.4 \cdot 10^{-4}$ M solution of Methylene Blue (MB) as a test case. 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. Recent results include the design and stable operation of two reactors operating in parallel. The dual-applicator operation was found to greatly improve decomposition times though overall decomposition efficiency remained approximately equal to that of a single reactor. Other developments include enhancements of the plasma-purification process, potential application to simulated agricultural runoff, scale-up studies, and the successful removal of algae-produced microcystin bacteria in preliminary studies. The presentation will begin with a glimpse into the importance of clean water for the world's population, and will be followed by the reasons NASA has interest in this technology. This research project is a collaborative effort between NASA GRC and the University of Michigan at Ann Arbor.

Isaiah M. Blankson received the BS (1969), MS (1970), and PhD (1973) degrees in Aeronautics and Astronautics, from the Massachusetts Institute of Technology, Cambridge, MA, specializing in Hypersonic Aerodynamics and Propulsion. He is currently a Senior Technologist (ST) in theR&T Directorate, at the NASA Glenn Research Center in Cleveland, Ohio, USA. His current research includes MHD Energy Bypass Engine Concepts(Mach 0–7) for Space Access vehicles, waverider aircraft, passive millimeter wave imaging applied to issues in aviation safety, and the use of weakly-ionized plasma (WIG) phenomena for aerodynamics, propulsion, liquid hydrocarbon fuel enhancement, water purification, energy, and environmental applications. Before joining NASA, 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 several US patents including one on an MHD-controlled turbojet engine. He is an Associate fellow of the AIAA. In 2012, he was the recipient of the Distinguished Presidential Rank Award of Meritorious Professional for sustained superior accomplishment.

John E. Foster received the BS (1991) inPhysics, Jackson State University, and the PhD (1996) in Applied Physics from the University of Michigan, Ann Arbor (1996). He was an NSF CPAM Postdoctoral Fellow at the University of Wisconsin, Madison from 1997 to 1998. He is currently a full Professor at the University of Michigan, in the Department of Nuclear Engineering and Radiological Sciences. 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.

Liquid Processing by RF Field

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Different studies for the last decade have shown that the sharp rise of oncological and cardiovascular diseases result from a chlorine disinfection of water and other liquids. Some methods use electric energy for liquid disinfection from microbe and other pollutants. For standard ionizers it is important to first generate anions and cations in a liquid, then efficiently separate them (by using ion-exchange membrane) in order to produce anion saturated (or cation saturated) liquid. Liquids could have a different pH, but perfectly correspond to the mineral's content. The system we developed does not purify the liquids. We keep naturally occurred minerals the same as before the treatment. At the first stage, the liquid is sterilized and micro-ionized. The most effective ways to do it are: pulse electric fields; glow discharge, streamer/corona discharge, gliding discharge, barrier discharge, and pulse spark discharge. All methods mentioned are of approximately equal efficiency for microbes' destruction because, in all those cases, the acting factors are almost the same: UV radiation, OH radicals, H_2O_2, O_3, etc.

Another approach for liquid treatment is to use plasma. There are a few different ways to do it: 1. Ozone. Ozone is generated by separate plasma unit and it is mixed with a liquid. This approach requires a long processing time and has a significant number of side effects. 2. UV, electron beam, shock waves. 3. Electrical discharges in liquid and 4. Plasma injection – discharges above or on the surface of the liquid. However, pulsed electric discharges (PEDs) have better advantages in comparison to the other approaches.

Two groups of factors cause bactericidal action of PED in liquid: 1) electric field strength, UV radiation and shock waves, which act at discharge time and 2) OH radicals, H_2O_2, which act after the treatment. RF pulsed electric field (PEF) processing as an alternative method for liquid processing, eliminate or at least reduce of all the effects accompanying the flow of electric current. Metallic particles might be released from the electrode material as a result of electrically-driven electrochemical reactions. The presence of such metallic particles can affect the quality and the safety of PEF processed liquid.
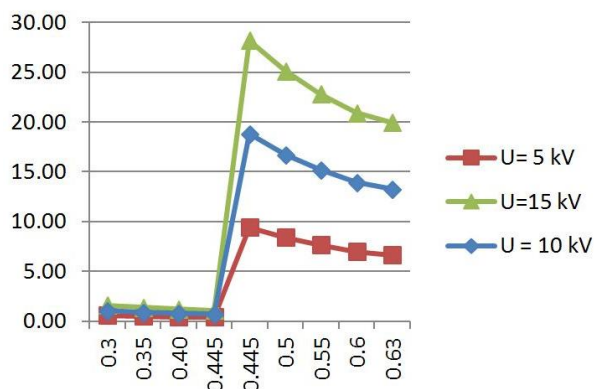

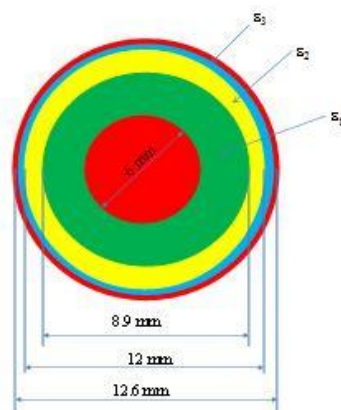*Fig. 1. Radial distribution of E-field*   *Fig. 2. Cross section of the reactor*

This study investigates the effect of varying parameters of applied electric pulses on the liquid sterilization effect using RF instead of DC pulse system. The system include: RF pulse power supply, matching network, reactor, pump, temperature sensors, 3-way valve. Electric field profile is shown on Fig. 1. The cross section of the reactor is shown on Fig. 2. By using short RF pulses it eliminates releasing metals from the electrodes, extends reactor's life time and reduces the running cost of PEF processing. When the liquid is exposed to high electrical field pulses, existing bacteria's membrane pores are enlarged or it generates new pores. The pores increase membrane permeability, allowing loss of cell contents or intrusion of surrounding media, either of which can cause cell death. PEF has a limited effect on spores and only appears to affect enzymes. Enzymes are important in juice processing because surviving enzymes can reduce pectin, which then can be less effective in keeping fruit particles suspended. PEF treatment could achieve 5-log reduction of most pathogens.

Process variables include: electric field strength, pulse width and repetition, electric field profile in the reactor; temperature; and time of exposure. A typical temperature processing parameters are shown in the Tables below for Water and Apple Juice).

