



11-th International Conference on Plasma Assisted Technologies (ICPAT-II)

**22-24 January, 2018
Abu Dhabi, UAE**

Hosted by New York University Abu Dhabi

**International Plasma Technology Center
www.plasmacombustion.org**

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A Tribute to Dr. Louis A. Rosocha



Dr. Louis A. Rosocha (February 7, 1950 – October 17, 2017)

The Steering Committee with great sadness acknowledges the passing away of Dr. Louis Rosocha on 17 October, 2017 at the age of 67.

Dr. Louis A. Rosocha received the B.S. degree in physics from the University of Arkansas, Fayetteville, AR, USA, in 1972, and the M.S. and Ph.D. degrees in physics (minor in chemistry) from the University of Wisconsin, Madison, WI, USA, in 1975 and 1979, respectively.

From 1978 to 1981, he was with the National Research Group of Madison, WI, USA, where he developed pulsed ultraviolet lasers, fast pulsed-power switchgear, and modeling commercial ozone generators.

From 1981 to 2008, he was a Technical Staff Member and a Manager with the Los Alamos National Laboratory (LANL), Los Alamos, NM, USA. Dr. Rosocha focused on large volume, how power KrF lasers for inertial confinement fusion applications in the 1980s–1990s. In the late 1990s until his retirement in 2008, he was a leader in research and applications of plasma-assisted combustion.

In 2003, he organized the first International Workshop on Plasma-Assisted Combustion, currently International Conference on Plasma Assisted Technologies, and became a Co-Editor of the IEEE TRANSACTIONS ON PLASMA SCIENCE Special Issue on Plasma-Assisted Combustion

After an early retirement from LANL in 2008, Dr. Rosocha became an independent consultant, focusing his research and development interests on CO₂ sequestration/global warming, national energy security, plasma-assisted combustion, and water/air pollution abatement. For the last ten years of his life, he focused on various projects including the use of various plasma devices in cleanup of frack and produced water from gas and oil hydrofracking drilling operations and the production of supercritical salt water using short pulse, high-power plasma discharges. Most recently, until Dr. Rosocha's premature death, he was developing a technique for sequestering in silica aerogels radioactive Cesium from the Fukushima nuclear reactor disaster.

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MEETINGS, DISCUSSIONS, NEGOTIATIONS, ENTERTAINMENT

Synopsis

First time in its history **ICPAT** will be held in the fastest growing part of the **Middle East** – capital city of the United Arab Emirates from 22–24 January, 2018.

ICPAT-11 host is the New York University of Abu Dhabi (NYUAD), Saadiyat Island Campus, building A6, P.O. Box 129188, Abu Dhabi, UAE, <https://nyuad.nyu.edu/en/>

ICPAT-11 is sponsored by: NYUAD, Applied Plasma Technologies, Corp. (APT), and International Plasma Technology Center (IPTC), both USA.

ICPAT-11 will have eight consecutive sessions: (1) plasma generation, diagnostics, and modeling; (2) plasma ignition and flame control, fuel reformation and activation; (3) plasma kinetics and dusty plasma; (4) new plasma effects and prospective applications; (5) electric propulsion; (6) coal, bio-mass, and waste into energy processing; (7) plasma treatment for coatings and surface modification; (8) nano-structures production, and seven round tables.

ICPAT-11 is expected to have over 30 oral presentations (30 minutes in duration, including questions and answers), and two plenary lectures.

During the conference, we plan to honor new members of the International Council of Experts in the field of PAT, 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 Technologies. ICPAT-11 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-11 has two new sessions – plenary lectures and electric propulsion. 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-11

Tentative Agenda

Monday, 22 January

8.30 – 9.00	Registration: Saadiyat Island Campus, building A6, Lobby. P.O. Box 129188, Abu Dhabi, UAE, http://nyuad.nyu.edu
9.00 – 9.15	ICPAT-11 OPENING Welcome remarks from <i>Dr. Igor Matveev, ICPAT-11 Chair</i> International Plasma Technology Center, Corp., USA Announcements
9.15 – 10.15	PLENARY LECTURES
9.15 – 9.45	Plasma-Assisted Planetary Life – A Conceptual Plan <i>Dr. Isaiah M. Blankson</i> (NASA Glenn Research Center, USA) <i>Dr. John E. Foster</i> (University of Michigan, USA)
9.45 – 10.15	Progress in RF Plasma Development <i>Dr. Igor Matveev, Svetlana Matveyeva</i> (Applied Plasma Technologies, Corp., USA)
10.15 – 10.30	Coffee break
10.30 – 13.00	PLASMA GENERATION, DIAGNOSTICS, AND MODELING Chaired by <i>Professor Alexander Ustimenko</i> Research Institute of Experimental and Theoretical Physics of Kazakhstan National University, Kazakhstan
10.30 – 10.55	Development and Creation of Microplasma Detector for Gas Chromatography Based on the Plasma Electron Spectroscopy (PLES) Method <i>A.A. Kudryavtsev, A.I.Saifutdinov, S.S.Sysoev, I.V.Trofimov</i> (St.-Petersburg State University, St.-Petersburg, Russia)
10.55 – 11.20	Application of High Pressure Helium Microdischarge with Non-Local Plasmas as a Gas-Analysis Sensor <i>A.A. Kudryavtsev, A.I.Saifutdinov, S.S.Sysoev, I.V.Trofimov</i> (St.-Petersburg State University, St.-Petersburg, Russia) <i>M. Stefanova, P. Pramatarov</i> (Institute of Solid State Physics, Bulgarian Academy of Sciences, Sofia, Bulgaria)

11.20 – 11.45	Langmuir Probe Studies of RIE and Hollow Cathode RIE Plasmas Using Carbon Tetrafluoride <i>R.S. Pessoa, G. Petraconi, H.S. Maciel</i> (Instituto Tecnológico de Aeronáutica, Universidade Brasil, Brazil)
11.45 – 12.10	Mathematical Simulation of Processes in ICP/RF Plasma Torch for Plasma Chemical Reactions <i>D. V. Ivanov, S. G. Zverev</i> (Peter the Great St.-Petersburg Polytechnic University, Russia)
12.10 – 12.35	High-resolution measurements of Doppler Shift and Zeeman Splitting in gas discharges <i>O. Batischev, A. Hyde</i> (Northeastern University, USA) <i>T.S. Matlock</i> (Aerospace Corporation, USA)
12.35 – 13.00	Study of Dielectric Barrier Discharge Plasma Assisted Combustion using Optical Emission Spectroscopy <i>R. B. Patel, C. Oommen, M. J. Thomas</i> (Indian Institute of Science, India)
13.00 – 14.00	Lunch
14.00 – 15.45	<p style="text-align: center;">PLASMA IGNITION AND FLAME CONTROL FUEL REFORMATION AND ACTIVATION</p> <p style="text-align: center;">Chaired by <i>Professor Serhiy Serbin</i> National University of Shipbuilding, Ukraine</p>
14.00 – 14.30	Effect of Nanosecond DBD Microplasma Discharge on Combustion Characteristics: Flammability Limit and Burning Velocity <i>A. Elkholy, Y. Shoshyn, S. Nijdam, J. van Oijen, L. de Goey</i> (Eindhoven University of Technology, Netherland)
14.30 – 15.00	Plasma Methane Pyrolysis for Spacecraft Oxygen Loop Closure <i>Z.W. Greenwood</i> (NASA, USA)
15.00 – 15.30	Fuel Additives for Coal Incineration in Combustor with Plasma-Aided Start <i>V.E. Messerle</i> (Combustion Problems Institute, Kazakhstan Institute of Thermophysics of SB RAS, Russia) <i>A.L. Mosse</i> (A.V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus, Belarus) <i>G. Paskalov</i> (Omstar Environmental Products DX1, Inc., USA) <i>A.B. Ustimenko</i> (Research Institute of Experimental and Theoretical Physics of Kazakhstan National University, Kazakhstan)

15.30 – 15.45 Round Table on Plasma Ignition, Flame Control, Fuel Reformation and Activation

15.45 – 16.00 Coffee break

16.00 – 18.30

PLASMA KINETICS AND DUSTY PLASMA

Chaired by *Prof. Anatoly Kudryavtsev*
Saint-Petersburg State University, Russia

Co-chair – Prof. Chengxun Yuan
Harbin Institute of Technology, China

16.00 – 16.30 **The Influence of Ambipolar Electric Field on the EDF Formation and the Electron Processes in Bounded low Temperature Plasmas**

A. A. Kudryavtsev, K. Rabadanov, Ch. Yuan, Zh. Zhou (Harbin Institute of Technology, China)

16.30 – 17.00 **Gas Discharge Ionization of Air and its Mixtures**

V.L. Bychkov (M.V. Lomonosov Moscow State University, Russia)

17.00 – 17.30 **The Non-Local Electron Kinetics for a Low-Pressure Glow Discharge Dusty Plasma**

C. Yuan, Y. Liang (Harbin Institute of Technology, Harbin, China)

A. Kudryavtsev (St.-Petersburg State University, Russia)

17.30 – 18.00 **Scaling Laws for the Formation of Spatial Distributions of Particles and Fluxes in a Dusty Plasma of a Glow Discharge**

D. Bogdanov, E. Bogdanov, A. Kudryavtsev (St.-Petersburg State University, Russia)

C. Yuan (Harbin Institute of Technology, Harbin, China)

18.00 – 18.30 Round table on plasma kinetics and dusty plasma

18.30 – 20.00 Welcome party

Tuesday, 23 January

8.30 – 11.45

NEW PLASMA EFFECTS AND PROSPECTIVE APPLICATIONS

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

8.30 – 9.00 **Behavior of Historical Printing Inks on Paper in HF Cold-Plasma Discharges**

E. G. Ioanid (“Petru Poni” Institute of Macromolecular Chemistry of Iasi, Romania)

D. Rusu, A.M. Vlad ("Moldova" National Museum Complex Romania,)

V. Frunză, G. Savin (S.C. Romcatel Impex Research Design S.A. of Iasi, Romania)

9.00 – 9.30 **Electron-Beam Plasmas for Plasma Aerodynamics and Combustion**

V.L. Bychkov (M.V. Lomonosov Moscow State University, Russia)

9.30 – 10.00 **Development of a Solar Photoelectric Converter Based on a Two-Chamber Photoplasma**

S.A. Astashkevich, E.A. Bogdanov, A.A. Kudryavtsev
(St.-Petersburg State University, Russia)

10.00 – 10.15 Coffee break

10.15 – 10.45 **Inactivation Process of Bio-Films of *Candida Albicans* by Gliding Arc Plasma Jet**

R.S. Pessoa, A.C.O.C. Doria, F.R. Figueira, G.R. Torello, J.S.B. de Lima, H.S. Maciel, S. Khouri (Universidade do Vale do Paraíba/IP&D/Laboratório de Biotecnologia e Plasmas Elétricos; Instituto Tecnológico de Aeronáutica/Departamento de Física; Universidade Brasil; Universidade do Vale do Paraíba, Brazil)

10.45 – 11.15 **Water Purification by Pulsed High-Voltage Nanosecond Plasma: New Results**

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

11.15 – 11.45 Round Table on New Plasma Effects and Applications

11.45 – 13.00

ELECTRIC PROPULSION

Chaired by *Professor Paolo Gessini*
University of Brasilia, Brazil

Co-chair Professor Oleg Batischev
Northeastern University, USA

11.45 – 12.10 **Analysis of Electrothermal Energetic Capillary Plasma Source Concept for Launch Applications**

N. M. Al-Mousa (Princess Nourah Bint Abdulrahman University, Saudi Arabia)

M. A. Bourham (North Carolina State University, USA)

12.10 – 12.35	A Multi-Propellant RF Plasma Thruster <i>I.B. Matveev</i> (International Plasma Technology Center, Corp.; USA) <i>P. Gessini</i> (University of Brasilia; Brazil) <i>S. Serbin</i> (National University of Shipbuilding, Ukraine)
12.35 – 13.00	Broad Spectral characterization of EP thrusters (Hall, DCF and Minihelicon) <i>O. Batischev, A. Hyde</i> (Northeastern University, USA)
13.00 – 14.00	Lunch
14.00 – 16.00	COAL, BIO-MASS, AND WASTE INTO ENERGY PROCESSING Chaired by <i>Anne J. Meier</i> NASA, Kennedy Space Center, USA
14.00 – 14.30	Arc and RF Plasma Sources for Environmental Applications <i>G. Paskalov</i> (Plasma Microsystem LLC, USA) <i>V.E. Messerle</i> (Combustion Problems Institute, Kazakh National University, Kazakhstan) <i>A.B. Ustimenko</i> (Plasmotechnika Ltd., Kazakhstan) <i>A.L. Mosse</i> (Luikov Heat and Mass Transfer Institute, Belarus)
14.30 – 15.00	Plasma Gasification of Fuel Biomass <i>V.E. Messerle</i> (Combustion Problems Institute, Kazakhstan Institute of Thermophysics of SB RAS, Russia) <i>A.L. Mosse</i> (A.V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus, Belarus) <i>A.B. Ustimenko</i> (NTO Plasmotechnika LLC, al-Farabi Kazakh National University, Kazakhstan) <i>Z. Jankoski</i> (University of Split, Split, Croatia) <i>R.V. Baimuldin</i> (al-Farabi Kazakh National University, Kazakhstan)
15.00 – 15.30	Trash-to-Gas: Efforts for Long Duration Space Logistical Waste Conversion <i>Anne J. Meier, Paul E. Hintze, Ph.D.</i> (National Aeronautics and Space Administration, Kennedy Space Center, USA)

15.30 – 16.00 **Plasma-Assisted Disposal of Sewage Sludge**

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

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

16.00 City tour

Wednesday, 24 January

9.00 – 11.00

PLASMA TREATMENT FOR COATINGS AND SURFACE MODIFICATION

Chaired by *Professor Homero Maciel*
UNIVAB, Brazil

9.00 – 9.30

Deposition of Hard, Adherent and Corrosion Resistant DLC Coatings using a Pulsed-DC PECVD System with an Active Screen

G. Capote (National University of Colombia, Bogota D.C., Colombia)

A. Capote (Universidad de los Andes, Bogotá D.C., Colombia)

V. J. Trava-Airoldi (Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil)

9.30 – 10.00

Surface Modification of Vegetable Fibers for use as Reinforcement in the Manufacture of Bio-Composites

M.L. Sánchez, L.Y. Morales (Universidad Militar Nueva Granada, Bogotá, Colombia)

G. Capote (Universidad Nacional de Colombia, Bogotá, Colombia)

10.00 – 10.30

Comparisons Between $\text{TiO}_2/\text{Al}_2\text{O}_3$ Nano-Laminates Grown by Thermal and Plasma Enhanced Atomic Layer Deposition

G. E. Testoni, R. S. Pessoa (Universidade do Vale do Paraíba, Instituto Tecnológico de Aeronáutica, Brazil)

M. A. Fraga (Universidade Brasil, Rua Carolina Fonseca, National Institute for Space Research (INPE), Brazil)

J. C. Sagás (Universidade do Estado de Santa Catarina, Brazil)

N. K. A. M. Galvao, H. S. Maciel (Instituto Tecnológico de Aeronáutica, Brazil)

10.30 – 11.00	Development and application of thermal plasma torches for materials processing: surface coating and solid waste vitrification <i>F.S. Miranda¹, F. R. Caliarí¹, G. P. Filho¹, H.S. Maciel^{1,2}.</i> (¹ Instituto Tecnológico de Aeronáutica, ² Universidade Brasil, Brazil)
11.00 – 11.30	Round Table on Plasma Treatment for Coatings and Surface Modification
11.30 – 11.45	Coffee Break
11.45 – 13.00	NANO STRUCTURES PRODUCTION Chair <i>Dr. George Paskalov</i> Plasma Microsystems LLC, USA
11.45 – 12.15	RF Plasma Systems for Material Processing <i>Dr. George Paskalov</i> (Plasma Microsystems LLC, USA)
12.15 – 12.45	Boron Particles Behavior in ICP/RF Plasma <i>Dr. Igor Matveev</i> (Applied Plasma Technologies, Corp., USA) <i>Serhiy Serbin, Nataliia Goncharova</i> (National University of Shipbuilding, Ukraine)
12.45 – 13.00	Round Table on Nano Structures Production
13.00 – 14.00	Lunch
14.00 – 15.00	DISCUSSIONS, NEGOTIATIONS Conference Closing
15:00	Desert Safari Reserve in advance

PLENARY LECTURES

Plasma-Assisted Planetary Life – A Conceptual Plan

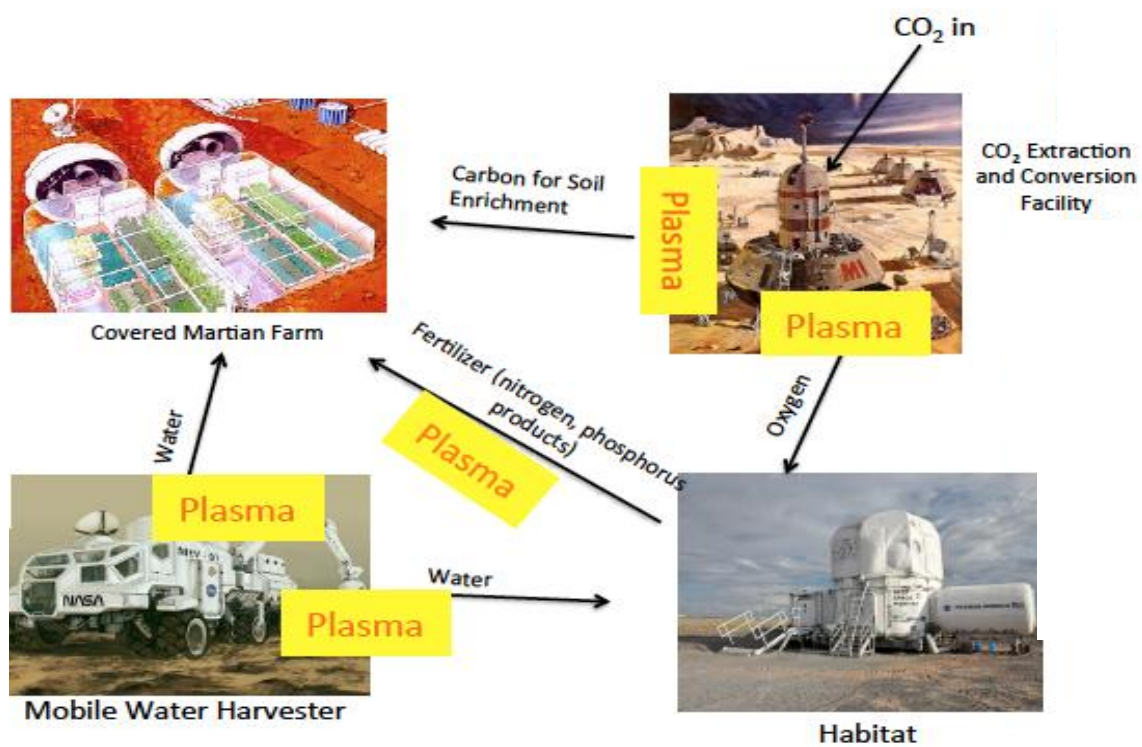
Dr. Isaiah M. Blankson

NASA Glenn Research Center, USA

Dr. John E. Foster

University of Michigan, USA

Practical implementation of long-duration human space missions require robust and reliable advanced life- support systems. Such systems have been the subject of research since the dawn of human spaceflight. Indeed, NASA's Controlled Ecological Life Support System program focused on the development of a closed loop geometry in which food, water, plants, and air were maintained sustainably. Such systems could substantially reduce system mass and ultimately simplify life support. These systems, which rely on atmosphere exchange through exchange with plants, however have still not been realized. Regardless of the configuration, however, a closed loop, atmospheric recycling system is a pre-requisite for long duration space flight, particularly for those voyages far away from LEO such as missions to Mars and beyond.



In this presentation, we will show how non-thermal plasma can potentially serve as the basis for astronaut life support by allowing for the prospect of closed loop utilization. We will address both in-transit and surface operations life support needs for a notional round-trip human expedition to Mars. We study an architecture that allows for close loop human life support and in situ utilization (ISRU) that exploits the capability of plasma. Once on the surface, food and water in addition to a sustainable, breathable atmosphere is also a necessity. In situ resource utilization (ISRU) on the surface can greatly reduce launch mass requirements and greatly extend surface operation duration, allowing more detailed

expeditions. We will address both in-transit and surface-operations life-support needs for a Mars expedition. At the center of this life support system is nonthermal plasma. Electrical energy will be used to convert “air” into a plasma activated gas that will allow for not only cabin atmospheric recycle and the utilization of gases such as carbon dioxide, but also water extraction from Martian permafrost. Specific areas of focus are:

Crewed transit to Mars

Through natural metabolic processes astronauts use oxygen and produce carbon dioxide. Advanced plasma methods could revolutionize the way spacecraft cabin atmosphere waste gases are recycled. Waste gas such as that rejected from the Sabatier reactor would be reformed in a plasma reaction cell. The use of plasma extends well beyond the Sabatier process in that it can be brought to bear on the complete decomposition of carbon dioxide as well as providing a path for completely closing the metabolic loop. The plasma reactor would act as a *molecular cracker*, taking in carbon dioxide waste gas and converting it into oxygen to maintain cabin atmosphere quality. The plasma source could be used for sterilization as well. The requirements of such a system to supply the needs of a crew of 4 to 6 over the estimated time of flight to Mars will be detailed.

Mars surface operations (see Figure)

Plasma based decomposition of CO₂ (The main Mars atmospheric constituent) has been demonstrated in laboratory scale experiments. A technology based on this science could greatly reduce the complexity and mass required for extended stays on the surface of Mars. An architecture that will be investigated is the deployment of multiple CO₂ crackers that would accumulate oxygen in advance of the human landing party. Given the decomposition rates, one can determine the accumulation rate of the oxygen and thus how far in advance should such units be launched – given the metabolic needs of the astronauts. The carbon by – product of this process could be used to enrich the Martian soil so that it can be conditioned for the growing of plants. The astronaut habitat in this scheme would separate the waste streams –liquid from solids. The liquid waste would go directly to a plasma reactor that would convert to ammonia to nitrates. This compound can then be used to fertilize the conditioned Martian soil. The plasma based life-support system also addresses the acquisition of water. Water molecules on the Martian permafrost can be desorbed via plasma bombardment. This study will include water acquisition rates dependent of what is known of the adsorbed water in Martian permafrost and the rate that plasma desorbs the water.



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 the R&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) in Physics, 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.

Progress in RF Plasma Development

Dr. Igor Matveev, Svetlana Matveyeva
Applied Plasma Technologies, Corp., USA
International Plasma Technology Center, Corp., USA

Significant progress was achieved last year in development of the RF plasma systems for synthesis of new materials and treatment of powders. Successfully commissioned APT-100-2 with reactor and mixing chamber for boron nitride nano-tubes (BNNT) production at 5 bar processing pressure [Fig. 1, (a)] and APT-100-3 combined with atmospheric pressure reactor, multi-channel mixing chamber, and advanced control system for super-fine powders treatment [Fig. 1, (b)] have created a solid foundation for further developments.

To help potential customers simplify access to high power RF plasma, Applied Plasma Technologies, Corp. (APT) in collaboration with International Plasma Technology Center, Corp. (IPTC) has initiated a project named “Lab Lease Initiative”. This project allows the third parties to lease APT-100-3 or similar systems with necessary auxiliary equipment for appraisal tests of their technologies according to jointly developed program at the APT test facilities in Springfield, VA with involvement of highly skilled company staff.



a)



b)

Fig. 1: a) APT-100-2 for boron-nitride nano-tubes production; b) APT-100-3 for powders treatment with manual and automatic operation modes

The first two tests were successfully performed in August-September, 2017 for a German customer. As a result, APT will supply a modified APT-100-4 system in early 2018 and both sides agreed to organize a Pilot Production Plant for a mid-scale treatment of the customer feedstock.

The target markets for our RF plasma products are:

- Synthesis of New Materials (BNNT, etc.)
- Modification of existing materials (CB, etc.)
- Enabling new technologies and processes with gases, liquids, solids
- Waste gasification, including sewage sludge & space waste
- Electric propulsion (multi-propellant plasma thrusters).

To address the above market needs APT and IPTC will work on (i) further improvement of the control system to allow remote selection of gas and power modes as the next step and complete remote control in the near future, (ii) development and experimental investigation of oxygen, CO₂ and water steam torches for waste gasification and electric propulsion, (iii) improvement of efficiency, gravimetric and volumetric parameters of the power supplies. Structural configuration of prospective power supply for space propulsion and waste processing is depicted in Fig. 2.

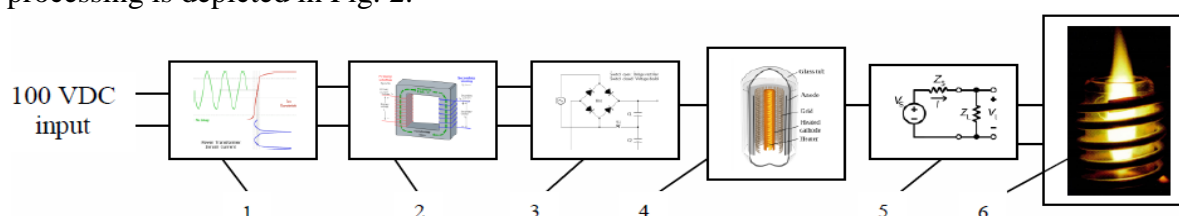
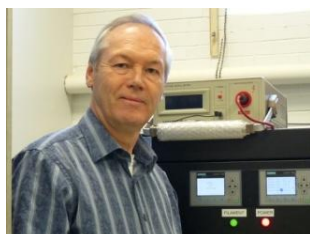


Fig. 2. Prospective power supply: 1 – mid-frequency converter; 2 – high voltage step-up transformer; 3 – rectifier; 4 – high frequency converter; 5 – matching network; 6 – torch



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PLASMA GENERATION, DIAGNOSTICS, AND MODELING

Development and Creation of Microplasma Detector for Gas Chromatography Based on the Plasma Electron Spectroscopy (PLES) Method

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Miniature gas analyzers able to work in high pressures are needed in many applications. A new gas analytical detector based on the plasma electron spectroscopy (PLES) method is

proposed and described in papers [1]–[5]. The results of these studies show that an important task is the practical realization and creation of independent, self-contained gas analytical instruments based on the developed microplasma PLES-detectors. This allows using them into various areas of the modern industry.

Analysis shows that the one of most effective way to introduce PLES method into practice is to combine PLES-detector in a single scheme with gas-chromatographic separation of compounds. Since in both cases a helium and/or argon buffer gas is used, this combination makes it possible to simplify and miniaturize the device design in one analytical cycle. At the same time, the problem of creating a sensitive detector, which allows recording not the integral current as in conventional plasma ionization detectors, but only current of the group of characteristic electrons. This will solve the important problem of increasing the sensitivity of a useful signal.

This work presents the development of a microplasma PLES-detector and demonstrating the possibility of analyzing the composition of gas mixtures by the PES method at atmospheric pressure in the gas mixture blowing mode.

To carry out experiments a discharge chamber was assembled, a schematic view of which is shown in Fig. 1. To create it, ceramic and tungsten plates were used. Two layers of ceramic plates 150 μm thick alternate with three layers of tungsten with a thickness of 100 μm . The holes in the plates were made with the help of the SpitLite 2000 laser of the Resource Center of St.-Petersburg State University "Optical and laser methods of substance research". Sequentially compressed, the plates form a cylindrical chamber with successive annular cathodes, an anode and a sensor separated by layers of a dielectric. The collected microplasma cell was a cylindrical channel with an annular cathode, an anode and a sensor. The diameter and the interelectrode distance were 400 μm . The sensor was located at an equidistant distance from the cathode and anode equal to 150 μm so that the nonlocality condition is fulfilled.

During the experiments for discharge ignition, an output voltage of up to 2 kV was applied to the cathode from a high-voltage power source. The discharge current from the voltage source was limited by the ballast resistance from 1 to 100 k Ω . Expiration of the helium carrier gas through the tube and the discharge cell was carried out directly into the air atmosphere of the laboratory. The gas flow rate was 8 l/h. Fig. 2 shows a photograph of the discharge cell in the work.

As a result of the experiments, a "growing" current-voltage characteristic (CVC) of the microdischarge was obtained, which indicates a stable burning of the microdischarge in the collected cell. To determine the composition of the gas mixture, the technique described in [5], [6] was used. Its essence lies in the removal of the current-voltage characteristics of the wall electrode (sensor) and their subsequent analysis. To do this, we used the "Multifunctional Plasma Probe Analyzer" (MFPA) scheme [7]. For discharge currents of 16, 20, 23 mA, the current-voltage characteristics of the wall electrode (sensor) were removed, and their second derivatives were obtained from the applied potential. The results are shown in Figs 3, 4.

Probe current-voltage characteristics, as well as their second derivative with respect to the potential for different values of the discharge currents, are presented in Figs. 3–4. The current-voltage characteristics of the wall probe have the typical shape shown in Fig. 4.

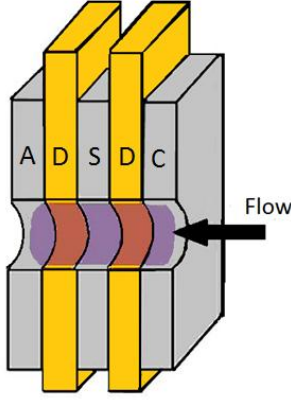


Fig. 1. The cross-section of the discharge chamber of direct current at atmospheric pressure is the cathode (C), the anode (A), the sensor (S) and the ceramic dielectric (D)[8]



Fig. 2 Photo of a gas discharge chamber

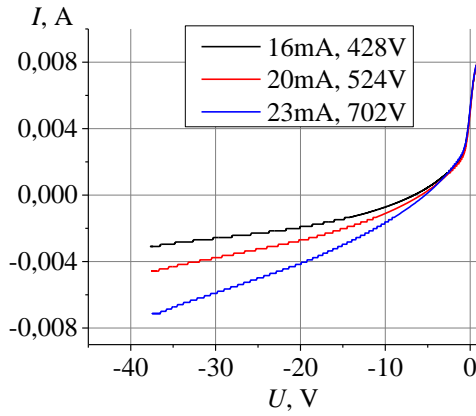


Fig. 3. Wall probe I-V characteristic for various currents

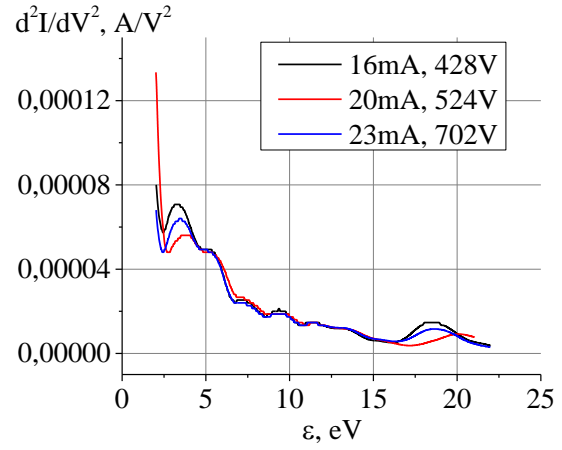
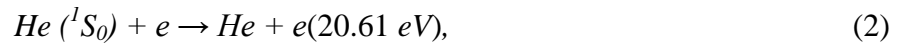
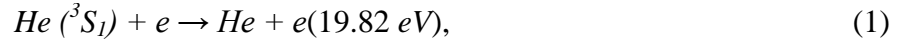
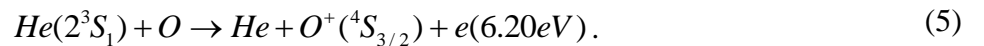
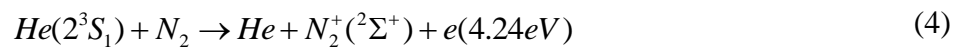
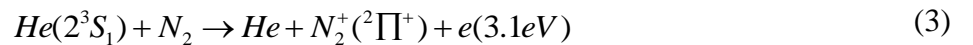


Fig. 4. The second derivatives of the wall probe I-V characteristic for different currents

As one can see from Fig. 2, spectra of characteristic electrons are observed around 20 eV, which is typical of fast electrons arising in collisions of the second kind,



while spectra corresponding to the group of electrons arising in Penning ionization of air particles by metastable helium can be seen in the interval 3–6 eV:



Thus, the conducted experiments demonstrate the possibility of determining the composition of the gas mixture in buffer helium under conditions of its purging through a discharge cell at atmospheric pressure. This means that the prototype of the PLES microplasma detector can be successfully integrated into modern gas chromatographic systems.

This work was supported by RNF №. 17-79-20032.

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Application of High Pressure Helium Microdischarge with Non-Local Plasmas as a Gas-Analysis Sensor

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Introduction

The plasma electron spectroscopy (PLES) method [1], [2] is based on measuring the energy spectra $R(\varepsilon)$ of fast non-local electrons released in Penning ionization of the impurities atoms or molecules by the metastable atoms of the main gas:



The Penning electrons' energy is $\varepsilon_p = \varepsilon_m - \varepsilon_i$, where ε_m is the excitation energy of the metastable particles A^* and ε_i is the ionization energy of the particles B . The use of helium as a main gas is convenient, since the metastable He levels have high excitation energies (19.8 eV and 20.6 eV).

The PLES method enables one to measure the energy spectra of groups of fast electrons in a collisional mode at high pressures, where the energy relaxation of electrons in different groups due to collisions does not occur, and the different groups of electrons behave independently from each other. This has to do with the fact that the electron loses only a small portion $\delta < 10^{-4}$ of its initial kinetic energy ε_p in one elastic collision with a He atom. As a result, the electron energy relaxation length, λ_ε , exceeds considerably the electron mean free path λ . In the case of He, the ratio is $\lambda_\varepsilon / \lambda \approx 70$, and the parameter $\lambda_\varepsilon p$ is $\approx 5 \text{ cm} \cdot \text{Torr}$, where p is the gas pressure of the main gas. When λ_ε is greater than the specific plasma length L ,

$$\lambda_\varepsilon > L, \quad (2)$$

the electron energy distribution function (EEDF) is formed in a non-local mode and the electrons move in the restricted plasma volume with conservation of their full energy $\varepsilon = w + e\varphi(r)$ (kinetic plus potential) [3]. If the Penning electrons' energy is $\varepsilon_p > e\Phi_w$ (where Φ_w is the potential between the discharge axis and the wall), these electrons reach the wall in a free diffusion. In the absence of an electric field, or when it has a small value (e.g., negative glow plasma, afterglow plasma, where the electron temperature T_e , and hence, $e\Phi_w$, are small), the Penning electrons' energy spectrum exhibits sharp peaks near the ε_p energies, reproducing the spectrum $R(\varepsilon)$ of reactions of type (1) [1]. The inequality (2) is known as the condition for non-locality. Over the specific plasma length L , the EEDF depends weakly on the local plasma parameters and is the same at any point of the plasma. As a result, the non-local plasma has an important feature: by measuring the EEDF at the plasma boundary, one acquires information on the whole plasma volume. In non-local plasma, each group of Penning electrons reaches the plasma boundary with its initial energy and, hence, the EEDF can be recorded by means of an additional electrode – a sensor located at the boundary of the plasma volume. Thus, in contrast to the classical Langmuir probe, a sensor with a large collecting area can be used in order to enhance significantly the sensitivity of Penning electrons measurements.

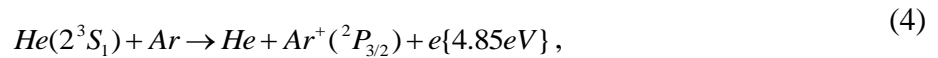
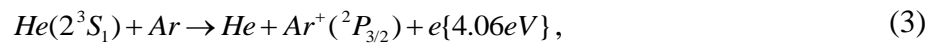
The negative glow plasma of a short dc microdischarge is the most suitable medium for non-local formation of the EEDF. The important characteristics of the non-local negative glow plasma are: high metastable atom density, high rate of Penning ionization, equipotentiality, small dimensions, stable operation at high pressures, low operating voltage, simple design and simple power supply. Temporal resolution of the recording system is not required, which further simplifies the device.

Experimental setup

The analyzer (schematic view shown in [2] and depicted in the Figs 1, 2 below) consists of a plane parallel disk-shaped Mo sensor and anode (3mm in diameter), placed at distance $L=1.2$ mm. A ring-shaped cathode (3mm in diameter, made of 0.4 mm Mo wire) is placed coaxially between the anode and the sensor. In this case the negative glow plasma was formed on both sides of the cathode, so that the discharge current was closed through the anode, and the sensor on the opposite side served as a recording probe.

Results

The PLES spectra measured at pressures 250 Torr He with 0.2% Ar admixture are shown in Fig. 1. Well-expressed maxima at approximately 4 eV and 4.8 eV are observed. The operating discharge currents were varied from 3 to 11 mA. At low discharge currents, only the maximum at 4 eV appears.



At higher discharge currents, the fine structure of the characteristic Ar maximum is recorded (Fig. 1 (curve 2)).

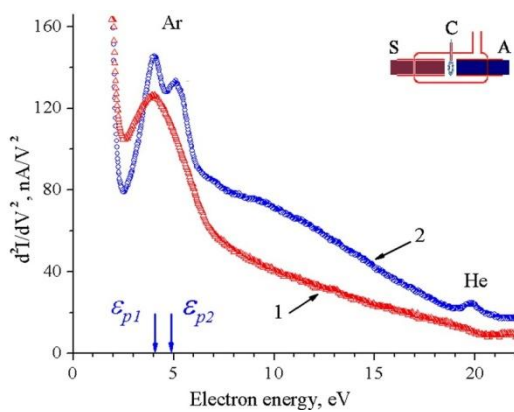


Fig. 1. PLES spectra of 0.2% Ar; He pressure 250 Torr; cathode–anode gap 0.4 mm; modulating voltage 0.6 V; discharge current: 1–6 mA, 2–10 mA

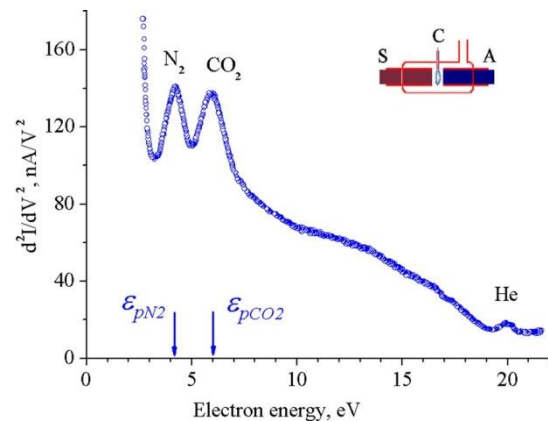
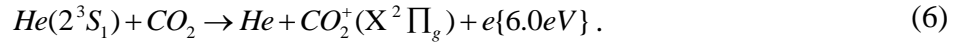
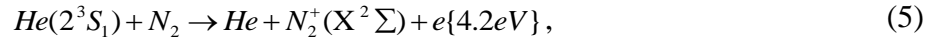


Fig. 2. PLES spectrum of 0.1% N₂ and 0.05% CO₂; He pressure 250 Torr; cathode–anode gap, 0.3 mm; modulating voltage, 0.8 V; discharge current, 11 mA

The PLES spectrum in double component admixture of 0.1% N₂ and 0.05% CO₂ is shown in Fig. 2. Two peaks are recorded, representing the characteristic maxima of N₂ at 4.2 eV (reaction (5)) and of CO₂ at 6.0 eV (reaction (6))



As observed in Fig. 1 and 2, a maximum at approximately 19.8 eV appears at high currents. It is associated with the electrons arising from super-elastic collisions of slow electrons with triplet He metastable atoms



The PLES method has been experimentally validated at high pressures. The PLES spectra recorded in main gas He at pressures up to 250 Torr with small admixtures of atomic and molecular gases prove that analytical information about the presence of gas impurities could be obtained. The PLES method lays the ground for a new field for detection and identification of gas impurities at high pressures.