ID	Material	Duty, %	Voltage, kV	Power, W	Flow,GPH	Temperature, C	Results, cfu/g	Reduction, %	Note
052213W-IN	Water						15,000,000		Initial
052213W-P1	Water	10	5.9	100	2	23	6,700,000	(55.33)	Internal electrode OD = 6 mm
052213W-P2	Water	25	5.9	1000	2.6	~ 50	480	(100.00)	Internal electrode OD = 6 mm
052213W-P3	Water	10	2.04	100	2.6	23	9,500,000	(36.67)	Internal electrode OD = 3 mm
052213W-P4	Water	25	2.04	700	2.6	n/a	7,900,000	(47.33)	
052213W-P5	Water	50	2.04	1200	2.6	n/a	3,100,000	(79.33)	
052813W-IN	Water						35,000,000		
052813W-P1	Water	10	4.16	100	2.8	23	15,000,000	(57.14)	
052813W-P2	Water	25	4.16	1000	2.8	44	23,000,000	(34.29)	
052813W-P3	Water	50	4	1600	2.8	n/a	880,000	(97.49)	
052813W-P4	Water	25	4.16	1000	2.8	44	22,000,000	(37.14)	
052813W-P5	Water	25	4.88	1080	2.8		9,300,000	(73.43)	better matching
052813W-P6	Water	25	5.6	1300	2.8	44	380,000	(98.91)	Change coil turns for better matching
052813W-P7	Water	50	5.6	2400	2.8	87	1,500	(100.00)	

ID	Material	Duty, %	Voltage, kV	Power, W	Flow,GPH	Temperature, C	Results, cfu/g	Reduction, %	Note
060313APP-IN	Apple Juice						820,000		Initial
060313APP-1	Apple Juice	25	6.56	1150	2.8	54	360	-100.0	
060313APP-2	Apple Juice	50	6.56	1800	2.8	64	360	-100.0	
060313APP-3	Apple Juice	50	6.56	1800	2.8	64	720,000	-12.2	
060313APP-4	Apple Juice	10	6.56	500	2.8	28	570	-99.9	
060313APP-5	Apple Juice	25	6.56	1150	2.8	54	430	-99.9	
060313APP-6	Apple Juice	50	6.56	1800	2.8	69	790,000	-3.7	
060713APP-IN3	Apple Juice						1,400,000		Initial

Conclusion

A few issues still exist and require future investigation and development, such as RF pulse frequency effect, study the RF field effect on enzyme and vitamins (especially vitamin C), other liquids testing. Efficiency of RF Pulse system is one of the critical factors.

Plasma System for Liquid Fertilizer Production from Air and Water

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Production of liquids with controllable composition and properties is a challenge for many industries, including pharmaceutical, production of fertilizers, and many others. This project

proposal describes a plasma assisted reactor for all four states of matter interaction (gases, liquids, solids, and plasma) together and simultaneously in one device to result in the new quality products - liquids with unique properties.

For example, all currently applied nitric fertilizers could not be accepted and used by plants in their existing state. So, mineral forms of nitrogen should pass through several stages in soil to be converted into NO_3- and NH_4^+ ions – the key elements for the nitrogen exchange processes in plants. As an alternative, we could use atmospheric nitrogen and oxygen as a feedstock to produce in a plasma torch initially NO_2 (nitrogen dioxide) and ozone O_3 – the only components to enable reaction $NO_2 + O_3 = NO_3 + O_2$ with further fast quenching and dissolving of the NO_3 ions in water to get a new form of liquid fertilizer, which could be immediately used for watering the plants. This three stage process of green production of important fertilizer with direct action and immediate effect on the plants growth and productivity could be realized in one new device, replace the whole industries of inefficient and polluting production of nitric fertilizers from natural gas, ammonia, and other feedstock, and successfully used on board of the International Space Station (ISS), for space exploration missions, greenhouses, polar stations and so forth.
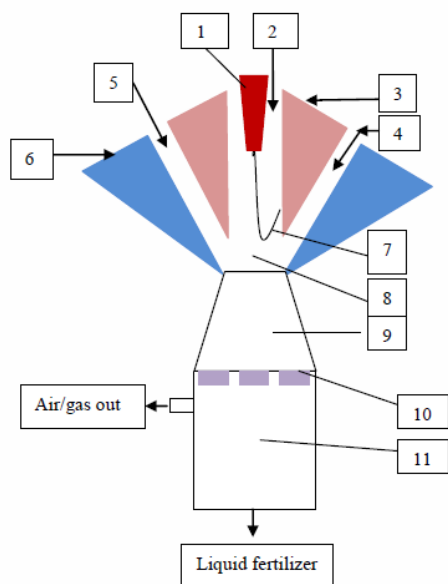

Fig.1. Reactor for liquid fertilizer production:

1 – cathode; *2* – plasma gas; *3* – plasma torch; *4* – water; *5* – atomizing air; *6* – water nozzle; *7* – plasma arc; *8* – primary reaction zone; *9* – aspiration zone; *10* – surface condensing zone; *11* – separation and cooling zone

Flow diagram of the developed and tested reactor is depicted in Fig. 1 (US Patent application # 62279735). This is a combination of a plasma torch *3* (gas ionizer), which is fed by one or more gases *2*, and powered by a specific power supply (not shown); a liquid centrifugal nozzle *6* with air enforced water atomization due to cross flow mixing device placed co-axially to the plasma torch with multiple exits directing swirling flow to the maximal internal diameter of the diverging channel of the nozzle *6*. Normally, mixing device and nozzle *6* are combined in one unit. We have a first stage reactor (zone *8*, Fig. 1. between the torch tip and converging nozzle) where plasma plume or ionized air or other gas with a lot of NO and NO_2 active species, formed by plasma activation of N_2 from plasma gas due to high temperature discharge zone inside the torch, meets with water or liquid mist created by a gas enhanced liquid nozzle. The downstream zone *9* limited by the surface condensers and saturators *10* provides enough residence time for NO_x (both NO and NO_2 species) to interact with ozone O_3 (also product of plasma gas ionization) to create NO_3 (negatively charged ion) with its further interaction with water droplets

to be quenched and partially dissolved in them (water) with formation of NO_3 solution, which is a fertilizer. The last zone *11* of the reactor is the final gas separator, water cooler, and a liquid fertilizer tank.

In the simplest case the above reactor has on the input just tap water, atmospheric air as a plasma gas and atomizing gas, and electric power to produce enough amounts of NO_2 and O_3 from air, enable NO_2 oxidation into NO_3 and it dissolving in water to get a liquid fertilizer. For more efficient and concentrated fertilizer production we expect using oxygen or enriched by 35% oxygen blend (normal atmosphere for ISS) as a plasma gas.