AAK, AIS, SSS and IVT thank for the support RNF №. 17-79-20032.

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Langmuir Probe Studies of RIE and Hollow Cathode RIE Plasmas Using Carbon Tetrafluoride

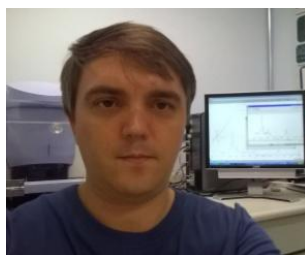
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Instituto Tecnológico de Aeronáutica, Universidade Brasil, Brazil

Carbon tetrafluoride (CF_4) is a common etchant in the field of dielectric etching in microelectronics fabrication. It is primarily applied for etching of silicon dioxide (SiO_2) [1], [2]. Several efforts have been made to understand the effects of process parameters such as discharge power, gas pressure, gas flow rate and gas composition on plasma parameters and the main Si etching agent, the atomic fluorine. Currently, inductively coupled plasma (ICP) and electron cyclotron resonance (ECR) reactors are preferred for the generation of these discharges, because they allow dense plasmas to be sustained at low operating pressures, conditions that are favorable for the current needs of micro- and nano-fabrication [2]. However, the complexities of these reactors translate into high costs for their implementation which often do not justify the investment. As an alternative to high-density plasma sources, currently modified versions of capacitive coupled reactor geometry (conventional reactive ion etching, RIE) such as magnetic enhanced reactive ion etching (MERIE) and hollow cathode reactive ion etching (HCRIE) have arisen. Recently, Pessoa et al. presented some physical and chemical studies of SF_6 and SF_6 / O_2 plasmas generated in HCRIE reactor [3], where it was showed the great capacity of these plasmas to enhance the gas dissociation and generation of atomic fluorine in comparison with conventional RIE geometry. However, little was presented about the chemistry generated during the fluorine-based HCRIE plasma and its mixture with other gases such as CF_4 for example. In this work, electrical studies of carbon tetrafluoride (CF_4) plasmas generated in a RIE and HCRIE reactor were performed using the single Langmuir probe technique. We carried out an investigation aimed to understand the influence of plasma power and gas pressure on plasma parameters namely electron temperature, electron density and electronegativity. Results showed that the electron temperature was reduced for HCRIE due to higher plasma density (between 10^{16} and 10^{17} m^{-3}) for all investigated process parameters. Moreover, it was observed that the electronegativity was considerably reduced in HCRIE in comparison with RIE plasma. Discussions are performed to evidence the best conditions for high etching rate of Si substrate.

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processes based on the ALD (atomic layer deposition) and ALD-e (atomic layer etching) technique for synthesis of advanced materials used in micro&nanoelectronics devices. He has also been involved in supporting private companies in projects of development of gas turbines and carbon fibers.

Mathematical Simulation of Processes in ICP/RF Plasma Torch for Plasma Chemical Reactions

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Today, the radio-frequency induction (ICP/RF) plasma torches are widely used in different technologies [1], [2]. One of the most effective ways of obtaining stable highly-enriched and high-purity isotopes of a number of elements for fundamental and practical research is a single-stage plasma chemical method of converting an isotopically-enriched fluoride to the non-volatile stable form [3]. To study the possibility of scaling the process, it is suggested to use plasma chemical hydrogen reduction of fluorides in thermal argon plasma of a powerful RF induction plasma torch. Therefore, the main goal of this paper is to study the influence of hydrogen presence in plasma on its parameters in the ICP/RF plasma torch.

Plasma chemical reactions in the gas discharges, containing fluorides of the elements of the III-VI groups, have been studied for a long time in respect to pickling processes in electronics and the processes of obtaining fine layers with complex structure for various purposes. Their conversion to elements and further synthesis with the necessity of different compounds should be effective and come with minimal losses. Not many corresponding technologies are known and they all have intermediate stages. The plasma chemical approach has one stage, which influences the economy of obtaining the target product.

The review of works on simulation of ICP/RF plasma torches is given in book [4]. The papers on developing a 2D-model of electromagnetic field of the ICP/RF plasma torch began to appear in [5], [6], including the space around the plasma torch [7]. The first models, which take into account the turbulence of plasma flow in the ICP/RF plasma torch, have appeared in papers [8] at the same time. They use the k - ϵ turbulence model. It was shown that the main part of plasma inside the ICP/RF plasma torch is laminar and the turbulence takes place in near-wall regions.

The analysis of preliminary calculation results using the laminar model showed that the laminar model produces inadequate results in the reverse flow area inside the ICP/RF plasma torch and in the plasma jet area, i.e. in the areas, where the hot plasma flow meets cold medium. Therefore, a plasma turbulence was taken into account using the SST-model, which is a combination of the k - ϵ and k - ω turbulence models: equations of the k - ϵ model are used to calculate the flow in a free area, and equations of the k - ω model – in the near-wall area.

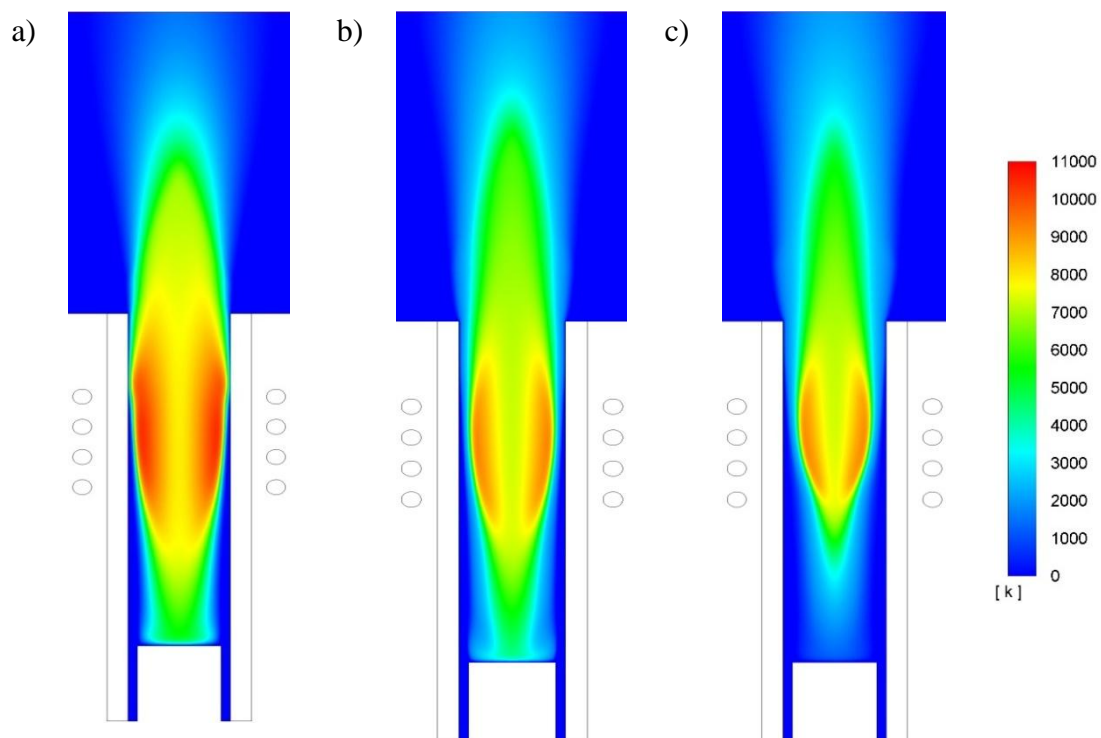


Fig. 1. Plasma temperature distributions (in K) in the ICP/RF plasma torch (power in plasma is 20 kW, plasma gas flow rate is 60 l/min):

a – pure argon; b – $H_2:Ar=1:20$, c – $H_2:Ar=1:10$

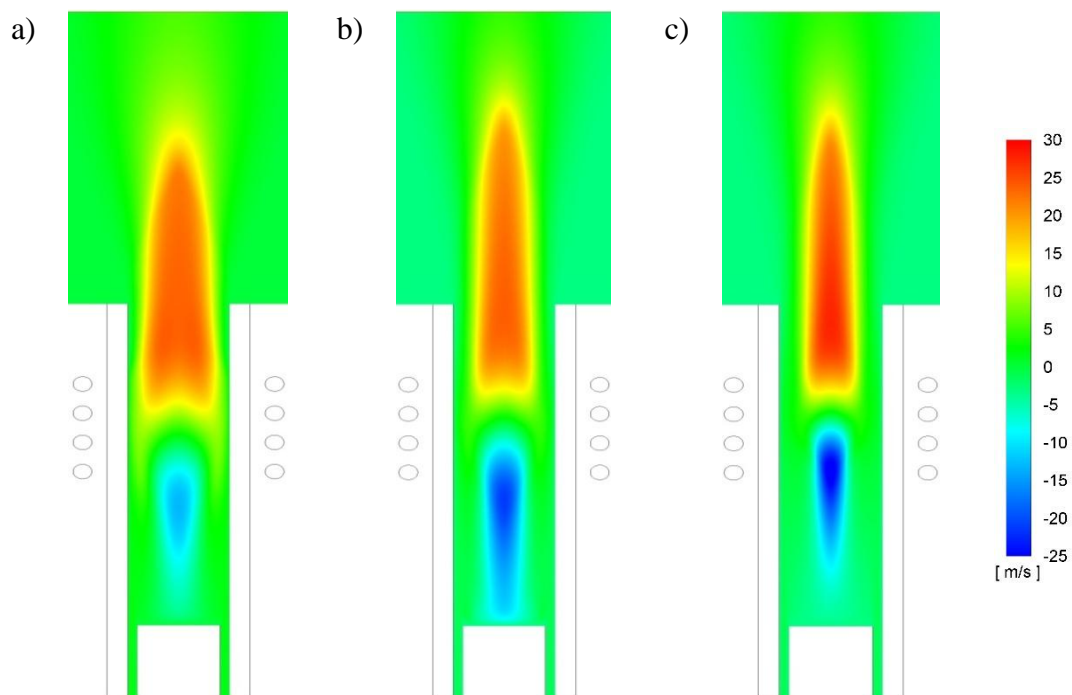


Fig. 2. Distributions of plasma axial velocity (in m/s) in the ICP/RF plasma torch (power in plasma is 20 kW, plasma gas flow rate is 60 l/min):

a – pure argon; b – $H_2:Ar=1:20$, c – $H_2:Ar=1:10$

The problem was solved in a two-dimensional axisymmetric setting. The power in plasma was maintained at 20 kW, the plasma gas flow rate in all cases considered was 60 l/min, coil current frequency was 5.28 MHz.

The results of computations when using different plasma gases are given in Fig. 1–2.

In future research, an experimental investigation of simulated operating modes will be carried out and its comparison with data of simulation will be performed.

This work was supported by the Russian Scientific Foundation, project № 17-13-01027.

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Extracting Plasma Parameters of Gas Discharges from Emission Line Shapes

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Non-invasive spectral diagnostics allows plasma parameters to be measured remotely without disturbing the very system being investigated. Immersive probes cannot survive heat fluxes typical for fusion plasma or high power-density plasma reactors. Therefore, it is very attractive and promising to use “passive” emission spectroscopy [1] to deduce important physical parameters such as plasma temperature, density, flow velocity, and so on. There are two extreme avenues to this approach: measurement of broad spectrum (several lines) with low resolution, or measuring individual lines with high spectral resolution.

Line shapes provide a unique opportunity to measure neutral/ion temperatures via Doppler broadening and individual species velocities via Doppler shift of the relevant spectral lines. They also allow to measure strong magnetic and electric fields through Zeeman and Stark Effects, respectively. The latter allows measurement of pressure in some cases. Line shapes can shed light on isotopic composition as well when applicable.

However, to resolve line shapes accurately one requires very high resolving power, $R = \Delta\lambda/\lambda \sim 10^6$. To achieve such resolution Fabry-Perot etalons are being employed, but they are usually fine-tuned to a single line, which restricts plasma diagnostics ranges. To overcome this we use custom high-resolution systems based on the 0.75–1m Czerny-Turner spectrometers. The systems’ design will be presented and discussed first.

Practical technique, its limitations and examples of measuring Ar and Xe plasma exhaust velocities in several Electric Propulsion devices [2]–[3] will be presented next. Two prominent cases – Stationary Plasma [4] and Minihelicon [5] thrusters are shown in Fig.1 below.

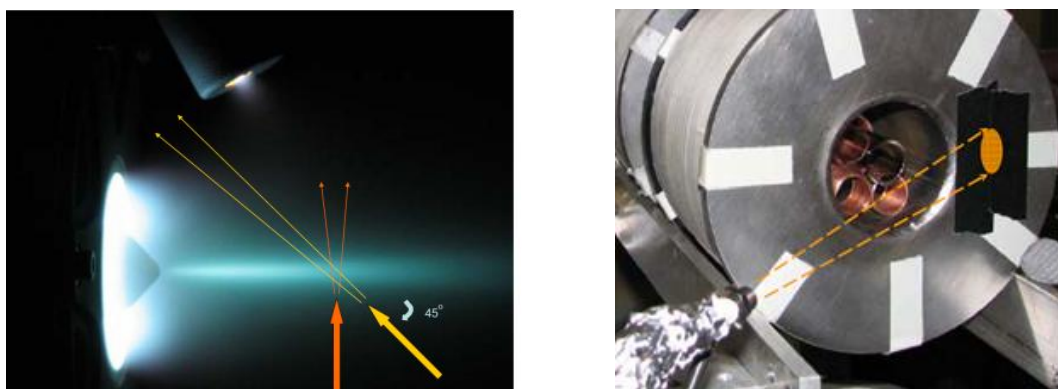


Fig. 1. Schematics of the Doppler shift measurement for SPT-type Hall-effect thruster (left) and Minihelicon thruster (right)

We will demonstrate very high spectral resolutions achieved on several examples of fine and super-fine line structure, like the isotopic shift in BII line shown in Fig. 2 (a).

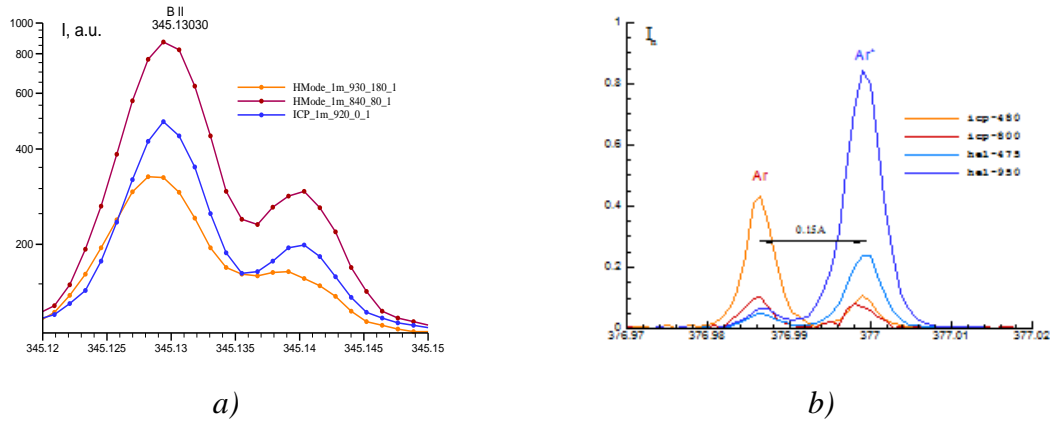


Fig. 2. a) Isotopic shift in BII 345nm line; b) close ArI–ArII lines vs input power in ICP–Helicon mode transition

Next we discuss the use of ratio of neutral to ionic emission line intensities to determine the degree of gas ionization in discharges, as indicated in Fig. 2 (b). In conclusion we will discuss application of very high-resolution spectroscopy [6] to Zeeman and Paschen-Back effects and laser harmonics.

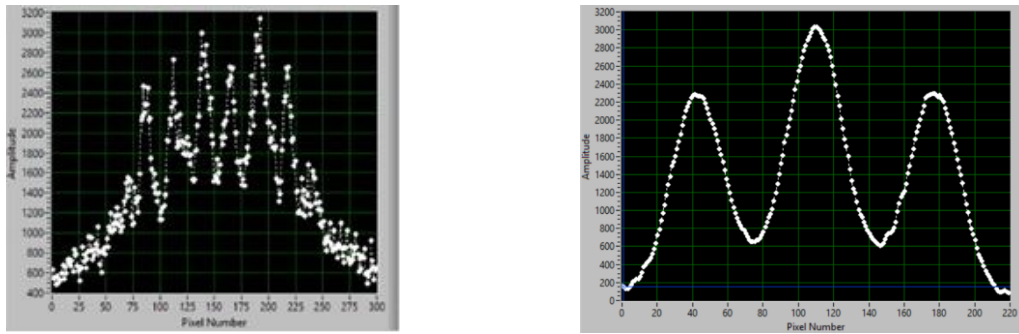


Fig. 3. Measured line splitting due to anomalous Zeeman Effect in Ar (left) and Paschen-Back Effect (right) in He gas discharge

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Study of Dielectric Barrier Discharge Plasma Assisted Combustion using Optical Emission Spectroscopy

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In recent years, non-thermal plasma generated using high voltage pulses of nanosecond duration has attracted lot of attention due to its use in various industrial applications. High power loading during the short duration of the pulse makes it more efficient to generate highly nonthermal and nonequilibrium plasma which leads to its applications for combustion enhancement. This paper presents the study of a nonthermal atmospheric air plasma excited by nanosecond pulses through imaging emission spectroscopy. A coaxial reactor configuration has been made such that the discharge gap can be varied by changing the diameter of the inner electrode so as to generate a wide range of reduced electric field for a chosen applied voltage range. Volumetric glow DBD is established in the gap using a 30 kV nanosecond duration pulse generator whose pulse repetition can be varied up to 3.5 kHz. This reactor has been used for low temperature plasma assisted methane oxidation studies. We have observed that low temperature plasma-combustion kinetics is highly dependent on various electric field generated by varying discharge gaps. It is difficult to estimate the E/N from the applied voltage measurement alone. So, optical emission spectroscopy has been done and reduced electric field has been estimated using relative irradiance method for various discharge conditions. Relative irradiance method suggests that intensity ratio of $N_2^+(B-X)$ and $N_2(C-B)$ transitions can be calculated as a function of the reduced electric field (E/N) and can be compared with measured intensity ratio from emission spectroscopy for E/N estimation. For this purpose, imaging spectrometer with ICCD camera and UV lens has been used to directly capture spectral image of plasma such that spatial resolution in radial direction can be achieved in a single image. Experiments are carried out for various discharge conditions by varying applied voltage, mass flow rate and discharge gap. From initial result analysis, spatially averaged E/N is estimated to be 284 Td, 355 Td and 372 Td for 3 mm, 2 mm, and 1 mm discharge gaps respectively at 30 kV. Details of the experimental setup and analysis of spatially resolved E/N for all discharge conditions will be presented in the final manuscript.



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PLASMA IGNITION AND FLAME CONTROL. FUEL REFORMATION AND ACTIVATION

Effect of Nanosecond DBD Microplasma Discharge on Combustion Characteristics: Flammability Limit and Burning Velocity

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Introduction

In this study, we have developed a novel microplasma burner to examine the effect of non-equilibrium plasma discharge on methane-air flame characteristics. The design principle of the microplasma reactor is based on the dielectric barrier discharge scheme which helps to generate a stable non-thermal plasma discharge driven by nanosecond high-voltage pulses inside the burner holes.

Experimental setup

Fig. 1 shows schematically of the burner setup. The main part of the setup is the plasma reactor which is the source of the non-equilibrium plasma. This reactor uses the DBD (dielectric barrier discharge) scheme for non-equilibrium plasma generation. As shown in Fig.1 (left), the reactor consisting of four layers of electrodes separated by three layers of dielectric material driven by Mega-Impulse pulse generator. The 1.5 mm thick perforated burner plate has holes of 0.4 mm diameter with 1.0 mm pitch

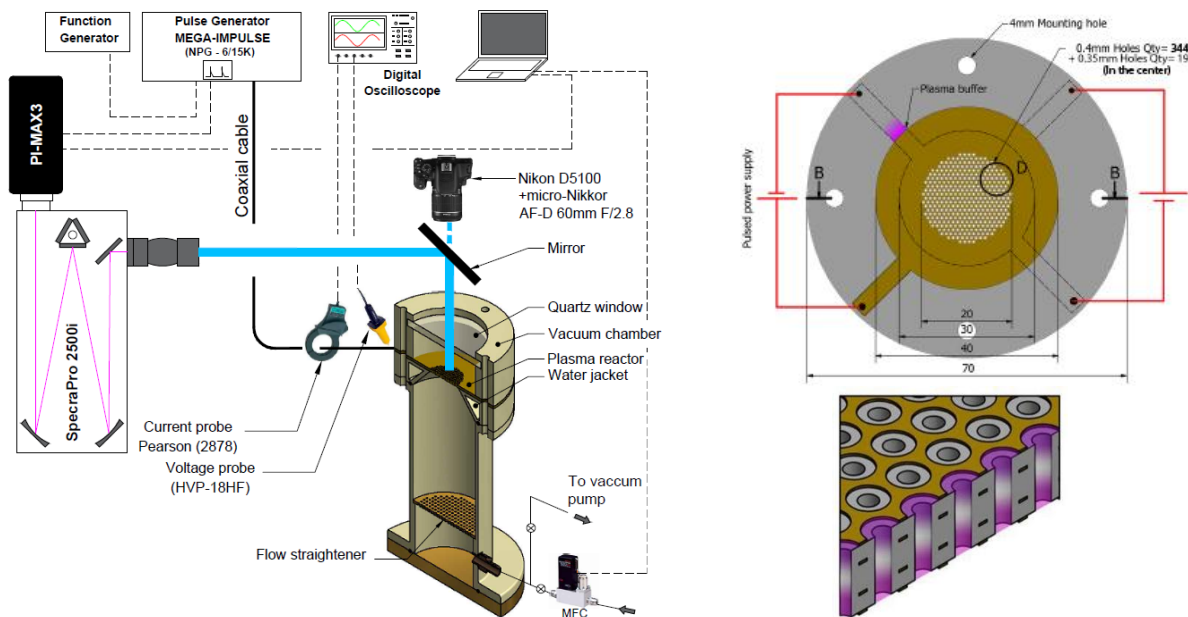


Fig. 1 Experimental setup

Results

Fig. 2. shows the CH chemiluminescence images of methane-air flame with an equivalence ratio of 0.6 and plasma voltage of 4 kV at different pulse repetition rate to address the effect of plasma discharge on burning velocity at atmospheric pressure. Fig. 3 shows an overview on the

effects of plasma repetition rate at different equivalence ratios on laminar burning velocity. The laminar burning velocity was calculated by conical flame area method which has been validated by other published data. The results show an increase of the burning velocity of about 100% in very lean ($\phi = 0.55$) flames as a result of the plasma discharge effect. Fig. 4 shows the effect of plasma discharge on lean blow-off limit of methane air flame. Plasma discharge was capable to extend to lean flammability limit about 6%.

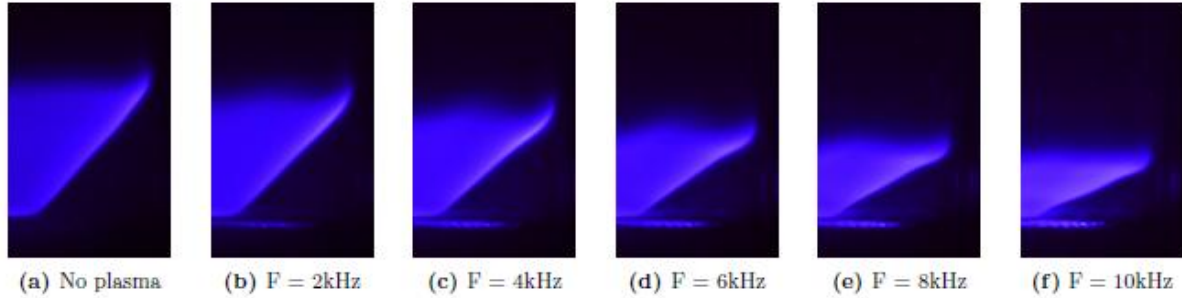


Fig. 2. CH chemiluminescence images for methane-air flame at different plasma frequencies for $\phi = 0.6$ and $V = 4kV$

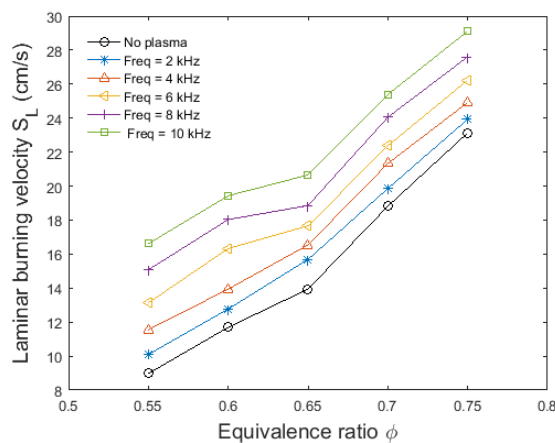


Fig. 3. Effect of plasma discharge frequency on laminar burning velocity for methane-air mixture at atmospheric pressure

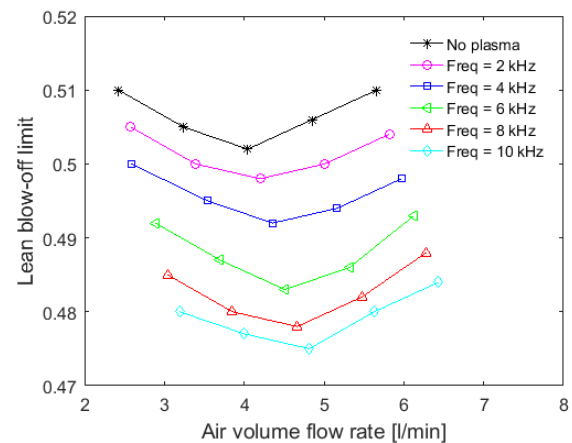


Fig. 4. Effect of plasma discharge frequency on lean blow-off limit for methane-air mixture at atmospheric pressure

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His research is focused on studies of the nanosecond pulse plasmas, DBD discharge and plasma assisted combustion using optical diagnostics.

Plasma Methane Pyrolysis for Spacecraft Oxygen Loop Closure

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Life support is a critical function of any crewed space vehicle or habitat. Human life support systems on the International Space Station (ISS) include a number of atmosphere revitalization (AR) technologies to provide breathable air and a comfortable living environment to the crew. The Trace Contaminant Control System removes harmful volatile organic compounds and other trace contaminants from the circulating air. The Carbon Dioxide Removal Assembly (CDRA) removes metabolic carbon dioxide (CO₂) and returns air to the cabin. Humidity is kept at comfortable levels by a number of condensing heat exchangers. The Oxygen Generation Assembly (OGA) electrolyzes water to produce oxygen for the crew and hydrogen (H₂) as a byproduct. A Sabatier reaction-based CO₂ Reduction Assembly (CRA) was launched to the ISS in 2009 and became fully operational in June 2011.

The CRA interfaces with both the OGA and CDRA. Carbon dioxide from the CDRA is compressed and stored in tanks until hydrogen is available from OGA water electrolysis. When the OGA is operational and there is CO₂ available, the CRA is activated and produces methane and water via the Sabatier reaction shown in Equation 1.



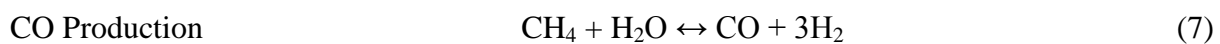
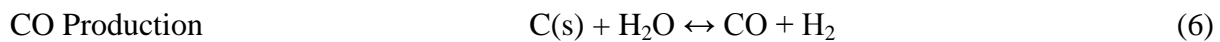
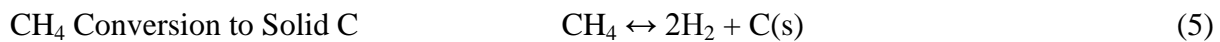
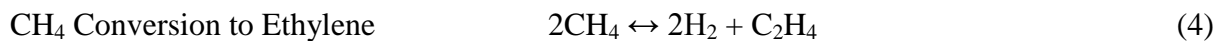
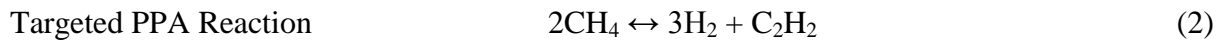
The water product is condensed out of the product stream, separated, and purified in the Water Processing Assembly before being recycled back to the OGA to be used to produce O₂ for the crew. Methane, saturated with water vapor at a dewpoint similar to the temperature of the ISS moderate temperature cooling loop that is used to cool the condensing heat exchanger, is vented to space as a waste product. The loss of H₂ in the form of vented CH₄ and uncondensed water vapor in the CH₄ stream limits the oxygen recovery to approximately 50% from metabolic CO₂.

Without the CRA, each Crew Member (CM) requires ~0.891 kg H₂O/day to be supplied from Earth to produce breathable oxygen via water electrolysis. The CRA can theoretically reduce this figure to ~0.459 kg/CM-day but that still equates to a total water resupply requirement of ~670 kg H₂O/year for a crew of four, just for breathable oxygen. To make long duration missions beyond Low Earth Orbit logistically feasible, greater oxygen recovery from metabolic CO₂ is needed. NASA is currently targeting technologies that achieve 75–90% O₂ recovery from metabolic CO₂ [1].

One approach to achieve these higher recovery rates builds upon the ISS AR architecture and includes adding a methane post-processor to recover H₂ from CRA methane. NASA has been developing the Plasma Pyrolysis Assembly (PPA) to fill the role of a methane post-processor [2]–[9]. The PPA uses a magnetron to generate an H₂/CH₄ plasma targeting Sabatier CH₄ conversion to hydrogen and acetylene (C₂H₂) as shown in Eq. 2. Fig. 1 shows the PPA plasma during methane processing. Secondary reactions with CH₄, as shown in Eqs 3–5, and reactions with residual water vapor as shown in Eqs 6–7, also occur in the PPA resulting in an effluent mixture containing H₂, unreacted CH₄, product C₂H₂, and trace quantities of H₂O, carbon monoxide (CO), ethylene (C₂H₄), ethane (C₂H₆), and solid carbon (C).



Fig. 1. PPA reactor chamber with hydrogen and methane plasma



When H₂ recovered by the PPA is recycled back to the CRA, and the CRA is operated at a H₂:CO₂ ratio of 4.25, a theoretical O₂ recovery of >86% may be realized (assuming a respiratory quotient of 0.92) from metabolic CO₂. This further reduces the water resupply requirement to ~0.18 kg/CM-day.

In this paper the development and testing of the PPA and associated hardware is presented and discussed.

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Fuel Additives for Coal Incineration in Combustor with Plasma-Aided Start

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Fuel additives based on light ethers increase the efficiency of combustion of liquid fuels. In this paper, the effect of such fuel additives on the combustion efficiency of solid fuels on the example of combustion of Ekibastuz coal was studied.

Experiments were carried out as following. On warming and getting required temperature (900 °C) of the combustor wall plasma torch was turned off. Thereafter pulverized coal and air were fed to the combustor with consumption 10 and 70 kg/h correspondingly. The gaseous products exit the gas and slag separation chamber and flow into the cooling

chambers. Then gaseous products are exhausted to ventilation.

Duration of the experiments was 1 hour. That is quite enough for all meters fulfilment and testing of the material and heat balance of the coal combustion. The duct of Ekibastuz bituminous coal (Table 1) was used in the experiments.

Table 1. Kazakhstan Ekibastuz coal of 40% ash content and 16,632 kJ/kg calorific value proximate and ultimate analyses, weight %

Proximate Analysis		Ultimate Analysis			
Moisture (Total)	5.8	Hydrogen	3.05	SiO ₂	23.09
Volatile Matter	24.0	Carbon	48.86	Al ₂ O ₃	13.80
Fixed Carbon (By Difference)	30.2	Sulfur	0.73	Fe ₂ O ₃	2.15
Ash	40.0	Nitrogen	0.80	CaO	0.34
Total	100.0	Oxygen	6.56	MgO	0.31
Higher Heating Value (Dry Mass Basis)	16,632 kJ/kg	Ash	40.00	K ₂ O	0.16
		Total	100.00	Na ₂ O	0.15
				Ash Σ	27.15

The coal dust for the experiments was taken from Almaty Thermal Power Plant-2. The sieve analysis of it revealed that mean size of the coal dust particles was 75 μm . It corresponds to the sieve residue $R_{90} = 25\%$ characterising milling finesse.

As a result of the coal combustion carbon conversion degree X_c and mass-averaged temperatures T_{av} were revealed. After starting-up and adjustment work two test experiments on Ekibastuz coal combustion in air and in oxygen-enriched air were carried out.

A complex of numerical and experimental studies of high-ash coal incineration in a specially designed combustion chamber with coal consumption of up to 10 kg/h, air flow up to 62 kg/h, and oxygen flow up to 20 kg/h allowed estimating the effectiveness of the fuel additives Omstar – DX1 and Open Flame [1]. During the tests 28 adjustment experiments and 26 serial comparative tests coal burning without the use of additives and by using additives of different weight ratio additive : carbon (0–5 ml/kg of coal) were conducted. As a result of commissioning tests consumption of coal and oxidant flow (air + oxygen) required for complete coal burning-out in the compact experimental combustion chamber were identified. The adjustment tests have shown that the fuel additives increase the flame temperature at the exit of the combustor and reduces the concentration of unburnt carbon in the ash and slag of combustion products by 1–2%.

Research results show that increasing the concentration of the additive Omstar – DX1 to 1.5 ml/kg of coal increases the temperature of the wall of combustion chamber, and therefore the flame, but has little effect at change in the measured concentrations of the gaseous products of combustion (SO₂, NO, CO, CO₂). At concentration of the additive 2 ml/kg of coal a slight decrease of SO₂, CO, CO₂, and a noticed decrease in the concentration of NO were recorded. The additive is beginning to have a significant impact on the efficiency of burning low-grade coal from 2.5 ml/kg of coal. The greatest influence of the additive on the effectiveness of coal combustion was recorded at a concentration of the additive Omstar – DX1 5 ml/kg of coal. For control tests concentration of both additives (Omstar – DX1 and Open Flame) was chosen 2.5 ml/kg of coal. In the framework of the tests of burning low-grade coal, both additives showed a similar efficacy. The degree of carbon conversion (X_c), which characterizes the completeness of burnout coal, is quite high when using both

additives. X_c varies in the range of 95.1–96.9%. Tendency to increase the degree of coal conversion with increasing concentration of additives is revealed. For example, Table 2 shows the characteristic effect of a fuel additive on the parameters of the combustion process of Ekibastuz coal.

Table 2. Results of the Experiments

T_{wall}^1 , °C	T_{wall}^2 , °C	Consumption, kg/h			Syngas compound					X_c , %
		coal	air	O_2	SO ₂	NO	CO	CO ₂	N ₂	
					mg/m ³			Volume %		
1. No additive										
1,135	870	9.63	20.3	11.4	1,150	599	695	16.3	77.2	96.1
2. Additive DX1 – 5 ml per 1 kg of coal										
1,075	1,165	9.68	20.3	11.4	1,137	403	105	16.5	77.1	96.1

In the experiments, the temperature of the wall of the combustion chamber was measured at points, T_{wall}^2 – near the nozzle of pulverized coal supply, and T_{wall}^1 – at the outlet from the combustion chamber. It can be seen from the table that the fuel additive increases the temperature of the wall at the inlet to the combustion chamber by 295 degrees and reduces the temperature at the outlet of the combustion chamber by 60 degrees. Note that the concentration of CO₂ in the off-gas corresponds to its normative value when burning coal in power boilers.

The final results of the tests of fuel additives Omstar – DX1 and Open Flame are gathered in Tables 2–4. Both additives significantly increase the efficiency of burning low-grade coal: the flame temperature, its brightness, and CO₂ concentration increase, emissions of CO, NO, SO₂ decrease, which indicates an increase in coal combustion efficiency.

Table 2. Tests of fuel additive Omstar – DX1

Quantity of the additive, ml per 1 kg of coal	0	2.5	5
Maximal temperature of wall on the combustor's exit, °C	1,115	1,147	1,173
NO _x , mg/m ³	518	315	274
SO ₂ , mg/m ³	1,109	1,102	1,050
CO, mg/m ³	520	64	53
CO ₂ , vol. %	11.9	13.7	15.9

Table 3. Tests of fuel additive Open flame

Quantity of the additive, ml per 1 kg of coal	0	2.5
Average temperature of wall on the combustor's exit, °C	1,115	1,140
NO _x , mg/m ³	518	276
SO ₂ , mg/m ³	1,109	1,106
CO, mg/m ³	520	237
CO ₂ , vol. %	11.9	13.6

Table 4. Indicators of the use of fuel additives in the combustion of Ekibastuz coal

NO _x decreasing by 47%	CO decreasing by 89%
SO ₂ decreasing by 5%	CO ₂ increasing by 25%

From the analysis of Tables 2–4 it follows that the use of Omstar – DX1 and Open flame fuel additives results in a significant increase in the efficiency of burning low-grade coal while reducing NO_x and SO₂ emissions. So, there is an increase in the completeness of coal combustion, which is manifested in an increase in the concentration of CO₂ by 25%, and a decrease in the concentration of CO by 89%. In the process of coal combustion, the concentration of nitrogen oxides decreases by 47% and sulfur oxides by 5%.

Taking into account the positive results of the tests of efficiency of the fuel additives in combustion of low-grade high-ash coal, we consider it expedient to test their effect on burning high-grade coal in test-bench conditions, and then go to the industrial testing fuel additives in thermal power plants.

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PLASMA KINETICS AND DUSTY PLASMA

The Influence of Ambipolar Electric Field on the EDF Formation and the Electron Processes in Bounded low Temperature Plasmas

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Knowledge of the electron distribution function (EDF) gives a lot of information about the processes occurring in plasmas [1], [2]. EDF determines such processes as ionization, excitation, dissociation, attachment etc. and can be determined from the kinetic equation. In general, it is impossible to get exact analytic form of EDF so some approximations are needed.

The isotropic part of the EDF f_0 depends on coordinate \vec{r} and electron velocity v and can be calculated from the Boltzmann kinetic equation [3],

$$\begin{aligned} & \operatorname{div} \left(\frac{v^2}{3\nu_m} \operatorname{grad} f_0 \right) - \frac{eE}{3m} \frac{\partial}{\partial v} \left(\frac{v}{\nu_m} \operatorname{grad} f_0 \right) - \frac{ev}{3m} \operatorname{div} \left(\frac{E}{\nu_m} \frac{\partial f_0}{\partial v} \right) + \\ & + \frac{\partial}{\partial v} \left(\frac{e^2 E^2}{3m^2 v^2 \nu_m} \frac{\partial f_0}{\partial v} + v \delta \nu_m f_0 \right) + \sum_k \nu_k^*(v) f_0(v) - \nu_k^*(v + v_k) f_0(\varepsilon + \varepsilon_k) = 0 \end{aligned} \quad (1)$$

where $\nu_m(v) = Nv\sigma_m(v)$, $\nu_k^*(v) = Nv\sigma_k^*(v)$ is the frequency of elastic and inelastic collisions; E is a total electric field at the given spatial coordinate \vec{r} ; $\delta = 2m/M$ is the energy transfer coefficient in inelastic collisions between electron with mass m and atom with mass M ; $\nu_k = \sqrt{2\varepsilon_k/m}$, ε_k is the k -th level excitation threshold energy. E is the total electric field at

the given spatial coordinate which can be written as a sum $\vec{E} = \vec{E}_{heat} + \vec{E}_{amb}$ of heating E_h and ambipolar E_a electric fields [1], [2].