Igor B. Matveev

Degradation of the Dye NA52 Present in Water Using a DC Plasma at Atmospheric Pressure

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Abstract

The analysis of the variation in physical and chemical parameters involved in the degradation by using plasma of the dye Acid Black 52 (NA52) was performed. The plasma, or electrical discharge, was generated in the gas-liquid interface at atmospheric pressure using a DC power supply. For each sample, were measured: Absorbance, Total Organic Carbon (TOC), Chemical Oxygen Demand (COD), pH variation, electrical conductivity, optical emission spectrum, and the change in volume and temperature, as a function of treatment time.

Introduction

Recently, advanced oxidation processes (AOPs), such as ultraviolet (UV) photolysis, Fenton process, direct ozonation, ultrasonification and non-thermal plasma, have gotten rapid developments, and some of them have been utilized for the purpose of degrade organic pollutants in wastewater [1]. The use of electric discharges is probably one of the most promising techniques available to solve environmental problems [2].

Experimental System

The reactor consists of two tungsten electrodes aligned as shown in Fig. 1, the anode is mobile and can be changed its height above the surface water, for all samples treated, and the distance from the anode to the surface was set at 5 mm. Plasma is generated in the space between the upper electrode and the surface of water, while the cathode is immersed in the solution. The electrical discharge is produced with a DC power supply (Mod HP 6525A), 1.0 kV and a current of 40 mA; the plasma treatment is applied to samples every 15 minutes, 15 to 90 minutes. The pH and electrical conductivity measurements were performed with a HACH HQ40d potentiometer; using a HACH DR6000 spectrophotometer, the absorbance was measured, using reagents low-ranking brand HACH COD and TOC was determined.
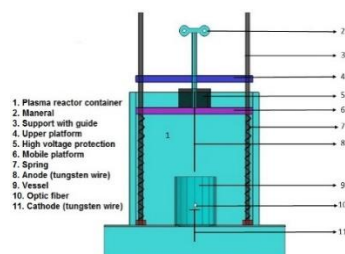
Fig. 1. Experimental Setup
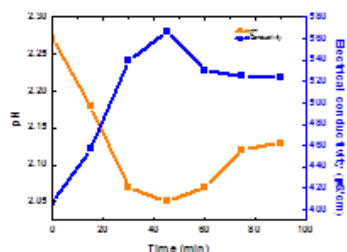
Fig. 2. pH and electrical conductivity versus time

Results

The obtaining of optical emission spectra was performed using a spectrometer Ocean Optics HR 4000CG-UV-NIR and an optical fiber, which passes through the sample container, which allows direct observation of the luminescence of the plasma. Samples treated NA52 have a concentration of 1.0 mM and an initial volume of 100 ml with 1.5 ml of a mixture of 50 mM $FeSO_4$, and 0.1 M H_2SO_4. Fig. 2 shows that the pH decreases and the electrical conductivity increases after the first 45 minutes are almost constant behavior. In Fig. 3, measuring absorbance presents a decreasing behavior in terms of time that the sample interacts with the plasma.
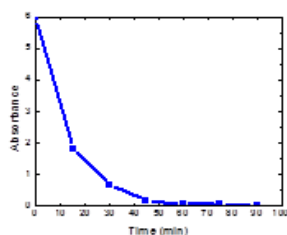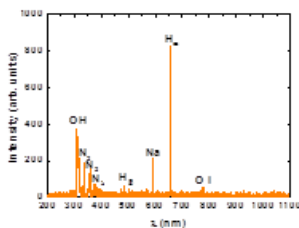

Fig. 3. Time vs Absorbance
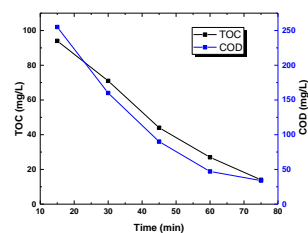

Fig. 4. Optical Emission Spectrum

Fig. 5. TOC and COD vs. time

The optical emission spectrum of plasma shown in Fig. 4, lines and bands H_α, H_β (656.52 nm y 486.36 nm, respectively), O I (777.23 nm), OH (309.41 nm), N_2 (336.71, 357.58, 375.25, 2nd Positive System $C^3\Pi_u \rightarrow B^3\Pi_g$) and the line of Na in 589.23 nm. In Fig. 5, COD and TOC decrease as a function of treatment time; indicating that the dye present in the solution is degraded as a function of treatment time with the plasma. This degradation is due to breaking of the chromophore in the dye molecule and the conversion of organic compounds to CO_2.

Conclusions

The absorbance decreased depending on the treatment time, indicating that the original dye molecule is breaking, i.e., the chromophoric group is splitting, so that the end of treatment shows no coloration. COD values demonstrate a decrease in the level of contamination because of degradation by-products require less oxygen. COT behavior suggests mineralization dye and its byproducts. With these results it follows that the cold plasma treatment at atmospheric pressure has reduced the amount of dye as a function of treatment time. The volume loss is negligible up to 75 minutes, sufficient time to achieve degradation of the dye.

Acknowledgement

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Horizontal Water Well Cleaning by Underwater Pulsed Spark Discharges

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We present a new method for the cleaning of horizontal water wells using impulsive shock waves generated by pulsed spark discharges in water. In this method, impulsive mechanical force exerted on well screens and gravel packs with a temporal duration of a few tens of microsecond plays a key role for the cleaning of the water wells. In this paper, we report the test procedure and results for the cleaning of horizontal wells using underwater pulsed spark discharges.

Introduction

It is known that the performance of clogged wells can be improved by various rehabilitation techniques based on either mechanical or chemical process [1]. Previously, we proposed a novel technique which can be potentially applied to the cleaning of clogged wells [2, 3]. In this technique, a strong, impulsive pressure wave acting as a mechanical force for well cleaning is generated by rapid expansion of a hot, dense spark plasma that is produced during a pulsed discharge in a spark gap immersed in water. This new technique is expected to be environment-friendly and cost-effective because no chemicals and expendables are used during the treatment. Although we previously showed the feasibility for detachment of incrustations in the vertical well [3], demonstration for the cleaning of horizontal water wells has not yet been attempted. In this paper, we report the result of a pilot-scale test for the cleaning of horizontal water wells with this new technique.
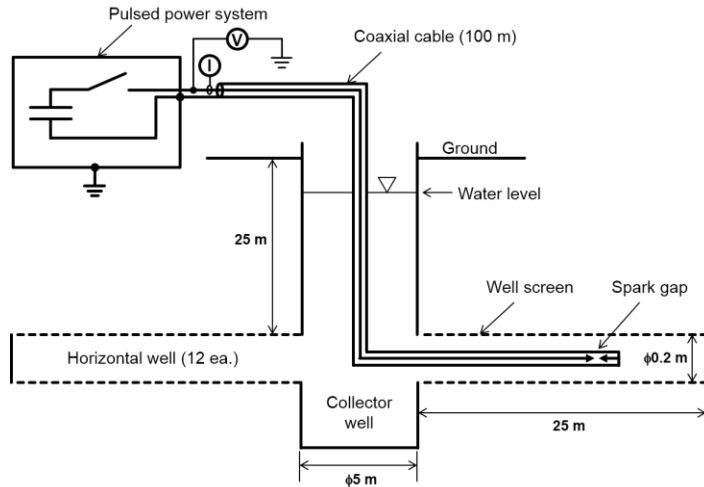
Experimental Setup