Eq. (1) cannot be solved in general case and the local approximation (LA) is usually used for the calculation of the electron distribution function (EDF) in plasmas. In framework of this approximation the terms corresponding to the spatial gradients in Eq. (1) can be omitted and the EDF $f(r, w)$ can be factorized as:

$$f_0(\vec{r}, v, t) = n_e(\vec{r}, t) F_0(v) \quad (2)$$

where $n_e(\vec{r}, t)$ is the electron density, v is the electron velocity, f_0 depends on local parameters such as the reduced electric field E/p , gas temperature, and density of excited particles. LA significantly simplifies kinetic equation and results in the following form of Eq. (1):

$$\frac{\partial}{\partial v} \left(\frac{e^2 E^2}{3m^2 v^2} \frac{v^2}{v_m} \frac{\partial F_0}{\partial v} + v^3 \delta v_m F_0 \right) + \sum_k v_k^*(v) f_0(v) - v_k^*(v + v_k) f_0(\varepsilon + \varepsilon_k) = 0 \quad (3)$$

Usually, this approximation is widely used to obtain electron transport and rate coefficients for fluid models [1]–[3].

Criteria of applicability of local approximation can be obtained by comparison of spatial gradients and energy derivatives in the kinetic equation (1). This estimation gives following applicability criterion for the local approximation (3) (see f.e. [1], [2]):

$$L \gg \lambda_\varepsilon \quad (4)$$

$$\lambda_\varepsilon = \sqrt{2D_r / \nu_\varepsilon} \approx \lambda \sqrt{\nu_m / (\delta \nu_m + \nu^*)} \quad (5)$$

where L is the plasma dimension, λ_ε is the electron energy relaxation length, $D_r = v\lambda/3$ is the electron diffusion coefficient in configuration space, $\nu_\varepsilon = \delta \nu_m + \nu^*$ is the energy relaxation frequency, which describes the energy transfer by elastic and inelastic collisions (see Eqns. (12, 59) in [3] for details).

In this paper is shown that the ambipolar electric field plays a significant role at the EDF formation and have to be accounted not only at the low pressures, but at high pressures where the EDF expected to be local and ambipolar field thought to be negligibly before.

To analyze influence of ambipolar electric field on EDF formation and electron processes in low-temperature plasma the simulations of positive column plasma have been proceeded. The

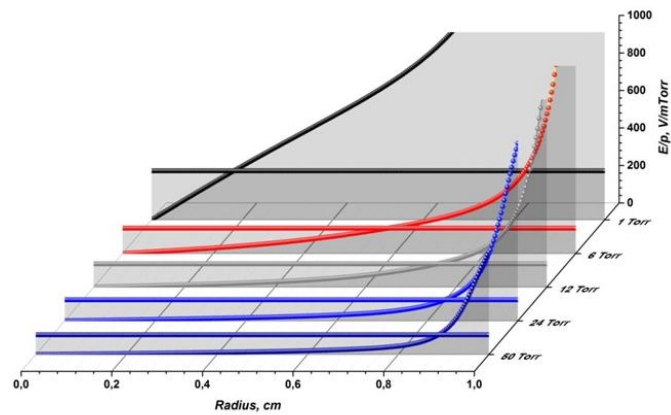


Fig 1. Comparison of the heating and ambipolar electric fields at the wide pressure range

modeling has been done using Comsol Multiphysics Software. The code includes kinetic module for calculation 2-dimensional (r, w) cylindrically symmetric EDF, fluid module which includes all neutral and charged particle densities, Poisson's equation for the electric potential.

Fig. 1. represents ambipolar and heating electric fields. According to Fig. 1, the ambipolar field shows a rapid growth and exceeds the axial electric field near periphery at the high pressures and at the positive column center at the lower pressures [4]. This fact means that radial electric field cannot be eliminated from the Eq. (1) even under local approximation. From the other point of view even at low pressure the ambipolar electric field is larger than the heating electric field near the center of gas discharge which means that the local approximation is not valid not only at the discharge periphery but in total plasma volume and the simulation of kinetic equation (1) is needed.

Arising of large ambipolar electric field results in numerous interesting effects [5]–[7].

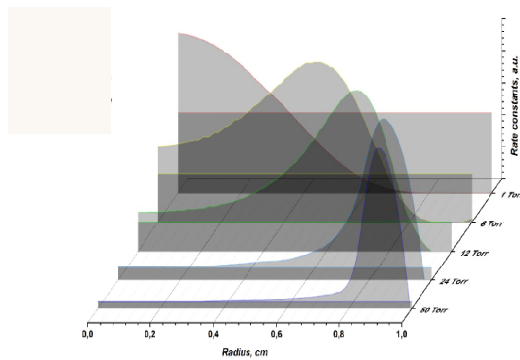


Fig 2. Excitation rates for the different

Fig. 2 illustrates that maximum of excitation profile (2) is shifted to the periphery with the growing pressure. According to Fig. 2, at high pressure (50 Torr) the local constant coincide with non-local calculation up to periphery where ambipolar field begin to play significant role in comparison with heating electric field. The strong radial dependence of excitation rate constant can be explained from the following consideration. This explanation is based on fact that at the local approximation the ambipolar electric field cannot be eliminated from the Boltzmann equation which results in the following form of EDF.

$$f(\varepsilon, r) = ce^{\frac{-\varepsilon - \varepsilon_1}{\lambda_e^* \sqrt{E_{heat}^2 + E_{amb}^2}}} \quad (6)$$

According to eq. (6), at high pressures local excitation constants (5) coincide with non-local values at the region where ambipolar field is low in comparison with heating electric field. At the periphery the EDF tail increases and produce the growth of the rate constants. For low pressures local and nonlocal excitation rates are drastically different and don't coincide even at center of discharge.

It is shown that the ambipolar electric field plays a significant role at the EDF formation and has to be accounted not only at the low pressures, but at high pressures where the EDF expected to be local and ambipolar field thought to be negligibly before. Moreover, its shown that the excitation profiles drastically depend on ambipolar field for the different pressures.

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Gas Discharge Ionization of Air and its Mixtures

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Solution of practical problems of electric-discharge devices applied in air and its mixtures at different altitudes requires knowledge of ionization mechanisms and thresholds because ionization is a source of charged particles in plasma and thus determines the efficiency of the applied devices. Therefore, knowledge of ionization mechanisms and ionization-threshold determination in electric-discharge devices at a given altitude actually comes connected to a set of applications and stimulates investigations devoted to these questions.

From data available in the literature, it is known that the development of discharge in air has been well described with respect to processes of origination and elimination of electrons in direct ionization, attachment, detachment, and other processes [1], [2]. Determination of effective ionization thresholds requires the rate constants of corresponding processes to be determined with sufficiently high accuracy in the vicinity of the ionization threshold. This condition requires clarification (on the basis of experimental measurements or calculations on the basis of solution of the Boltzmann equation to determine an Electron-Distribution Function over Energies (EDFE), and the subsequent integration of electron-molecule process cross sections with EDFE) the rate- constant values of the basic processes [3].

Nevertheless, there exist many questions about the initial stage of ionization in air and air mixtures under real conditions. According to the works of [4], [5], which was devoted to the research of ionization processes near aircrafts in the troposphere at altitudes of 4–12 km, it was shown that the measured breakdown of air electric field strength is approximately 3 V/cm, which is considerably lower than the breakdown of electric field strength near the surface of the Earth. In the work of [6], which discusses questions of ionization in the longitudinal discharge in a stream of air, there are breakdown fields considerably smaller than those near the Earth. Research results of ionization processes at higher altitudes where ionization processes can take place, leading to electric discharge phenomena, such as sprites, jets, etc. are of great interest.

The purpose of this report is consideration of a breakdown stage of discharge development in air and its mixtures with water and propane; determination of the dependence of ionization in air on a value of the reduced electric field (E/N , where E is the electric field strength, and N is the concentration of neutral particles of the gas); and determination of ionization threshold in air at different altitudes above the Earth. Values of the E/N parameter will be compared with those that are typical for glow discharges.

A brief section of this review is devoted to questions about the determination of electron-molecule rate constants on the basis of the Boltzmann equation solution.

Modeling was performed for conditions close to those of the experiments. Rate constants of ion-molecular processes, i.e., processes with the participation of electronically excited molecules and chemical reactions, as a rule are determined from experimental works and theoretical data. Many works on determination of these rate constants have been published; many tables and reviews are devoted to these processes. However, regarding the concrete conditions of modeling, it is not always possible to locate all of the required information, and it becomes necessary to use poorly proven interpolation and extrapolation. Gathering data on energy values (formation enthalpy) passing into gas or reaction products is extremely difficult from an unambiguous point of view under the nonequilibrium conditions of discharges. Often a check of those or other assumptions underlying the consecutive analysis, or a performance of complex model calculations, reveals difficulties of interpretation; in this case, simple models of a considered situation are helpful.

In this review, concrete examples of consecutive computations of gas-discharge plasma in dry and at different altitudes, humid air and propane-air mixtures for practical applications are presented.

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The Non-Local Electron Kinetics for a Low-Pressure Glow Discharge Dusty Plasma

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Dusty plasma is usually loosely defined as normal electron-ion plasma with an additional charged component of micronized particulates. Usually, one uses the orbital motion limited (OML) theory to calculate dust particle parameters (such as dust charge number and ion/electron fluxes on dust particles) and assumes that electrons are in Maxwellian equilibrium [1]. However, for most industrial and laboratory plasmas the electron distribution usually deviates from Maxwellian because of many different electron collision processes [2]. The electron energy distribution function (EEDF) should be calculated self-consistently taking into account the effect of the dust particles for describing processes in dusty plasma.

For a low-pressure ($10^{-2} < pR < 1$ Torr·cm) DC glow discharge plasma, the local field approximation is usually inadequate to simplify the Boltzmann equation, since the mean free paths of electrons is less than the tube radius R , and electron energy relaxation length $\lambda \varepsilon$ exceeds the radius of the tube. The nonlocal approach should be used to obtain simplified kinetic equations, and obtain the nonlocal EEDF in this situation [3].

The electron kinetics in low-pressure glow discharge argon dusty plasma is studied based on Boltzmann equation. Under conditions of weak anisotropy, the kinetic equation with the total energy ε ($\varepsilon = mv^2/2e + \varphi(r)$) as variable, for the isotropic part of the electron distribution function for an axially homogeneous positive column can be simplified by averaging over the radial transits and written as

$$\begin{aligned} \frac{E^2}{3N_g} \frac{d}{d\varepsilon} \frac{w}{\sigma_e^\Sigma(w)} \frac{df_0(\varepsilon)}{d\varepsilon} = & -2 \frac{m}{M} N_g \frac{d}{d\varepsilon} \overline{w \sigma_e^{el}(w)} f_0(\varepsilon) \\ & + N_g \overline{w \sigma_e^{inel}(w)} f_0(\varepsilon) - N_g \overline{(w + U_{ex}) \sigma_e^{inel}(w + U_{ex})} f_0(\varepsilon + U_{ex}) \\ & - 2 \frac{m}{M_d} N_d \frac{d}{d\varepsilon} \overline{w \sigma_d^{el}(w)} f_0(\varepsilon) + N_d \overline{w \sigma_d^{inel}(w)} f_0(\varepsilon) \end{aligned} \quad (1)$$

Here E is longitudinal electric field, N_g is density of neutral atoms, $w = mv^2/2e$ is electron kinetic energy, σ_e^{el} , σ_e^{inel} , σ_e^Σ are elastic, inelastic, and total collision cross section of electron and neutral atoms; σ_d^{el} , σ_d^{inel} are the elastic and inelastic cross section of electron and dust particles; m , M , M_d are electron, ion, dust particle mass.

The finite-difference method [4] was employed to solve the kinetic Eq (1). The calculated result is shown in Fig. 1:

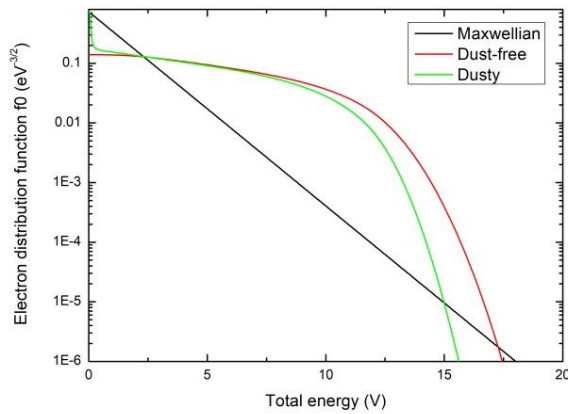


Fig. 1. Electron distribution for dust-free and dusty plasma.

The conditions are $p=1$ Torr, $E=4.3$ V/cm;
dust radius $r_d = 1 \mu\text{m}$; $T_e = 2$ eV;
 $N_d = 105 \text{ cm}^{-3}$, and $n_e = 1 \times 10^{10} \text{ cm}^{-3}$

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Scaling Laws for the Formation of Spatial Distributions of Particles and Fluxes in a Dusty Plasma of a Glow Discharge

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The influence of dust particles on a gas discharge plasma began to be actively investigated recently. The main attention was paid to the analysis of the formation of a plasma crystal in striations of a DC discharge [1]. However, the problem of quantitative description of the stratified discharge still is not solved. Therefore, the most convenient and promising for studies of dusty plasma is the horizontal positive column of a homogeneous (unstratified) gas discharge [2]. Some interesting results of modeling of spatial distributions of parameters in the PC dusty plasma were represented in [3]–[6].

We developed 1D axisymmetric model of PC of DC glow discharge in argon with cloud of dust particles in the Comsol Multiphysics software package. This model was solved for different dust particles spatial distribution ([0–R/4], [0–R/2], [0–3·R/4], [0–R] (entire cross section of the tube)) in wide range of dust particles density N_d ($10^9 - 10^{14} \text{ 1/m}^3$) and current I_0 (0.5–50 mA). Radius of discharge tube $R = 1$ cm, radius of dust particle $r_d = 10^{-6}$ m, gas pressure $p = 1$ Torr, and gas temperature $T = 293.15$ K. Radial distributions of electrons and heavy particles density, charge of dust particles, space charge density, electric field strength and potential, electron's temperature and

fluxes of plasma components were performed in a wide range of parameters. Obtained data allowed us to identify the main scenarios of formation of spatial distributions of particles and fluxes in positive column of DC glow discharge. For example for current 1 mA and size of the dust cloud $R/2$

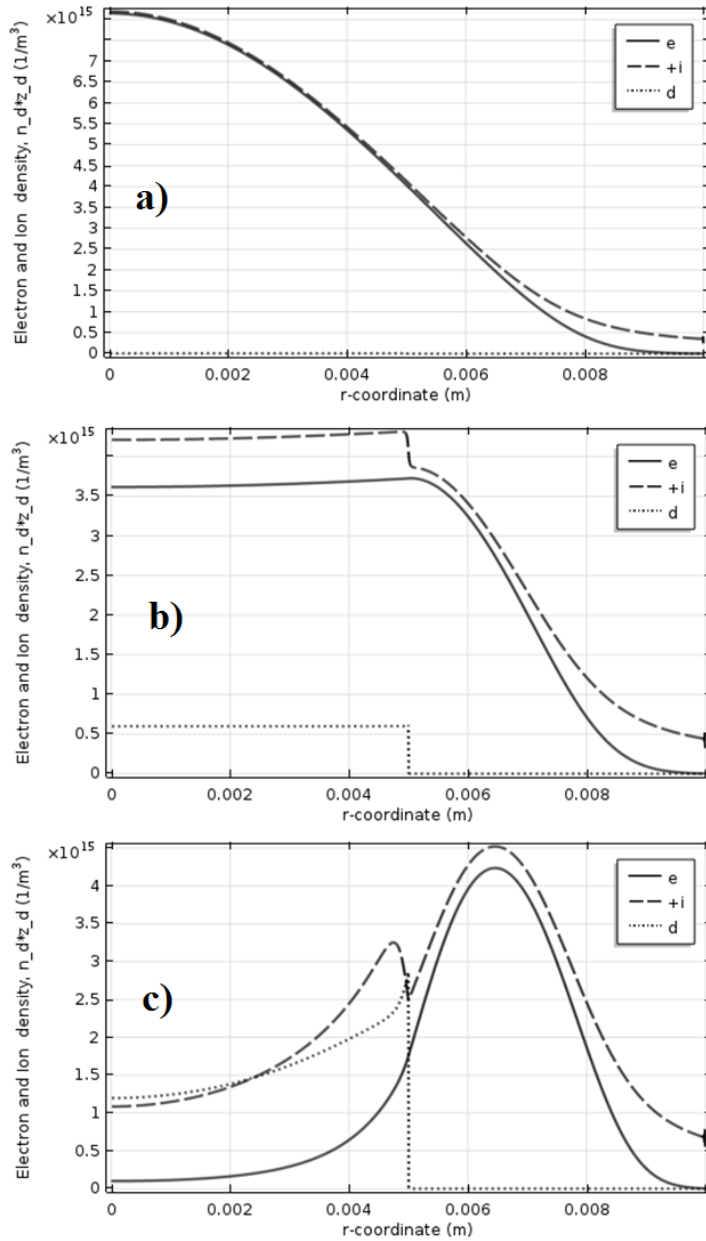


Fig. 1. Radial distributions of electron (solid) and ion (dashed) densities and $n_d Z_d$ (dotted) for dust particles number density (N_d) a) -10^9 , b) -10^{11} , c) $-5 \cdot 10^{11}$ 1/m³ correspondingly.

Fig. 1 shows the three main types of radial distributions of the electron and ion densities and $n_d Z_d$ (n_d – dust particles density radial distribution, Z_d – charge of dust particle in units of elementary charge e) for different densities of dust (N_d): a) dust does not affect the parameters of PC (Bessel distributions); b) ionization is equal to the loss on the dust in the dust cloud (in the dust cloud observed similar profiles of densities of charges and the diffusion profiles in the outer region); c) the ionization is almost absent in the dust cloud so that the charge balance is determined by the arrival of ions and electrons from the external region and the loss on dust, while in the external region ionization is equal to the sum of the diffusion losses on the wall and in the dust cloud (border of the dust particles cloud become almost like another wall for electrons and ions generated as a result of ionization in the outer region (non-monotonic profiles are observed)). The obtained results allow to predict the influence of dust particles on the properties of gas-discharge plasma in a wide range of conditions.

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NEW PLASMA EFFECTS AND PROSPECTIVE APPLICATIONS

Behavior of Historical Printing Inks on Paper in HF Cold-Plasma Discharges

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We present a report on the behavior of printing inks from a middle–19th century book when treated in high-frequency discharge plasma (13.5 MHz), by means of the device presented in Fig. 1, [1], [2] treatment applied for decontaminating and cleaning naturally aged printed paper.



Fig. 1. Plasma equipment

To separate the effects of plasma species on the two linseed oil-based printing inks that contain black carbon and the red-colored cinnabar (αHgS) as pigments [3], [4], we studied the time dependence of the plasma discharge in two types of working gases: inert (N_2) and oxidative (Ar/O_2).

Scanning electron microscopy, energy dispersive spectroscopy, and AFM analysis were used to study the influence of high-frequency discharge plasma on red-colored cinnabar. In an N_2 discharge there are no significant changes, but in Ar/O_2 the EDX data (Table 1) reflected the onset of a change in cinnabar-based inks, which can be associated with plasma exposure [5].