Fig. 1. Schematic diagram of the experimental setup for the cleaning of horizontal wells (not to scale)

The schematic diagram of the experimental setup for the cleaning of horizontal wells is depicted in Fig. 1. The diameter and depth of a collector well are 5 m and 45 m, respectively. Twelve horizontal wells with diameter of 0.2 m spread out radially at the position ~ 25 m deep from the ground level. The length of the horizontal wells is 25 m. A spark gap is inserted into the horizontal well through a 100-m long coaxial cable by a diver. A strong shock wave is generated at the spark gap when a high-voltage is applied to it from the pulsed power system. The strength of shock pressure at a well screen is controlled by a capacitor charging voltage, based on the calculations using a numerical code which was developed for simulating pulsed spark discharge in water [3].

Experimental Results

In Fig. 2, we compare the camera images for the horizontal well before and after the cleaning by underwater pulsed spark discharge. It is clearly observed that almost all incrustations attached on the well screen is removed by shock pressures. In addition, the step-drawdown test [4] reveals that the well efficiency increases by 21.3% after the cleaning with pulsed spark discharges. More

Fig. 2. Comparison of camera images before and after the well cleaning by underwater spark discharge

important thing is that the present technique decreases the head loss at the well itself, not disturbing aquifer layer. Indeed, the head loss at the well is reduced by 80%, while the head loss at aquifer layer is only reduced by 10%. These results indicate that the well cleaning by underwater pulsed spark discharge is a useful tool in well rehabilitation without side effects on surrounding environment.
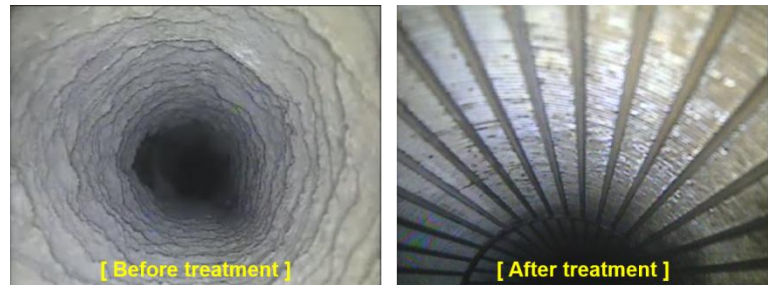
Conclusion

In this paper, we demonstrate the possibility of the cleaning of horizontal water wells constructed for riverbank filtration using shock waves generated by underwater pulsed spark discharges. It is meaningful in that the horizontal water wells are neglected for 7 years after construction because there is no appropriate cleaning method to be applicable to them. This study makes a new plasma application in the area of water resource engineering.

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PLASMA MINERALOGY

RF Plasma Ore Processing: Development and Commercial Applications

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Introduction

Over the past decades RF plasma technology has been used in many areas, such as material science, electronics, basic physics, etc. Typically, the RF plasma system includes power supply (RF generator and matching network), plasma torch and reactor. Depending on the applications two different RF plasma sources are used: inductive and capacitive. Most thermal plasma processes are based on inductively coupled plasma (ICP), which generates equilibrium plasma in the temperature range of 8000 to 12000 K. We will focus on the present situation in this field by discussing the commercial and R&D efforts. In this overview an attempt is made to present existing and future research and development related to RF plasma technology used for ore processing.

1. Ore Processing

This technology refers primarily to the treatment of powdered ore, which content platinum group metals (PGM). The process of powder treatment contains a few stages: in-flight melting of the material, quenching and collection. RF plasma was successfully employed for a large number of different types of ore and a wide range of particle size. Powders injected into the plasma change the shape, morphology, chemical composition, and crystal structure. These changes occur with the plasma exposure time measured in tens of milliseconds. The process is based on RF inductive power used to create plasma at atmospheric pressure. Advanced schemes have been developed to increase the heat transfer from the plasma to particles by up to 35%. Full or partial spheroidization of powders can be achieved by the process. A typical layout of a basic RF plasma system include: the RF generator, RF plasma torch consisting of quartz or water cooled metallic chamber, reactor, powder feeder and collector, emission control system (Fig. 1).
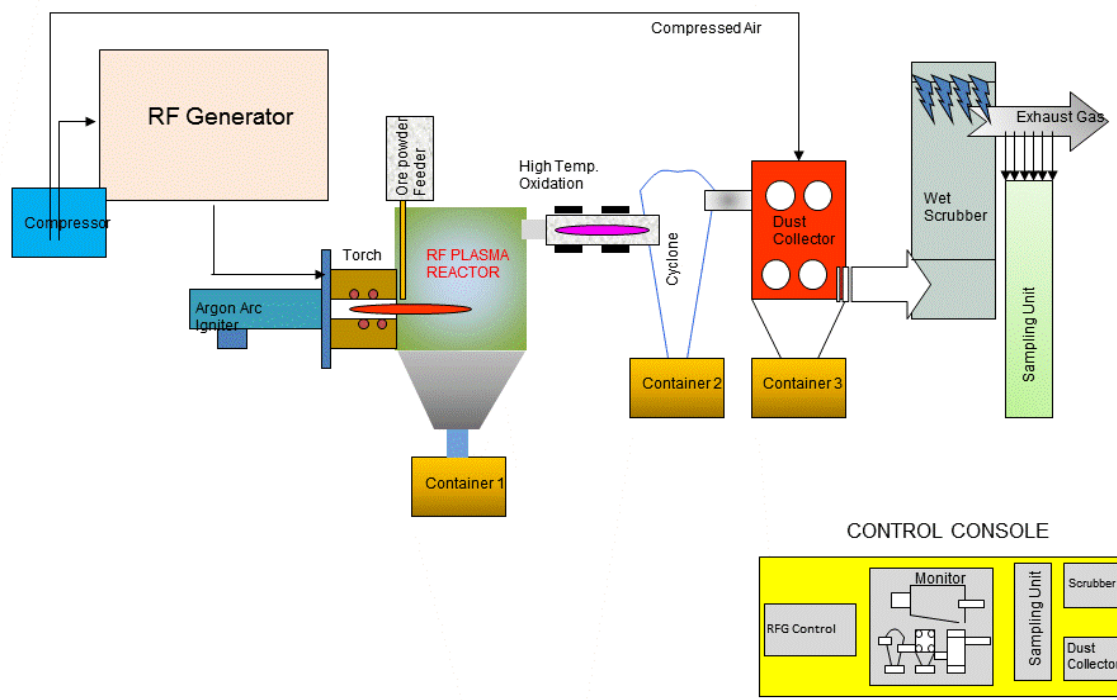
Fig. 1. RF plasma system design schematic