Table 1. Chemical composition of the cinnabar-based ink layer in the oxidative (Ar/O_2) plasma discharge

Content in Hg and S for the red printing ink HgS		Exposure to HF discharge in Ar/O_2 , min.		
		0	5	30
Element	Hg (atomic %)	49.72	21.67	22.20
	S (atomic %)	10.31	03.33	03.26
S/Hg ratio		0,207	0,15	0,146

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Merit" in rank of Knight, 2002, Elite Inventor Title cls I - V offered by SIR and Inventiv ommision of Romanian Academy - OSIM special price for the inventive activity 2011 - Special diploma and price AGEPI at Geneva 2011 - Certificate of Excellent Achievements at Geneva 2009

Electron-Beam Plasmas for Plasma Aerodynamics and Combustion

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New applications of weakly ionized plasma to plasma assisted combustion and plasma aerodynamics require large volumes of chemically active gases to be ionized at relatively high pressures, from a few Torr to 1 atm and higher and temperatures from 300 K to about 3,000 K, with an ionization level of $N_e/N \sim 10^{-6} - 10^{-4}$ (electron concentration N_e , neutral gas concentration N). In a number of these applications, the ionization level and electrical conductivity related to it are of principal interest. Practical applications of plasmas critically depend on the ability to generate and maintain a large number of ions, active particles and radicals using a very low power input. From the point of view of the ionization efficiency, electron beams are an optimal choice for a means of ionization and excitation of molecules. Electron acceleration in vacuum is not accompanied by large inelastic energy losses. Injection of the electrons, accelerated to tens or hundreds of keV energies, into a gas results in their energy degradation in ionization cascades, as beam electrons propagate in the gas and lose their energy. Because the electrons in high-energy electron beams are the most efficient ionizers, electron beams entering the combustor sections of vehicle are the most attractive approach to maintain the conductivity and a high level of active particles; in so doing the non-self-maintained discharge controlled by the electron-beam possesses the property of stability. The goal of this work is to consider electron-beam plasma for PAC applications in

the range 10–760 Torr and temperatures from 300 K to about 3,000 K. Chemical and plasma chemical schemes will be considered concerning this topic.

An electron – beam plasma (E_b -plasma) is created during the injection of an electron beam (E_b) into a dense medium. During the penetration of an electron beam through a plasma-forming medium, its energy is gradually spent in different inelastic interactions with the medium in the processes of ionization, dissociation and excitation of molecules. Finally the beam energy transfers into the heating of the medium and to phase transitions and radiation.

Properties of the generated E_b -plasma are characterized both by the parameters of the injected E_b (energy of electrons and current density of E_b) and by the properties of the plasma-forming media employed (type of a gas, its temperature and the partial pressure of components).

The application of prospective for PAC stationary electron beams with sub-relativistic energies was limited for a long time by the technological processes of welding and metal treatment. Difficulties of such E_b delivery from vacuum into a dense gaseous environment did not allow one to use them for plasma generation. Now there exists the possibility of E_b -plasma application, which is generated by a stationary E_b with the following parameters: power 1–100 kW, E_b energy 20–100 keV, current density $J_b = 0.1\text{--}10^3 \text{ A/cm}^2$.

The first, that attracts attention, it is the noncriticality of the E_b plasma generation technique as a choice for forming a plasma environment. Electrons can be injected practically into almost any gas and in gas mixtures of many chemical compounds. The pressure of the plasma-forming medium in E_b -plasma generators and the power of the injected beam are not bound together and can be changed independently; it is possible to inject both low-current, and high-current beams into a medium with set pressure, and in both cases there will be plasma generation.

Naturally, the characteristics and properties of an E_b -plasma essentially depend on a combination of the pressure of the medium and the power of the beam. It is possible to consider some variations of the combination of these parameters.

In the region of high pressures interesting for PAC applications, and values of the ionization degree in range $10^{-7} \leq N_e/N \leq 10^{-3}$ in the development of plasma the main mechanism for retardation of the beam electrons is connected with electron-gas molecule collisions. In this case, the main part of the electron beam energy goes into the ionization of gas molecules. The secondary electrons, created in the course of this process, rapidly decrease their energy from elastic and inelastic collisions with gas molecules. For a wide range of plasma parameters, the characteristic time of electron cooling is much less than the recombination time of electrons with positive ions. By changing the electron beam current density at a given pressure, one can realize several modes of plasma existence necessary for PAC application.

In this review we present information on excitation of molecular gases including air and its mixtures, since their behavior in complex plasmas are of primary interest from the point of view of PAC. We discuss: electron-beam devices; physical processes at electron beam impact on gases; two-atomic molecular gases excited by electron beams; electron-beam plasmas of air; application of a flow in electron-beam ionized gas; influence of electron beams and external electric fields on chemically active gas mixtures.

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Development of a Solar Photoelectric Converter Based on a Two-Chamber Photoplasma

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The importance of creating photovoltaic plasma converters is obvious from the point of view of diversification of energy, environment and responds to the global trend of increasing the relative share of renewable energy in the modern energy industry [1]. Such sources may have certain advantages compared to commonly used semiconductor solar cells [2], [3]. There are some approaches to convert solar energy into electrical energy based on photovoltaic effect in photoplasma [4], [5] containing a gas of an alkali metal (mainly Na and Cs): MHD generators [2], thermionic converters [6], non-uniform plasma [3]. In our recent papers [7], [8] it is shown that two-chamber 2D plasma cell allows obtaining large space gradients of electron density and temperature and thus create appreciable electric potential between chambers. So far the investigations of photovoltaic plasma converters (see [3] and bibliography in this paper) limited by one dimension case.

The aims of the present work are developing two-chamber plasma model for study photovoltaic plasma converters and 2D simulation of parameters photoplasma for Na-Ar gas mixture on the example two-chamber cell of conical geometry which conforms to one of a solar collector.

Let us consider conical two-chamber plasma geometry which conforms to one of a solar collector (see Fig. 1) and is similar the geometry of the experiment work [2].

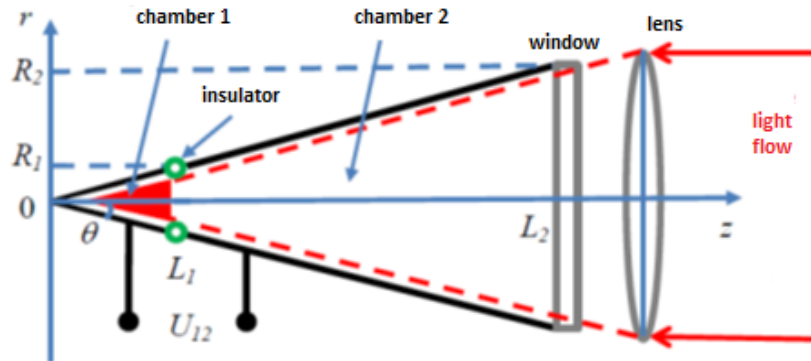


Fig. 1. Cross section of a conical photoplasma sell

In the present work we study two-chamber resonance photoplasma for the Na-Ar mixture. The Ar as buffer gas serves to provide diffusive regime of destruction of the charged particles in both chambers.

Two-chamber cell (α is a chamber number: $\alpha = 1, 2$) with open joint border (see Fig. 1) can have different space cross profile as in form so size. Continuity equations with the drift-diffusion approximation for each chamber α (see f.e. [5])

$$\frac{\partial n_j}{\partial t} - \nabla \cdot (D_{j\alpha} \nabla n_j) = I_{j\alpha} - R_{j\alpha} \quad (1)$$

where subscript j indicates j th specie, n is the density, I and R is creation and destruction rates, and D is the diffusion coefficient.

The electron energy balance equation (T_e – the electron temperature)

$$\frac{3}{2} \frac{\partial}{\partial t} (n_e T_e) + \frac{5}{2} \nabla \cdot (T_e \Gamma_e + D_e n_e \nabla T_e) = S_T \quad (2)$$

where the electron energy transfer is due to the convective electron flux Γ_e and thermo-diffusion. S_T describes the electron heating and cooling sources.

The conditions of 2D simulation are follows: the Ar pressure $p_{Ar} = 1$ Torr; the ratio of Ar and Na pressures $p_{Ar}/p_{Na} = 100$; the geometric sizes of the first and second chambers are ($L_1 = 10^{-3}$ m; $R_1 = 0.5 \cdot 10^{-3}$ m) and ($L_2 = 6 \cdot 10^{-3}$ m; $R_2 = 10^{-3}$ m) respectively. 2D simulation was fulfilled in the Comsol plasma module accounting Eqs (1)–(4).

2D space profile distribution of the electric potential is shown at Fig. 2 and electric potential at the z -axis is given at Fig. 3. Calculated photo-emf for considered conditions is 0.93 V.

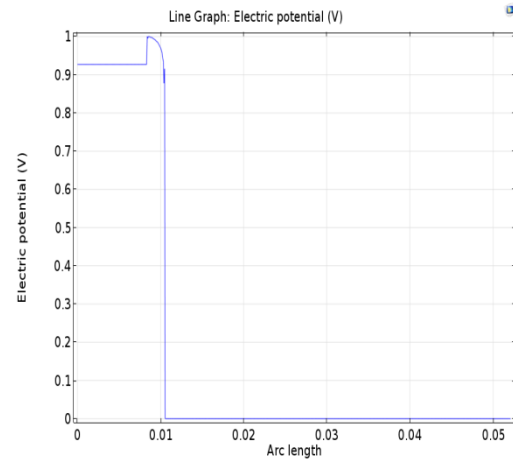
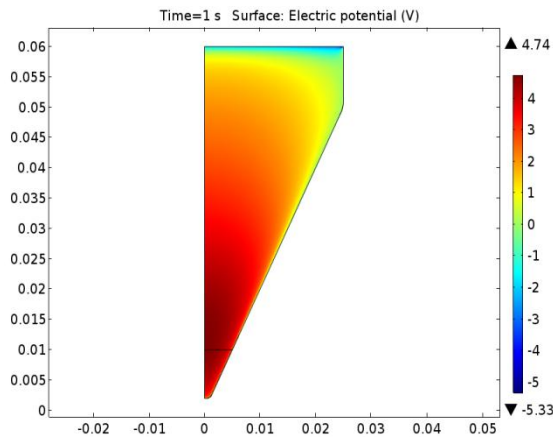


Fig. 2. 2D space profile of the electric potential Fig. 3. The electric potential at the z -axis

The present study shows strong space non-uniformity of electron density and the electric potential distributions in the photoplasma two-chamber cell that provides notable value of photo-emf. The further research suggests more detailed accounting of photoplasma reactions and optimization plasma geometry and conditions.

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Inactivation Process of Bio-Films of *Candida Albicans* by Gliding Arc Plasma Jet

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Candida spp have a high frequency of colonization and opportunistic infection in humans and are included among the microorganisms that cause bloodstream infections, occupying the fourth position, as shown in North American and European studies [1], [2]. New technologies for the sterilization of hospital supplies are needed in the face of high costs and difficulty in treating these contaminations and in this scenario, the use of atmospheric plasmas has been gaining attention. In this work, we present a detailed study about the inactivation of biofilms of *Candida albicans* by gliding arc plasma jet. The methodology used in this study comprises the preparation of suspensions of standard strain of American Type Culture Collection of *C. albicans* (10231) in the concentration of 10^6 CFU/ml in Dextrose Sabouraud broth (DIFCO), in which polyurethane and silicone plates of 2 mm thick and 2 cm² area were inserted under sterile conditions, and incubated at 37 °C for 48 h, under constant agitation (110 rpm), thereafter washed with phosphate buffer (PBS) to remove non-adherent cells and then treated. The samples were divided into 3 groups (A) control; (B) treated with 6L / min Argon + 4L / min of compressed air; and (C) treated with 6L / min Helium + 4L / min of air. Subsequent to treatment, the colony forming units (CFU/ml) were counted and images of treated surface were taken by scanning electron microscopy (SEM). Subsequent to treatment, the colony forming units (CFU) were counted, and the chemical bonding (FT-IR) and morphological

(SEM) analyses of the surface of the polyurethane substrate plus biofilm were investigated. Furthermore, optical emission spectroscopy technique was applied in order to characterize the plasma chemistry and measure the OH concentration and rotational temperature. Results show that there was a reduction in CFU/ml of 81% in group B and 96% in group C when compared to the control group (Fig. 1). In the SEM images, it was possible to observe some changes in the cells along biofilm surface, evidencing a visualization of the effects of the different plasma conditions on biofilm inactivation. Although the OH concentration (Fig. 2) and rotational temperature of helium/air plasma jet is lower in comparison with argon/air, a drastic increase of substrate temperature during treatment (up to 70 °C) was observed for this plasma chemistry.

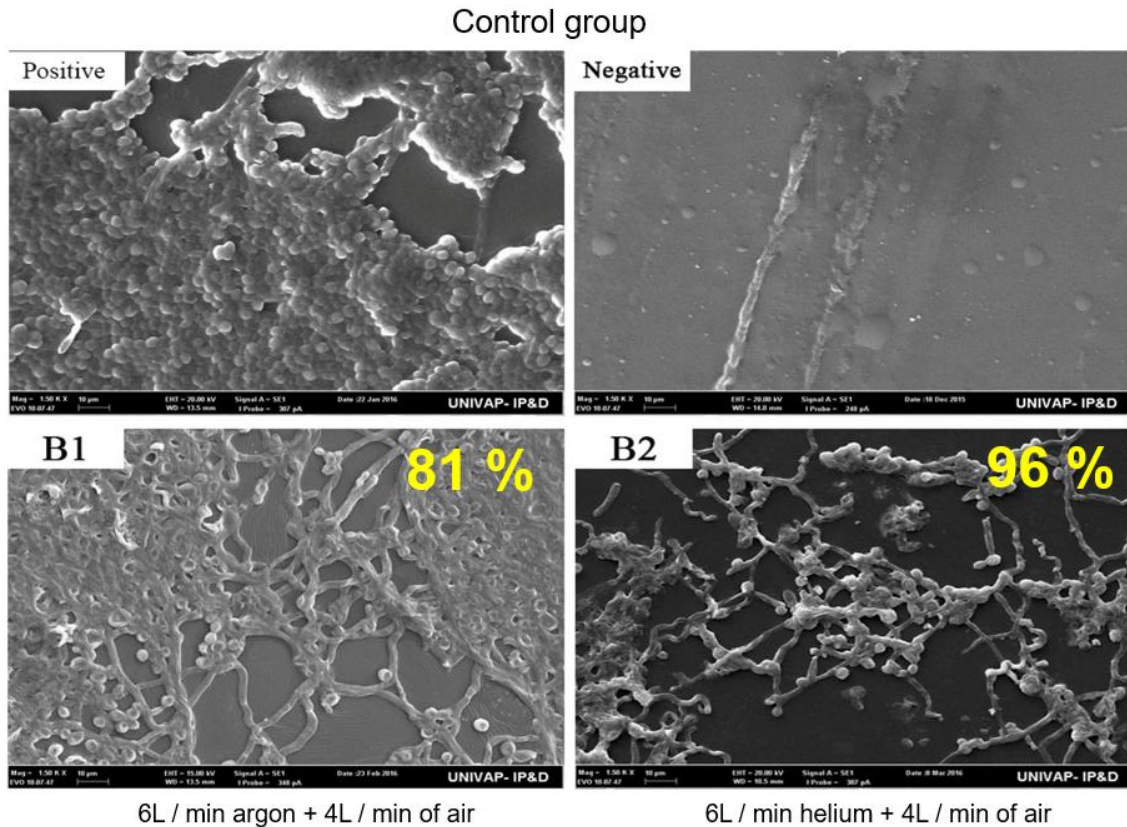


Fig. 1. SEM images with magnification of 1500x for group control positive and negative, groups B and groups C.

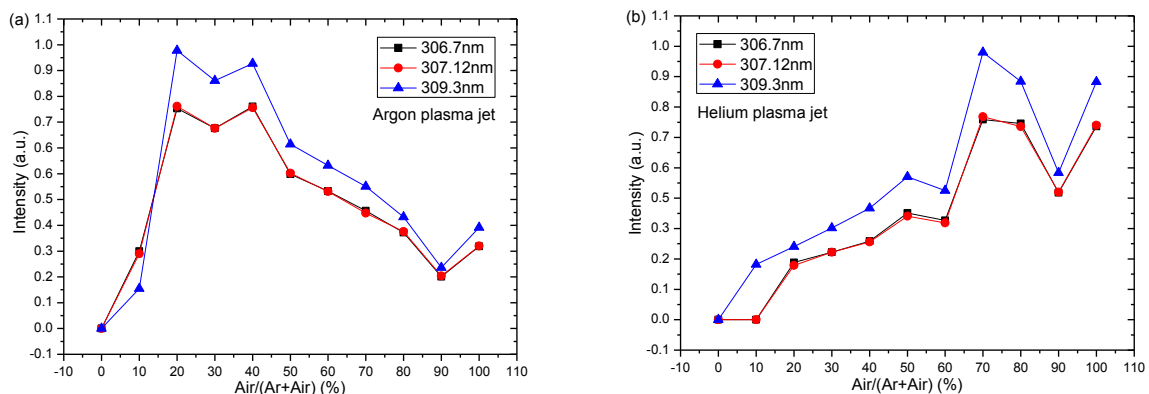


Fig. 2. OH main lines as a function of air percentage in argon (a) and helium (b) plasma gas mixture.

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Water Purification by Pulsed High-Voltage Nanosecond Plasma: New Results

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We have continued our research on water purification based on the application of fast, repetitive, nanosecond pulsed non-thermal plasma discharge. Plasma-based treatment methods are under development for Earth needs and are promising. Water is also a critical resource for space missions (Space Station, Mars, etc), especially those involving life-support systems. Storage and transport requirements place strict limitations on the amount of water available for these missions; thus, effective water recycling is essential. A plasma-based water purification system will require a compact, robust, and scalable design, capable of meeting mission-specific power restraints and processing flow-rates. We have developed several reactor designs that make use of fast ionization wave discharge geometries, and the most promising designs have been selected for optimization. Microgravity aspects, scalability, throughput, electrical efficiency, and chemical conversion efficiencies are considered in the context of a water purification system for space missions.

Most conventional water treatment processes are based on filtration, ozonization, UV-treatment, reverse-osmosis, and chemical consumables (e.g. chlorine). These processes have complexities due to cost, additional infrastructure, and consumables delivery. The appeal of the plasma-based method is that it generates in the plasma an array of advanced oxidation

processes (AOP's) which reacts with the contaminants in solution, and is thus the equivalent of many conventional treatments and the associated effectiveness. Plasma, when in contact with water, produces OH radicals, hydrogen peroxide, UV light, reactive oxygen species such as singlet oxygen, ozone, ultrasound, and shockwaves. Thus, the technology does not involve the importation of chemicals. All the chemical species and UV required for purification are generated in the plasma. And average power consumption is low (~500 Watts)! In addition, the extremely high electric fields kill bacteria by rupturing their cell membranes.

This presentation will focus on results obtained using a single basic reactor (Figs. 1 and 2). We will address microgravity design concepts, and scale-up for terrestrial requirements. For plasma-based purification technology to be practical, the issue of scale-up for high throughput must be addressed. We will discuss the development of a methodology for scaling up plasma-based water purification approaches to accommodate large volume applications. We have focused our efforts on the major impact of scale-up by defining requirements for any plasma-based system including minimum throughput definition, and the lower limit electrical efficiency for practical implementation. Because the objective is to enhance plasma contact time with liquid water under elevated throughput conditions, any progress in this area will advance the field paving the way for successful embodiments in the future.

For Earth-bound applications, the next logical step is a demonstration pilot at a water treatment plant or facility. As a spinoff, point-of-use systems can be piloted in remote underdeveloped villages using solar power. Because the application space of this technology is broad, a number of additional development paths are also possible. Those investigated include: (1) Cell Lysing to Enhance Methane Gas Production in Anaerobic Digesters. (2) Dissipation of Trace Organic Compounds (pharmaceuticals/antibiotics) in Municipal Wastewater Effluent. (3) Dissipation of Various Color Dyes such as Indigo Blue and Azo Dyes from Industrial Effluents.