The following gases having rates G_p ranging from 0.2 to 5 m^3/Hr has been employed: Ar, O_2, Air, Ar + H_2, N_2 + H_2. Initial materials are introduced through the powder feeder by the carrier gas G_c and a water cooled probe. Powder injection locations include: the center of the plasma streams, the exit of the plasma chamber, or counter flow to the plasma stream. The primary reason to apply RF plasma to mineral ore processing is to gain higher recoveries then what can be otherwise achieved from conventional hydrometallurgy or pyro metallurgy. As an example, an original ore before processing shows less than 1 troy ounce of gold per ton and 0.5 troy ounce of platinum per ton, as determined by fire assay. The same piece of ore after RFP treatment shows 40 – 50 troy ounces of gold per ton and 70 – 80 troy ounces of platinum per ton.

2. Dore Bar treatment

The separation of metallic elements and isotopes in fully ionized metal plasma has been studied since 1966. In this paragraph we describe the characteristics of a system in which metallic elements: copper and gold are separated by using ionized plasma in a strong magnetic field. Experimental set up is shown on Fig. 2. Copper/gold alloy was sputtered in microwave plasmas, ionized and accelerated by RF antenna in an axial magnetic field. The uniformity of plasma was controlled by optimizing plasma parameters and the axial magnetic field. Control of the plasma profile has been carried out by using microwave ICRH and special RF antenna configuration. The sputter plate (copper Dore bar) was biased by negative DC voltages in the range of –100 to 1,000 Volts. The RF antenna was tuned to the ion-cyclotron frequency and sharp resonances were observed for collected material. The purity of the product (gold) depends on the configuration of the collector and substrate's material.
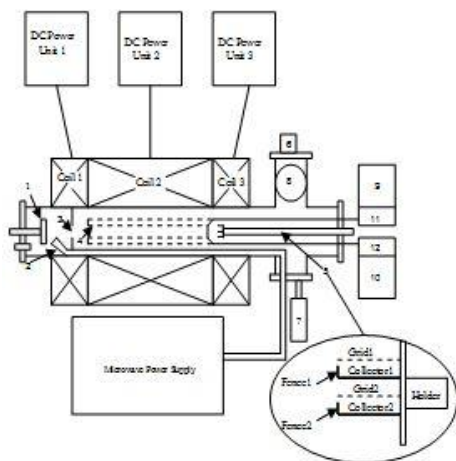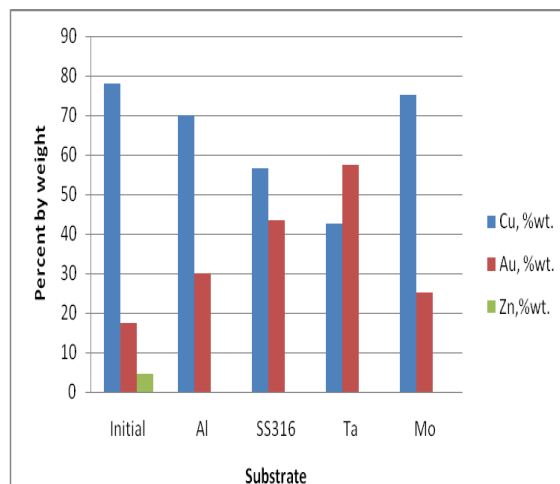
Fig. 2. Schematic Diagram

Fig. 3. Collected product vs. substrate material

Conclusion

The following conclusion is related only to the areas, which have been described in this overview. A few issues still exist and require future investigation and development, such as ignition of RF plasma discharge at atmospheric pressure, precise control of the plasma parameters and efficiency of RF power supplies. Solid state RF generators, having efficiency of 90% and higher, are successfully used for low pressure and low power plasma torches. High power (>25 kW) solid state RF generators are in the development stage. Efficiency of plasma processes is one of the critical factors for existing and new plasma systems.

Preliminary Estimations of Ore Processing Efficiency

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Plasma mineralogy is one of the newest branches of plasma science focused on significant recovery rate increases for the latent metals, particularly ones with contents lower than 3-–5 grams per ton of ore.

Thermal plasma with ion temperature over 4,000 $^{\circ}$C provides super fast heating of treated particles. This enables several processes: (1) Fast heating causes thermal shock, what helps to break down bonds between the components of complex alloys and formations. This is the process that disintegrates complex alloys; (2) Melting nano-particles and growing bigger clusters. This is a process of the latent metals particles transition from sub-nano to nano- and micro-scale level; (3) Burning out organics and light-weight components (i.e. the non-precious metal material found in the tailings or ore). This is a process of enriching the precious metals concentration; (4) Reacting with plasma gas and by-products of the plasma chemical reactions. Plasma gas can vary depending on initial ore composition. This is a process of plasma chemistry;

(5) Quenching or fast cooling down. This is thermal shock 2 with further complex alloys or solid solvents disintegration.

In case of RF (radio frequency) application as a plasma source, feedstock at treatment additionally experiences the influence of a high strength magnetic field and current. Physically, this can enforce the second process by speeding up the clusters growth, and the fourth one by promoting the reactions.

In the table below we provide the results of three different ore samples treatment. It should be noted that the results significantly depend on initial ore composition.

		Weight fraction of element, g/t						
		Platinum Pt	Palladium Pd	Rhodium Rh	Ruthenium Ru	Iridium Ir	Gold Au	Silver Ag
Sample I-338	Initial sample	4.62	21.4	0.256	0.078	0.0256	1,19	32.2
	After the plasma treatment (mode 1)	11.3	25.9	0.320	0.088	0.025	1.00	11.6
	After the plasma treatment (mode 2)	8.7	25.8	0.331	0.128	0.045	1.18	15.8
Sample I-342	Initial sample	1.10	3.50	0.193	0.051	0.0210	0.173	2.54
	After the plasma treatment (mode 1)	0.67	0.77	0.041	0.012	0.0035	0.028	0.76
	After the plasma treatment (mode 2)	0.71	0.84	0.025	0.007	0.002	0.042	0.94
Sample I5-2682	Initial sample	0,22	1,10	0,18	0,050	0,024	0,030	–
	After the plasma treatment	0,23	1,11	0,171	0,059	0,017	0,022	0,79

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COAL, BIO-MASS, AND WASTE INTO ENERGY PROCESSING

Carbon Containing Waste Plasma Processing

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Processing of solid carbonaceous waste (SCW), including municipal and biomedical waste in the Republic of Kazakhstan is now practically not carried out. The need for the annual disposal of hazardous SCW in Kazakhstan is relatively small and amounts to about 35 tons. Therefore, the problem of their disposal until recently considered to be little relevant to the country coinciding with a global estimate of its importance. However, hygiene and sanitary study of typical medical-biological waste made in Kazakhstan, Russia, Belarus and other countries [1, 2] show that their risk to the environment is much higher than that of most chemical wastes. For example, toxicity SCW containing cytotoxic drugs and antibiotics is comparable to toxicity of radioactive waste of high and medium level activity.

This paper presents the results of the thermodynamic analysis of thermal processing of SCW and experiments at the developed plasma unit for processing. Fig. 1 shows the average composition of SCW used in this study.
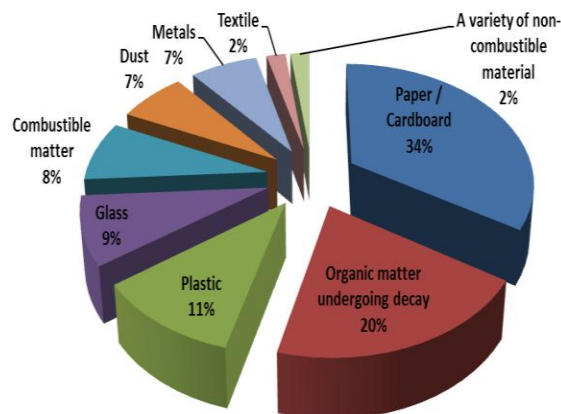
Fig. 1. Qualitative composition of SCW

To perform thermodynamic calculations software package Terra was used [3]. Calculations were carried out in the temperature range 300–3,000 K and a pressure of 0.1 MPa for the following original composition of technological mixture: 10 kg of SCW and 4 kg of air. To use in the calculations the qualitative composition of SCW (Fig. 1) was converted to the following chemical composition, %: C – 34.14; O – 6.29; H – 5.85; N – 8.16; S – 0.94; Cl – 5.3; H_2O – 32.31; $CaCO_3$ – 2.01; Fe_2O_3 – 3; SiO_2 – 2.

Processing of organic part of SCW within the temperature range 1,150–3,000 K leads to formation of 81.8–82.7% of the combustible components (Fig. 2). For air gasification of SCW, synthesis gas yield is high. The condensed phase is represented mainly by iron and calcium compounds: iron silicate, carbide and elemental iron ($FeSiO_3$, Fe_3C, Fe) and calcium silicate, chloride and sulphate (Ca_3SiO_5, $CaCl_2$, CaS), the total concentration does not exceed 5.5%. Silica (SiO_2) is also observed at a concentration not exceeding 1.4%.

Degree of carbon gasification reaches 100% at temperature 1,150 K. Specific power consumption for SCW plasma processing increases from 1.65 to 3.4 kWh/kg with the temperature throughout its diapason 1,150–3,000 K. To minimize the specific power consumption to carry out the processing of SCW is expedient at the minimum temperature at which complete gasification of organic mass is achieved. However, for vitrification of the mineral part of SCW required temperature 1,600 K, which corresponds to the specific power consumption 1.9 kWh/kg.

Fig. 2. Dependence of the gas phase on temperature of SCW plasma processing

Experimental study was carried out in a plasma chamber furnace (Fig. 3). This is device of periodic action. The arc plasma torch of 90 kW electric power is used for its heating [4]. The structure of the installation, except the plasma chamber furnace, includes systems of power supply and ignition of the plasma torch, as well as system of gas and water supply of the plasma torch with the combustion chamber of the furnace. Installation is supplied by system of sampling of the gaseous products for analysis. Consumption of SCW was 30 kg/h. Flow of plasma-forming air was 12 kg/h. Under the influence of air plasma flame weight average temperature in the chamber reaches 1,800 K, the organic part of the waste is gasified and inorganic part of the waste is melted. The resulting synthesis gas is continuously withdrawn from the installation through the cooling and cleaning system. Molten mineral part of the waste is removed from the furnace after it has been stopped.

Fig. 3. Chamber furnace of 30 kg/h of SCW productivity with plasma torch of 90 kW

Experimental studies allowed determining operating modes of the plasma chamber furnace, the exhaust gases was analyzed, samples of condensed products in the combustion chamber were assembled and their chemical composition was determined. Gas at the outlet of the plasma furnace has the following composition (vol.%): CO – 39.7; H_2 – 40.1; N_2 – 15.4; other – 4.8. The total concentration of synthesis gas ($CO + H_2$) is 79.8%, which agrees well with the calculation. The discrepancy between the experiment and calculation does not exceed 4%.

Specific power consumption for processing of bone tissue in the plasma chamber furnace by results of experiments was 3 kWh/kg of SCW.

Research has shown that the complete processing of organic and mineral parts of SCW is provided at the level of the temperature of at least 1,600K. The weight ratio of SCW to air should be at least 0.4 kg/kg.

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Plasma Processing of Organic Materials

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The worldwide energy demand per capita has been increasing over the years, and will continue to increase in the years to come. This ever-increasing energy demand has forced us to look at other sources of energy over the traditional fossil fuels for a long-term approach to energy generation. According to the US Energy Information Administration [1], were consumed 10.14 Exa Joules (EJ) from renewable energy sources in 2014. An expected 10.47 EJ will be consumed in 2016, which is an increase slightly higher than 3 percent. Several renewable energy resources such as solar and wind are currently being utilized to provide part of the electricity and heat needed in the commercial and residential sectors, but these sources suffer from intermittency and variability. Organic matter or organic materials are composed of compounds that contain carbon that comes from the residue of living organisms, which includes agricultural waste, forest woody biomass, animal manure, and sewage sludge, among others.