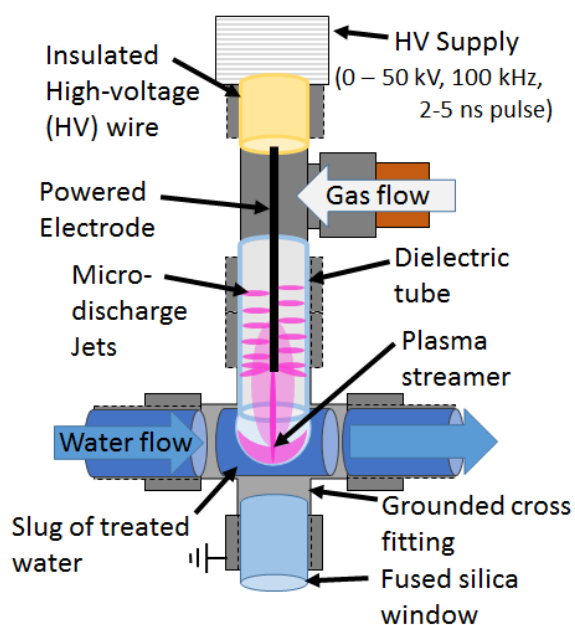


Fig. 1. Schematic of an individual plasma applicator exposed to liquid-cross flow. Slugs of water are dosed with reactive chemical species as they flow past the DBD plasma jet

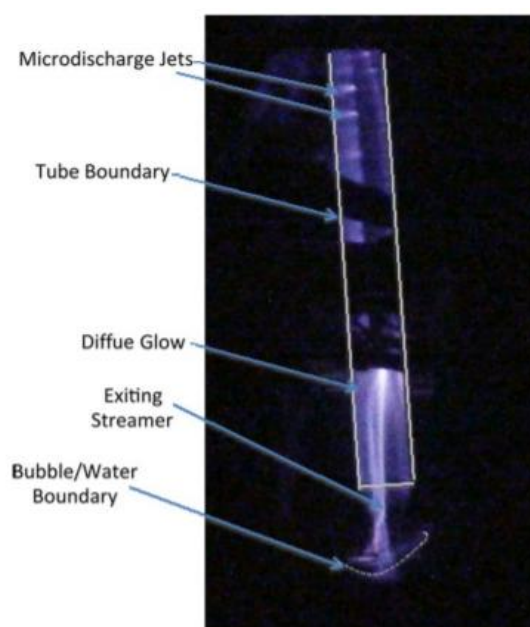


Fig. 2. Various discharge modes in underwater DBD plasma jet operation

The DBD plasma-jet applicator (Fig.1) provides the basis of a modular architecture for scaling up to high throughput liquid processing. A reactor design is proposed that features several individual plasma applicators arranged in parallel and series in order to achieve a high degree of scalability. In microgravity, special designs are under development since fluid flows are driven dominantly by surface tension forces, and can lead to seemingly anomalous liquid behavior. Plasma-based water purification as demonstrated in small-scale experiments clearly illustrates the promise of this technology. Scale-up remains perhaps the biggest challenge. A better understanding of the physical processes taking place at the interface and how to best control them is key to further advances in reactor efficiency.



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 the R&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.

ELECTRIC PROPULSION

Analysis of Electrothermal Energetic Capillary Plasma Source Concept for Launch Applications

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Electrothermal (ET) plasma sources are of interest for a variety of applications such as hypervelocity launch devices, fusion reactor pellet injectors, and pulse thrusters. The ET plasma can be generated in capillary sources by discharging a high current to initiate an electrical arc of sufficient radiant heat flux to initiate ablation of an inner material, followed by evaporation and ionization. ET plasma sources that operate under ablative regime have been widely studied for fusion fueling and electric launcher applications [1], [2]. However, various studies have been

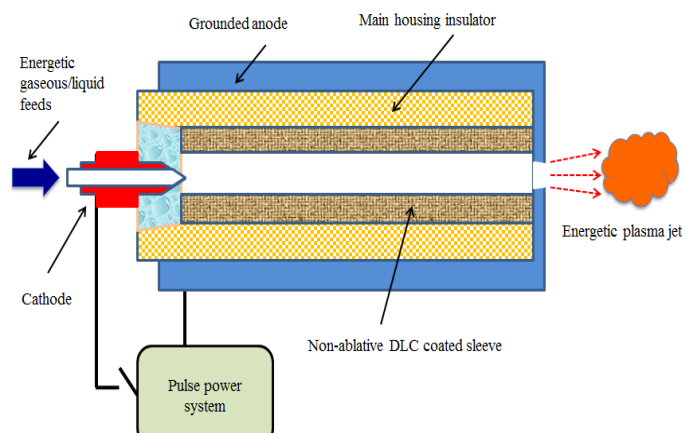


Fig. 1. Nonablative energetic electrothermal source with gas/liquid injection

also conducted on ET sources including the electrothermal-chemical (ETC) devices in which plasma interacts with solid or liquid propellants [3]. The ET source can also be operated under combustion regime in which the capillary is either lined or injected with energetic materials [3].

Considerable interest has been focused on injecting energetic gaseous/liquid materials into the ET plasma source as a technique for space propulsion and hypervelocity launchers. This technique can be illustrated by the diagram in Fig. 1. An ablation-free ET source is powered by an external pulse power system that delivers the energy and initiates the electrical arc. Firing the arc and injecting of the liquid/gas propellants occur simultaneously. The arc energy deposits thousands of joules sufficient to dissociates, ionizes and combusts the injected energetic material which generates highly energetic plasma.

In the present study, computational experiments have been conducted using different gaseous/liquid energetic materials with different mixing ratios to investigate the performance of the energetic plasma jet parameters at the source exit. These parameters are the exit pressure, velocity, and heat flux as they are the important parameters for launch applications and ETC devices. An ET energetic plasma code ETCOMBFLOW models the plasma formation and flow in the ET source, and self-consistently solves the set of governing equations. ETCOMBFLOW is coded to read the input discharge current, injected energetic material, and geometry of the capillary. The basic equations are the conservation of mass, momentum, and energy with the appropriate plasma models and essential plasma equations [3]. The energy equation accounts for the total energy released from combustion of the energetic material injected into the plasma source that can be written as:

$$H_{rels} = \frac{1}{2} \dot{M}_{energ} R_{plasma} H_{burn} \quad (2)$$

where \dot{M}_{energ} is the total released heat from energetic mass per unit time in a plasma capillary of radius R_{plasma} and H_{burn} is the energy release (J/kg) of the energetic material and may be taken equivalent to heat of formation. Assuming total decomposition of the energetic mass, \dot{M}_{energ} in (Eq.1) is found by dividing the total released heat on the required heat per mole of both sublimation and dissociation, and can be given by:

$$\dot{M}_{energ} = 2(H_{rad} + H_{rels})/R_{plasma} (H_{vap} + H_{diss}) \quad (2)$$

where H_{rad} is the radiated heat, H_{vap} and H_{diss} are heat of vaporization and dissociation respectively.

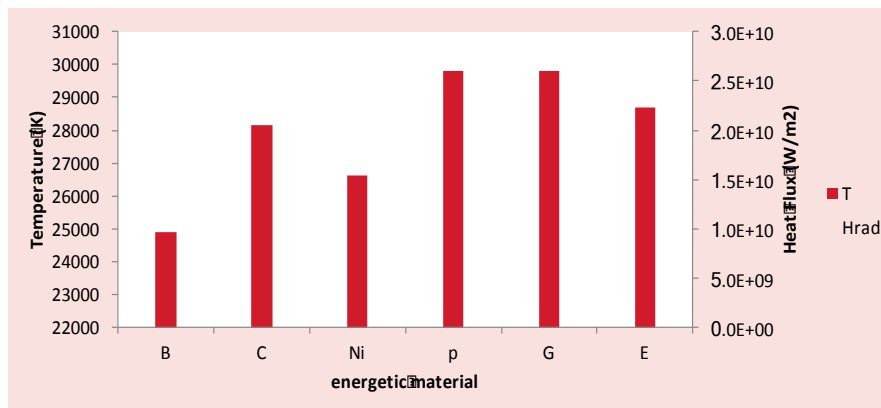


Fig. 2. Radiant heat flux and exit peak temperature for various energetic material

Simulation results indicate that the mixing ratio of the energetic material injected into the source plays a significant role in the parameters of the generated plasma jet. A set of code runs have been conducted at various magnitudes of the discharge current to explore the effect on the plasma jet behavior. It has been shown that increased discharge current increases the plasma kinetic temperature and the radiant heat flux. The plasma kinetic temperature and the resulting heat flux are strong functions of the energetic material properties as shown in Fig. 2.

Furthermore, a case study of mixed nitrogen/ethanol has shown increase in the exit heat flux and the plasma bulk velocity with increased ratio of the energetic material, but a decrease in the pressure and density. For a mix of 30% nitrogen and 70% of one of the set of selected energetic material, the generated highly energetic plasma flow at very high pressure (4.8–7.2 100s MPa), velocity (4.6–6 km/s), and Heat flux (1.3–2.6 10s GW/m²) as summarized in Table 1. These exit parameters are suitable for launch applications and ignition of electrothermal-chemical launching systems.

Table 1. The energetic plasma exit parameters for a mixture of 30% nitrogen and 70% of the energetic material

Energetic material		V_{bulks} m/s	H_{rad} W/m²	T, K	P, N/m²	N_p, #/m³
Butane	C ₄ H ₁₀	5,565.168	1.31E+10	2,4915.73	7.28E+08	2.36E+27
Cellulose	C ₆ H ₁₀ O ₅	5,154.033	2.14E+10	2,8151.79	5.77E+08	1.61E+27
Nitromethane	CH ₃ NO ₂	4,689.914	1.71E+10	2,6635.13	6.39E+08	1.89E+27
Phenol	C ₆ H ₆ O	5,456.198	2.68E+10	2,9798.16	5.39E+08	1.42E+27
Gasoline	C ₈ H ₁₈	6,062.928	2.68E+10	2,9793.16	4.89E+08	1.21E+27
Ethanol	C ₂ H ₆ O	5,699.114	2.31E+10	2,8708.97	5.35E+08	1.40E+27

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sources operating in the confined arc capillaries. Her research focuses on plasma material interactions with application to fusion reactors, space thrusters, launch devices and electrothermal plasma deposition and coating techniques. She is a licensed RSO (radiation safety officer) in Saudi Arabia.



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A Multi-Propellant RF Plasma Thruster

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As suggested by Dr. I. Matveev, the concept of a multi-propellant RF plasma thruster presented in this paper could be considered as a development of the well-known VASIMR project by Ad Astra Rocket Company (<http://www.adastrarocket.com/aarc/VASIMR>), which uses Ar as plasma gas. Progress in engineering of high-pressure RF torches, achieved by Applied Plasma Technologies, Corp., makes operation with multiple gases possible. In this case the core element of such a thruster, the Ionizer – RF torch, could also be used as a platform for different planetary life and operation support systems, including liquid and solid waste processing, CO₂ decomposition, just to mention a few. This thruster, depicted in Fig.1, would have such a flexible operation as to make possible, in many cases, In-Situ Resource Utilization (ISRU) Propellant gases could be readily obtained, for example, from the atmospheres of Mars or Venus, mostly composed of CO₂, or from water present, as ice, on many bodies of the outer Solar System.

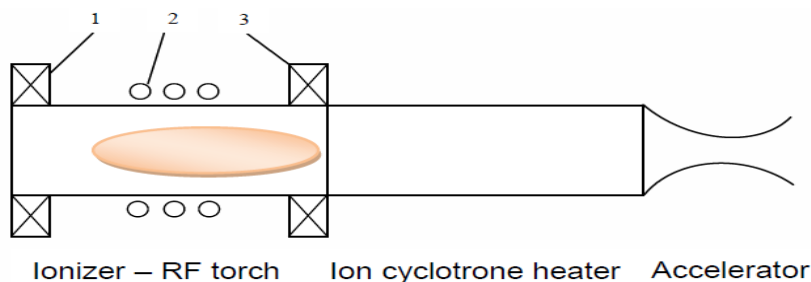


Fig. 1. Schematics of a preliminary RF plasma thruster design concept:

*1 – direct vortex swirler,
2 – inductor, 3 – reverse
vortex swirler*

The preliminary performance of this core element was estimated with three different propellant gases, by simply assuming a 75% thermal torch efficiency and calculating the plasma temperature T . The results of these estimates are presented in Tables 1 and 2. In a VASIMR – type design, such core element is only the first stage, and is followed by an Ion Cyclotron Heater (ICH) and an accelerator of the magnetic nozzle type. A comparison with results from VASIMR experiments [1]–[4], in particular with early results with a first stage operating at 25 kW power with 0.1 g/s mass flow rate of Ar [1], can be done.

With the current torch design, mass flows as low as in [1] are not practical at our power levels, as they would entail very high losses into the walls. At 25 kW power, the minimum flow for efficient operation is about 0.5 g/s, hence the values in Tables 1 and 2 (0.5 to 1 g/s). The addition of a strong axial magnetic field would confine the plasma, by actually “squeezing” it away from the walls, and therefore decreasing losses. The same field, as it diverges out from the thruster, can form a magnetic nozzle.

At higher values of mass flow rate such as those in Tables 1 and 2, the first stage would be an essentially electrothermal device, with thermal energy converted into directed kinetic energy and a lower performance than in [1]. In such a device, the specific impulse (I_{sp}) would depend on the square root of T/m (where m is the average atomic mass). In order to estimate the first stage performance parameters in Table 2, we assumed the generation of thrust to be happening through such a process, with a conversion efficiency (thrust efficiency) of 80%. This yields an overall efficiency of electric power conversion into thrust of 60%.

*Table 1. Average plasma temperature, T (K).
Plasma power 25 kW, 75% torch thermal efficiency*

Mass flow rate, g/s	0.50	0.75	1.0
H ₂ O	3,650	3,450	3,150
CO ₂	7,400	6,600	5,100
Ar	13,200	12,300	11,400

*Table 2. First stage performance parameters.
Mass flow rate 0.5 g/s, 80% thrust efficiency*

Plasma gas	T (K)	F (N)	I_{sp} (s)
H ₂ O	3,650	1.3	260
CO ₂	7,400	1.15	235
Ar	13,200	0.95	190

With the addition of a second acceleration stage, we could already have an interesting performance. For example, by operating with water and assuming that by adding 26 kW of power in the ICH stage, as in [1], the exhaust velocity would approximately double, thrust levels of nearly 3 N, at values of I_{sp} in excess of 500 s, could be obtained at 0.5 g/s mass flow rates and ~50 kW input power. This is competitive with arcjets and much better than

monopropellant chemical rockets, which are both in the same N-class thrust levels. Moreover, our thruster lifetime is not limited by electrode erosion, as would be the case with an arcjet, and can use a wider range of propellants than the aforementioned devices.

At a later stage, evolution of the design could lead to significant improvements in performance, with similar thrust levels produced at higher values of I_{sp} , possibly in the order of thousands of seconds.

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Broad NUV-VIS-NIR Spectral Characterization of Electric Propulsion Thrusters

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Spectroscopy is a useful tool for characterizing plasmas at a moment in time without altering them in the process. This allows for remote, near-instantaneous testing of in-space plasma systems like Electric Propulsion (EP) devices [1]. We utilize this experimental technique to investigate three such devices: an RF-driven Minihelicon [2] and two Hall Effect-based (BHT-200 [4] and DCF [3]) thrusters (shown in Fig. 1).



Fig. 1. BHT-200 and DCF Hall-effect ion thrusters (HETs) at the left (external cathode-neutralizer installed on the latter), and electrodeless Minihelicon plasma engine at the right

Broad emission spectra of the three EP thrusters running on standard Xe propellant are collected and compared for various operating regimes (Fig. 2). The features of these spectra uniquely indicate plasma composition, and can provide information about the operational parameters [5], efficiency, and prevailing reactions in each regime.



Fig. 2. Photos of HETs in-vacuum operation: (left) BHT-200 in high-voltage spike and DCF in the low-voltage diffuse mode (middle). Mini-helicon operation on Xe is shown in the right photo

Absolute intensity calibration is performed using a tungsten bulb light source with known gray-body radiation curve, see Fig.3.

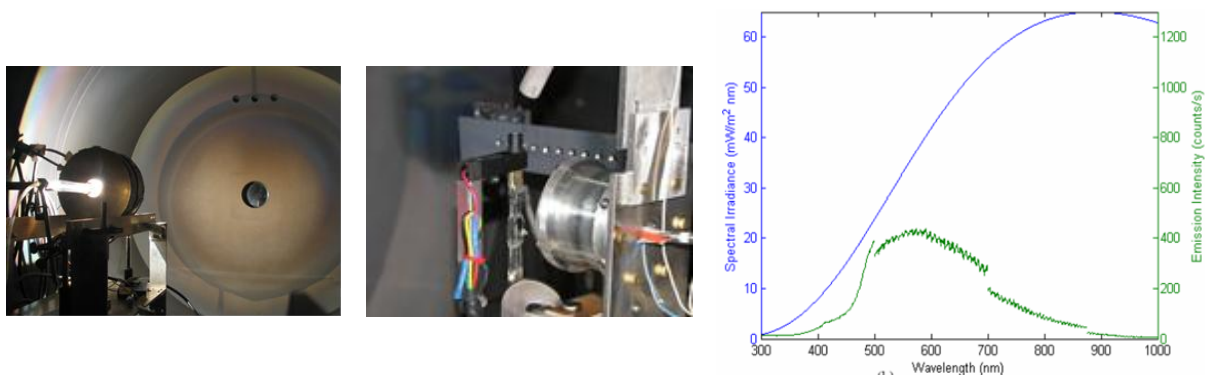


Fig. 3. Photos of bulb placement inside the quartz tube in case of Mini-helicon, and in front of HET for absolute calibration (left); right – measured spectral intensity curve of the Mini-helicon

High-resolution spectra are taken in the NUV-VIS-NIR 300nm-1 μ m range. Many strong emission lines are identified. We present a complete list of the atomic Xe I and ionic Xe II lines observed. Several higher-ionization lines, as well as emission from impurities and higher spectral harmonics, have also been detected.

Aside from characterizing composition, we will discuss using the broad emission spectra of EP devices such as these to derive plasma parameters like electron temperature and level of gas ionization. Additionally, the degree to which these spectra shed light on other important aspects of the thrusters, such as life time and performance optimization, will be examined.

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COAL, BIO-MASS, AND WASTE INTO ENERGY PROCESSING

Arc and RF Plasma Sources for Environmental Applications

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Introduction

One of the most serious ecological problem is a pollution of the environment with dangerous domestic and industrial carbonaceous wastes, of which toxicity, carcinogenicity, mutagenicity, corrosive action, and flammability risks are typical. Among the dangerous waste types, a special place belongs to the used tires and so-called medico-biological wastes (MBWs), that in fact can be classified as household wastes. It was found that the risks caused by such wastes for environmental medium are much higher in comparison with the risks caused by chemical wastes. Typical waste treatment methods are combustion and gasification. Of the known gasification methods of carbonaceous wastes, the least harmful one to the environment is plasma gasification. A key difference of plasma gasification from the flame methods of carbonaceous-waste destruction is the high temperatures in plasma reactors (1,500–3,000 K).

1. Dissociation of the hydrogen chloride in the RF plasma. The dissociation of HCl in the RF plasma discharge with the temperature above 6000K has thermodynamic character. The full dissociation of HCl to hydrogen and chlorine is achieved at the following conditions: plasma gas consisting of the mixture of Ar and HCl at ratio 1:1; plasma gas rate = 1 liter per second; discharge power = 10 kW. These results are confirmed by gas analysis of the product before and after the quenching device. The analysis of the gas mixture in the reactor shows that they contain argon, chlorine and hydrogen in molecular form. A similar RF plasma system was developed for plasmachemical decomposition of hydrogen sulphide. The efficiency of the process was demonstrated by using a 100 kW plasma torch. The pilot unit, having 600 kW power level was designed and tested at a gas refinery plant. An industrial plasma chemical reactor is based on a RF plasma system at a power level of 3 to 5 MW with optimal conversion level of hydrogen sulfide about 50–70% at a pressure of 1–10 atm, and an energy consumption of $\sim 1.2\text{--}1.5 \text{ kWh/nm}^3 \text{ H}_2$.

2. RF Plasma system for medical waste treatment. This work is focused on the studies of RF plasma discharge with respect to use on bio-hazardous medical waste. The system includes: liquid nitrogen crushing unit, plasma reactor, high temperature oxidizer and

emission control system. The medical waste is processed in the plasma reactor under nitrogen at atmosphere and reduces to carbon residue. The off gas is directed to the oxidizer and scrubbed before being discharged. The system works as a continuous batch. Processing rate is 1 ton/day. Total power required – 160 kW.