While conversion of organic residues into different forms of fuel or useful chemicals by means of conventional thermochemical processes is a subject that continues to be researched, it is only briefly described in this paper, in order to provide a description of different forms of plasma processing of organic materials. The paper also describes some emerging applications that utilize plasma discharges to process residues from thermochemical processes, such as biochar, to convert it to activated carbon, which finds applications in filters for air pollution and water treatment.

Biomass processing

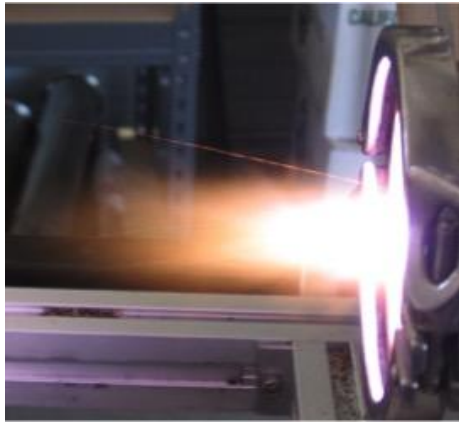One of the methodologies that has received significant attention for the conversion of biomass into synthesis gas, as well as, for the treatment of hazardous organic matter obtained, for instance from hospitals, is plasma gasification utilizing thermal plasma torches. Gasifying agents include Ar, N_2, Air, CO_2, steam, among others, which alter the chemical composition of the resulting product gas. Power requirements of these torches range from around 20 kWe to 1 MWe, with voltages of over 100 Volts. Fig. 1 shows a 35 kWe DC thermal torch with temperatures over 3,000 ^{o}C were measured at the exit of the nozzle utilizing an optical pyrometer [2], where steam was obtained from contact glow discharge electrolysis of liquid waste [3]. Different torch configurations have been tested, some of them requiring an electrode that is consumed during the operation of the torch [2]. Other torch designs do not utilize electrodes [4].

Fig. 1. 35 kW thermal plasma torch for processing agricultural and industrial waste

Another technique for processing organic materials that has been studied in detailed utilizes the principle of operation of gliding arcs [5]. The electrical discharge formed at the closest distance between electrodes is close to thermodynamic equilibrium (quasi-equilibrium), since the power delivered by the power supply compensates for the heat losses. When the discharge reaches the input power limit of the power supply, transition to non-thermal arc occurs, where the gas temperatures falls to a value between 800 and 2,100 K, which can be used for processing of biomass [6].

The purpose of utilizing plasmas to process organic materials is to take advantage of ionized species and the large number of highly-reactive radicals, which modify the chemical species formed during the conversion of biomass [7]. In certain occasions, the plasma is not directly in contact with the organic matter so that the benefit of the ionized species is not obtained. The biomass is decomposed mainly by the heat of radiation emanating from the torch. One way of ensuring the surface of the organic material is in contact with the plasma discharge is by inducing dielectric breakdown of the biomass. Thus, the organic material becomes part of the electric circuit by flowing a current through it, which generates heat directly inside the material by establishing small channels of gases formed by the devolatilization of the organic matter.

Fig. 2. Dielectric breakdown operation with almond hulls.

Fig. 2 shows a picture of a plasma arc in complete contact with the surface of almond hulls, operating in dielectric breakdown mode. Current flows through the material, thus, closing the electric circuit. Voltages of the order of 10 kV to 20 kV have been tested, where the surrounding gas can act as an oxidizing atmosphere, in case of utilizing oxygen or air, or with a neutral atmosphere, in the case of utilizing Ar or N_2. Plasma-enhanced steam reforming can also be achieved with steam generally obtained from industrial waste heat [8].

Biochar processing

Biochar is one of the byproducts of many conventional gasification processes. It has become apparent that commercial success in conventional gasification, particularly in the higher-cost forested settings depends on the sale of the biochar byproduct as much as the sale of electricity. The State of CA has mandated through SB 1122 that 250 MW of projects be developed from a variety of sources, which forecasts a rapid expansion of biochar supply. Biochar can be utilized as soil amendment in order to increase water retention and to provide a source of nutrient retention for plants. However, soil amendment does not constitute a stable market and many biochar producers are analyzing the conversion to activated carbon, which currently constitutes a $2 billion market related to filters for air pollution and water treatment.

Activated carbon is one of the most effective materials for removing a wide range of contaminants from industrial and municipal wastewater, agricultural drainage water, landfill leachate, and contaminate groundwater. Its large surface area (from 200 on the period of activation, which produces micro pores for short times and meso pores for long activation to 1,600 m^2/g) contains a large number of macro, meso, and micro pores where the large pores are used for the transport of liquid through the carbon, and adsorption of contaminants occurs

Fig. 3. Scanning electron microscope image of the structure of biochar processed with steam

in the medium and small pores. A method to produce activated carbon from biochar involves steam activation where superheated steam at temperatures near 1,000 °C is put in contact with biochar produced by conventional gasification. This process volatilizes some of the material leaving pores behind. The size of the pores depends periods. The energy utilized to generate the steam is significant in addition to the pollution generated by burning coal or natural gas. This paper will also describe research being performed by the authors in which a pulsating non-thermal plasma discharge is generated in a low-grade steam atmosphere to modify the internal structure of the biochar, with the intention generating similar structure characteristics as obtained with conventional thermal activation. Fig. 3 shows the structure of processed biochar.
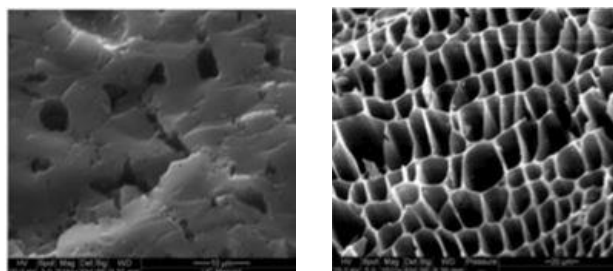
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Sewage Sludge-to-Power

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There are over 18,000 waste treatment plants in the United States. Each of them processes human and other waste in a series of steps that, in the end, result in a byproduct known as biosolids (sludge). 10 million tons are produced each year, and there are currently few options for responsible disposal.

Biosolids can be dried in a kiln and used as fertilizer, but more often, they are incinerated and the ash is transported to a landfill. We have an environmentally sound alternative. Proposed technology can be used to convert the biosolids into syngas [1, 2]. The syngas can then be used onsite to produce electricity and heat – two forms of energy that can be used immediately by the waste treatment facility. About 18,000 GW*h of clean energy can be produced. That will cover about 0.5% of the national electricity consumption and provide electricity to over 1.5 million of population.

A general schematic of a technological complex for plasma biosolids processing into syngas with further electric power and heat production is developed in [1, 2] and depicted in Fig. 1.

We have calculated the performance indicators of the complex, defined all the required process parameters for the process equipment, as well as the specific power cost for the syngas production from biosolids of 24.6% humidity for two variants: biosolids consumption of 10 tons/day (case 1) and for the gas diesel with the given power of 330 kW (case 2). The results are shown in Table 1.

The calculations were carried out for the direct flow biosolids gasifier with the plasma process initiation at 0.15 MPa pressure inside the apparatus, so the largest power consumptions were required for the syngas compressor drive – from 40% up to 71%. The calculations show that

power consumption for the own needs of the technological complex are approximately 33% of electricity generated by the gas diesel. The rest 67% could be marketed. In the total structure of energy distribution the maximum amount (44%) goes for the plasma torch power supply, about 29% – for the power for oxygen production and feeding, 27% – for the syngas compressor drive and about 0.3% – for the water electric pumps drive and biosolids feeding.

Fig. 1. Schematic flow diagram of the plasma biosolids treatment complex.
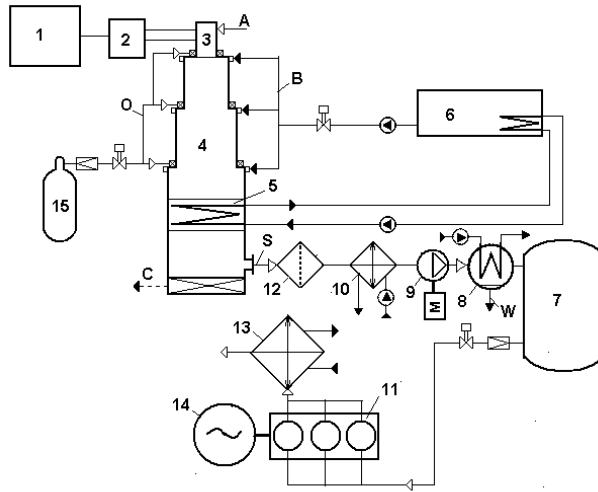
Units: 1 – plate module of a power source; 2 – RF module; 3 – RF plasma torch; 4 – multistage sewage gasifier; 5 – thermalclamping heater of water №1; 6 – tank for sewage storage and preparation; 7 – syngas storage tank; 8 – final syngas cooler; 9 – syngas compressor; 10 – preliminary syngas cooler; 11 – gas engine; 12 – module of syngas cleaning; 13 – thermalclamping heater of water №2; 14 – electrical generator; 15 – source of blowing oxygen (or oxygen production module).

Working mediums: A – plasma gas; B – biosolids (sludge); C – extracting ash; O – blowing oxygen; S – syngas after gasifier; W – water condensate.

Table 1. Expenditures for syngas and power production from biosolids

Case	1	2
Power consumption for plasma torch, kW	62.15	47.99
Power for oxygen production and feeding, kW	40.7	31.4
Power for pumping, kW	0.41	0.31
Power of a synthesis gas compressor, kW	38.21	29.52
Total energy balance for the plant needs, kW	141.45	109.25
Diesel engine electrical power output, kW	427.16	330.00
Thermal power for sewage preparation, kW	251.33	194.16
Thermal power for district heating, kW	517.66	399.92
Electric power excess, kW	285.71	220.75

The proposed approach to human and animal waste treatment demonstrates not only positive energy balance, but also its high electrical and thermal efficiency. The performed preliminary feasibility study shows high profitability and a good prospective for the technology marketing.

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Investigation on the Treatment of Fly Ash by Plasma Vitrification

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Waste-to-Energy (WtE) by incineration is considered as a vital alternative for treating municipal solid waste (MSW) to other treatment technologies (e.g. lanfilling, composting) [1–3]. However, this thermal process results in a production of undesirable secondary byproducts, e.g. toxic gas, cinder, or fly ash. Among them, fly ash contains highly concentrated levels of heavy metals and persistent organic pollutants, such as dioxins and furans [4].

China is now experiencing an arduous task to MSW management. A series of national policies have been implemented to provide better conditions for the development of WtE industry for energy recovery [2]. The incinerated volume of MSW in China increased from 3.7 million tons in 2003 to 46.3 million tons in 2013 and the number of WtE plants increased from 47 to 166 [5]. China TIANYING Inc. is one of the major pioneers in investment, build, operation and maintance of MSW incineration power generation. The company has already put 14 large-scale MSW incineration projects into operation throughout the country. The total treatment capacity of "TIANYING grate furnace" is estimated at 12,800 tons per day, exporting over 400 tons of fly ash. Currently, most of fly ash generated by incinerarors are directly landfilled after solidification and stabilization. This not only poses potential risk to environment but also occupies millions of acres of land. It is a challenge waiting for our solution.

Thermal plasma has been used extensively in researches dealing with solid waste, as they have high arc temperature, high intensity and energy density and most importantly high reactive radicals which are useful in converting waste into useful products in an eco-friendly manner [6]. Therefore research of new and efficient fly ash plasma conversion process is very practical. Recently, researchers from China TIANYING Inc. are attempting to develop novel thermal plasma fly ash gasification technology. The purpose of this project is to develop prototypes of marketable systems for more stable and cleaner conversion of fly ash with dangerous properties into glassy slag and to demonstrate that this technology can be used for a variety of applications. This type of glassy slag could be used in construction. Hence, by processing fly ash in plasma reactor, the environmental problems related to deposition of dangerous waste at landfill will be solved and, moreover, the waste will increase in value (Fig. 1). The research team's ultimate goals are to adapt and commercialize their advanced plasma technologies for other applications.
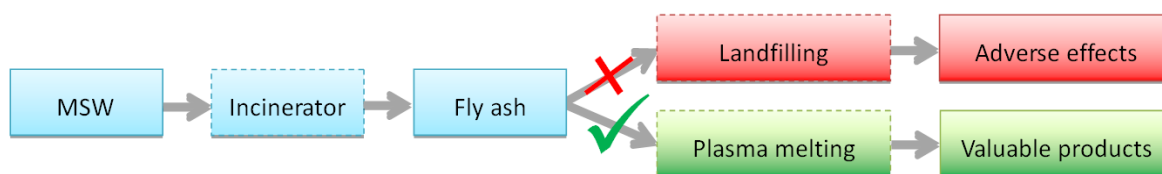

Fig. 1. Plasma vitrification was choosen as alternative for treating TIANYING MSW incineration fly ash

This paper is devoted to provide the results of fly ash vitrification by the use of thermal plasma. Feasibility analysis, including technical feasibility analysis and economical feasibility analysis, will be also discussed.

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