3. Arc plasma system for bio-medical waste treatment. High temperature plasma ensures an almost complete conversion of waste carbon into carbon monoxide (CO) and neutralization of all the toxic substances. The synthesis gas formed in the gasification process consists mainly of hydrogen (35–45%) and CO (35–55%). The calorific value of the resultant gas typically reaches 30–35% of the calorific value of natural gas and, occasionally, even exceeds the above values. This enables the use of synthesis gas for powering gas turbines and gas generator units as well as for generation of electric power with low-calorific gas steams. A typical composition of carbonaceous wastes is presented below: 47% – paper and paper board, 21% – food wastes, 12% – glass, 3% – iron and ferric oxides, 5% – plastics, 5% – wood, 3% – rubber and leather, 2% – textile, 2% – calcium carbonate. The thermodynamic calculation for the plasma gasification of carbonaceous wastes was carried out using the TERRA program. The calculations covered a temperature range from 300 to 3,000 K at pressure of 0.1 MPa. The air and steam gasification of carbonaceous wastes, respectively, for the following compositions of the initial technological mixture was calculated: 1) 10 kg CWs + 4 kg air; 2) 10 kg CWs + 1 kg steam. The thermodynamic calculations have shown that the maximum syngas yield for the plasma gasification process of carbonaceous wastes in an air and steam environment was achieved at a temperature of 1,600 K. In air-plasma and steam-plasma gasification of carbonaceous wastes, a high-calorific syngas, respectively, with concentrations 82.4% (CO = 31.7%, H₂ = 50.7%) and 94.5% (CO = 33.6%, H₂ = 60.9%) can be obtained. The specific heat of the syngas obtained in the air gasification process amounts to 3,410 kcal/kg, and that of the syngas obtained in the steam gasification process, to 4,640 kcal/kg. At the optimal temperature, 1,600 K, the power input into the air and steam gasification process of carbonaceous waste amounts, respectively, to 1.92 and 2.44 kWhr/kg. The obtained characteristics and revealed regularities of the plasma gasification process of carbonaceous wastes in various gasifying agents were used in developing and constructing an experimental plasma facility. According to the results of a thermodynamic analysis and an experimental study of plasma gasification of carbonaceous waste, no detrimental impurities were detected in the gaseous and condensed products of the process. From the organic and mineral mass of carbonaceous waste, respectively, high-calorific syngas and a neutral slag, predominantly consisting of ferric carbide, calcium mono-silicate, silica and iron, were obtained. A comparison between the experiment and the calculations showed a good consistency between the data.

4. Plasma processing of used tires. This system is used to study the process of recycling waste tires. Defined regimes where typical products are distinguished during the tire recycling process, such as: Synthesis Gas, Liquid Fraction and Carbon. In some experiments we observed only Synthesis Gas and Carbon Black (without Liquid Fraction). Particle size of carbon black is within nano-size range. Process parameters vary considerably and are dependent of the process temperature and energy used. The module is equipped with RF ICP torch and RF generator (2 MHz Frequency at power level of 100 kW). Additional to the plasma part, the reactor contents low-frequency (LF) induction heater. LF frequency heating generators are in 20–40 kHz frequency range at 15 kW power level. Modular construction of the installation allows different connection combinations of process equipment and the establishment of technological regimes depending on tasks. For example, the process system could use RF plasma torch or LF induction heater only or combined treatment (HF + LF).

This principle provides the flexibility of the equipment by transforming internal and external structure of a plant depending on its purpose. Temperature processes can be adjusted from 500 °C to 5,000 °C.

Conclusion

The following conclusion is related only to the areas, which have been described in this overview. For the last decade a big progress was made by introducing RF plasma to some of bio-medical, water treatment and waste-to-energy applications. Efficiency of plasma processes is one of the critical factors for existing and new plasma systems. The combination of RF and DC plasma with other heat sources is one of the way to optimize the treatment systems.

Plasma Gasification of Fuel Biomass

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The aim of the work was to conduct complex thermodynamic and experimental studies of FW plasma processing, comparison of the calculated and experimental data and the development of technological process recommendations. In this paper we discuss the results of thermodynamic analysis of high-calorific fuel gas production by gasification of fuel biomass (FBM) in air. Also experimental installation is presented and the results of experiments on gasification of FBM in air plasma compare with the computation.

A typical chemical composition of FBM is represented by the following components, wt.%: C – 49.88, O – 43.81, H – 5.98, N – 0.10, K₂O – 0.01, CaO – 0.12, MgO – 0.02, MnO – 0.01, Fe₂O₃ – 0.01, Al₂O – 0.01, SiO₂ – 0.01, SO₃ – 0.01, P₂O₅ – 0.02, Na₂O – 0.01. The organic part of FBM is represented by carbon, oxygen and hydrogen with a total concentration of 99.7%, whereas the mineral part is only 0.3%

Software package Terra [1] was used to perform thermodynamic calculations of FBM plasma air gasification. Calculations were carried out in the temperature interval 300–3,000 K and a pressure of 0.1 MPa. The aim was to determine the integral parameters of the gasification process: equilibrium composition of the gas phase of the gasification products, the degree of carbon gasification and specific power consumption for the process. The calculations showed that the maximum yield of the synthesis gas at plasma gasification of fuelwood in air medium is achieved at a temperature of 1,600K. At the air plasma gasification of FBM synthesis gas with a concentration of 77.1% (CO – 42.0, H₂ – 25.1) can be obtained. Specific heat of combustion of the synthesis gas produced by air gasification

amounts to 9,450 kJ/kg. At the optimal temperature (1,600 K), the specific power consumption for air gasification of FBM constitutes 1.53 kW h/kg. Found parameters and discovered patterns of the process of plasma gasification of FBM have been used to design an experimental plasma installation.

Experimental studies of FBM gasification were performed on the installation, main elements of which are a plasma chemical reactor with productivity by FBM up to 50 kg/h and long live DC plasma torch of 70 kW nominal power [2].

Gas analysis showed the following composition of the gas at the exit of plasma installation, vol.%: CO – 42.0, H₂ – 25.1, N₂ – 32.9. Specific heat of combustion of the synthesis gas produced by air gasification amounts to 9,450 kJ/kg. The total concentration of the synthesis gas was 77.1%, which agreed well with the calculations.

Carbon content of the slag in the sample was 1.13 wt.%, which corresponded to the degree of FBM carbon gasification 96.6%. Specific power consumption for FBM gasification in the plasma reactor according to the results of experiments amounted to 1.53 kWh/kg of working substance. In the experiments, as well as in calculations, no harmful impurities were found in the products of FBM plasma gasification.

This work was supported by Ministry of Education and Science of the Republic of Kazakhstan.

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Trash-to-Gas: Efforts for Long Duration Space Logistical Waste Conversion

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Currently on human spaceflight missions, logistical and mission waste are stored in cargo transfer bags until a disposal vehicle is ready to be detached and jettisoned from the International Space Station, and the trash is burned up in Earth's atmosphere. On a long duration deep space or planetary habitat mission, more logistical items, including food, hygiene, and supplies will be required for crew transport, which means more waste generation. Trash disposal strategies are being investigated for different mission scenarios.[1] On a long duration space mission, a four person crew will produce approximately 2,500 kg of waste materials in one year, consisting of food packaging, used clothing, hygiene items, human waste, life support system supplies and other crew supplies.[2] Jettisoning trash from a vehicle during transit to a deep space location (i.e. Mars) could become an orbital debris issue for future missions, and also requires an air lock which uses energy for pressurization and depressurization. Leaving waste on a planetary surface also risks the violation of planetary protection rules. The reuse of discarded materials on a long duration or planetary habitat is beneficial as it will reduce the overall mission mass, increase usable spacecraft and habitat volume, and can be converted to fuel, water and repurposed construction materials. A space technology alternative for converting trash and other waste materials into high-value products was investigated by the National Aeronautics and Space Administration (NASA). Six technologies for waste-to-fuel production were initially investigated, including catalytic wet air oxidation, pyrolysis, ozonation, incineration/gasification, and steam reforming. [3]–[5] These technologies were part of the Trash to Gas (TtG) project and were mainly thermochemical processes that converted the raw elements of a uniform waste simulant into new products. Other options investigated compressing waste into radiation shielding material via a heat melt compactor.[6], [7]

TtG provided stabilization of all combustible waste including human metabolic wastes and brine, volume reduction of waste, and production of useful gases for

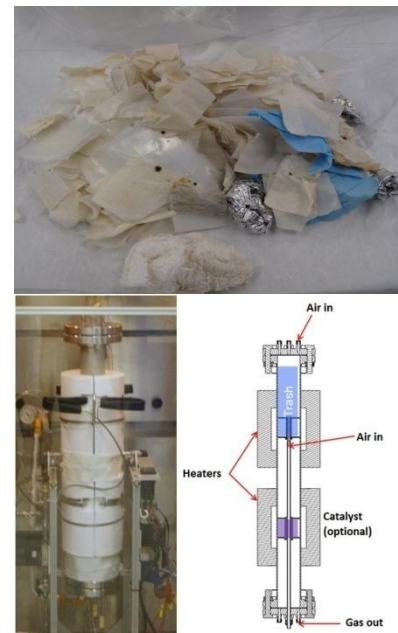


Fig. 1. Top: 100g of high fidelity waste simulant.

Bottom: Steam reforming reactor and schematic at KSC

propulsion and recovery of water for life support. The high fidelity waste simulant (HFWS) processed in these TtG technology demonstrations included a prepared composition of human metabolic waste (urine and fecal simulant), food, packaging, clothing, and other logistical waste (Fig. 1, top).[5], [8]

The result of the TtG project determined that a steam reforming reactor was the most effective for power, mass, and conversion purposes.[5] The steam reformer required 2 kW of power for operation. Concluding these results, the gasification reactor at Kennedy Space Center (KSC) was then converted into an oxygen enriched steam reforming reactor (Fig. 1, bottom). Processing the HFWS in this reactor showed that up to 1,540 kg of methane or 270 kg of water can be produced over a yearlong mission from the waste generated by a crew of four. Waste processing can also result in a waste volume reduction of 19 m³ over the course of a year, equivalent to the pressurized volume of one Orion spacecraft (a multipurpose crew vehicle) [2]. A human factors investigation of waste generation and crew interaction during a 120 day Mars analog simulation was tested with the reactor performance of waste from a crew of 6 people in 2014. [9], [10] Basic human factor statistics on crew time spent for preparing trash for operation, delivering trash to the reactor system and mimicking operations of the trash reactor system were logged in various tasks to evaluate the crew interactions with waste disposal systems and determine the waste generation profile over the course of the mission. It was determined that waste conversion could power items such as plant growth light chambers, and crews are very much willing to separate out the materials from waste for the ease of processing conditions in a waste conversion system.

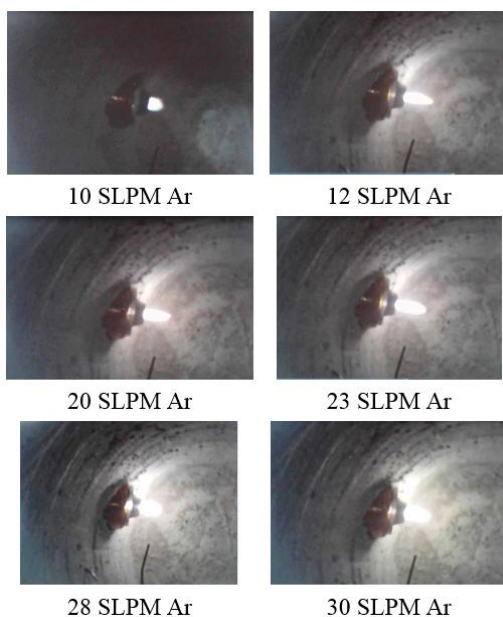


Fig. 2. AC plasma arc plume observed inside the waste reactor at varying carrier gas flowrates (standard liters per minute argon)

A follow on investigation of plasma arc gasification was performed to see if the HFWS could be converted into a synthesis gas and solid slag material. A waste feed system, reactor vessel, and post reactor gas processing system were successfully built and integrated with an alternating current (AC) plasma arc torch and custom built power supply.[11] The plasma torch was operated for short periods of time, with < 2kW of power needed during stable plume formation (Fig. 2). Instability of the plume resulted in large power draws and it was unable to process waste in the system setup. Even though large-scale plasma arc gasification has been demonstrated industrially, low-power plasma arc gasification for waste degradation for space is at a lower technology readiness level (TRL) than initially thought. A desire exists to test space waste conversion concepts with other small-power plasma arc loads needs in order to see whether plasma is comparable to the other waste conversion technologies studied in the TtG

Project. These strategies on space mission waste conversion efforts will be presented, along with solutions for advancing the TRL so that a waste conversion system can be utilized in reduced gravity operations.

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She currently supports NASA technology development projects as a test engineer and researcher for deep space exploration and resource reutilization for human spaceflight. Focuses have included logistical waste conversion, and in-situ resource reutilization (ISRU) systems to convert the Mars atmosphere into methane (fuel) and water. She is currently the principal investigator for development of photocatalysts that are activated under ultra violet and visible light to support the conversion of carbon dioxide into fuels.

Meier was selected as a crew member in the 120 day Mars analog HI-SEAS II mission in 2014. At HI-SEAS, Meier performed various research projects while living in an isolated Mars-like habitat with an international crew.

Ms. Meier is a graduate of the 2012 NASA FIRST leadership development program and a recipient of the Space Flight Awareness Trailblazer Award, Future Space Leaders Grant, NASA Space Flight Awareness Team Award for Orion Chemical Analysis Support and NASA Environmental and Energy Team Award.

Paul E. Hintze grew up in Baton Rouge, Louisiana. He earned a B.S. in Chemistry with a minor in Mathematics (1996) from Louisiana State University, Baton Rouge, Louisiana, USA and a Ph.D. in Chemistry (2002) from the University of Colorado, Boulder, Colorado, USA.

He was awarded a National Research Council Resident Research Associateship to work at NASA’s Kennedy Space Center (KSC) in 2003 and then began working for NASA in 2005. He started his career working on projects that identified and developed materials for use in KSC’s unique launch environment. In addition, he used this knowledge to develop methods for building launch and landing pads on the Earth’s moon and Mars. He believes in sustainable approaches to spaceflight operations, and as such works towards this goal

developing technologies for ground and space systems. Projects include solvent-free precision cleaning methods that minimize waste generation at KSC. He has led and contributed to projects in the field of in situ resource utilization, or ISRU, including the Trash to Gas project, which converts waste generated during human spaceflight into propellant and projects that seek to make rocket propellant on the surface of Mars.

Dr. Hintze was awarded a 2015 Presidential GreenGov Green Innovation Award and selected as a 2015 LAUNCH Green Chemistry Innovator for his work on environmentally friendly precision cleaning. He led the Trash to Gas and Green Solvents teams which were won Kennedy Space Center Environmental and Energy Program Awards in 2013 and 2014, respectively. He has twice been selected as Most Supportive Mentor.

Plasma-Assisted Disposal of Sewage Sludge

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One of the promising ways of the sewage sludge utilization is combination of the cutting-edge plasma-chemical and gas turbine technologies. Plasma-assisted disposal of sewage sludge for power systems in some cases is more preferable compared with thermochemical methods because they are much more compact, more mobile, provide processing of sewage sludge with a broad fractional composition, and would replace digesters.

There were some attempts to use plasma to treat human waste. Our approach [1], [2] differs from all known ones by using the radio frequency plasma torch with the virtually unlimited lifetime and minimal power consumption due to the multistage plasma reactor design similar to that for the coal gasification.

The raw sludge after dewatering process with the initial moisture content of about 75% is fed into the drying device. There, under the impact of heat of the gas turbine (GT) exhaust gases, which previously pass through the waste heat steam generator, it is dried with the moisture decrease down to 45%. The sludge prepared in such a way is fed to the reactor. There occurs the process of sludge gasification provided by operation of the high-frequency plasma torch. The process takes place at the air excess ratio of 0.2–0.3, and the air is supplied by the blower. High power RF plasma torch provide unique efficiency both thermal and electrical, generate pure plasma with temperature up to 12,000 K, output velocity from 20 to 300 m/s, completely free of contamination from the electrodes erosion, and have almost endless lifetime.

Incoming and outgoing streams of the plasma-assisted system are presented in Table 1. They correspond to the nominal mode of the GT operation for two different compositions of synthesis gas: synthesis gas 1 obtained by plasma-assisted disposal of sludge with the moisture content of 45% (case 1) and synthesis gas 2 obtained by disposal of the same sludge with 10 % additive of waste oil (case 2).

The study of the system operation in the range from 55 to 100% of the nominal productivity (for sludge with the moisture content of 75%) shows that technological process with disposal of the mixture of sludge and the waste oil is more effective in all modes of partial loads.

The proposed new system for plasma-assisted disposal of sewage sludge allows to process up to 100 tons of sewage sludge with production usable (external) electric power, heat energy, and technical water.

Table 1. Incoming and outgoing streams of the plasma-assisted system

Parameter/Case	1	2
INCOMING STREAMS		
Heat release in the reactor from sludge with 45% moisture, kW	12,077	6,748
Heat release in the reactor from additional waste oil, kW	0	2,018
INTERNAL SYSTEM CONSUMPTION		
Heat power for drying of sludge with 75% moisture, kW	2,658	1,492
Parasitic loads, kW	1,370	821.3
OUTGOING STREAMS		
Net power production, kW	2,986	2,953
Process water output, t/day	63.85	16.46

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PLASMA TREATMENT FOR COATINGS AND SURFACE MODIFICATION

Deposition of Hard, Adherent and Corrosion Resistant DLC Coatings using a Pulsed-DC PECVD System with an Active Screen

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Plasma surface treatments have been used to modify the surface properties of metallic materials [1], [2]. These surface treatment techniques increase the mechanical and tribological properties of the metal surfaces, but for several industrial applications harder and more wear and corrosion resistant surfaces are required. In order to improve surface properties, protective coatings have been used. Diamond-like carbon (DLC) coatings have widely used due to their high hardness and elastic modulus, low friction, chemical inertness, biocompatibility, and high wear resistance [3].

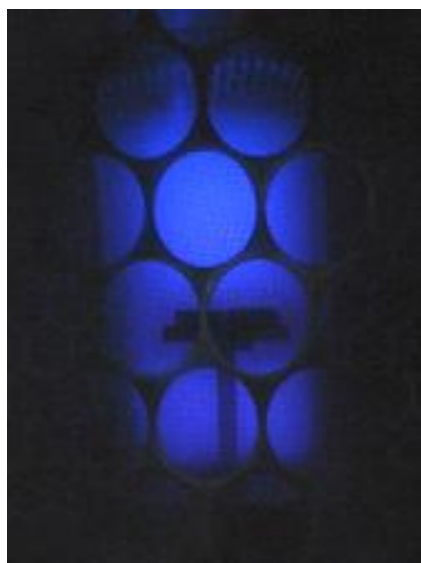


Fig. 1. Acetylene plasma into the active screen

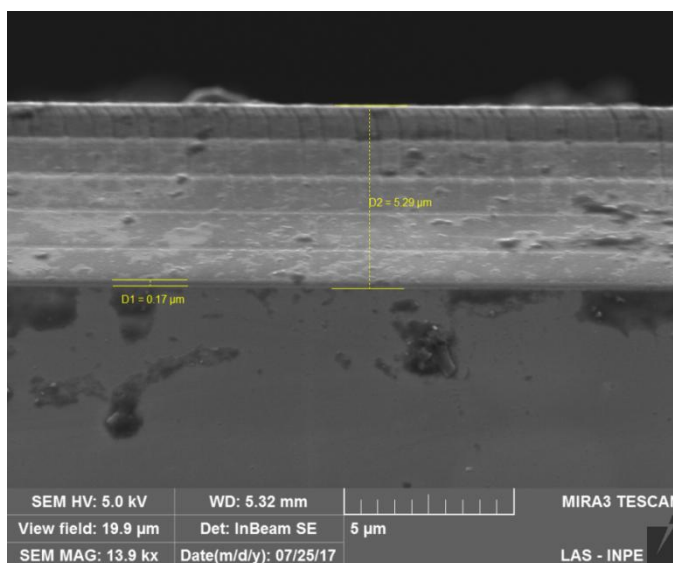


Fig. 2. HR SEM micrograph of the multilayer (five layers) DLC coating on silicon surface

Deposition of hard, adherent and corrosion resistant DLC coatings onto several metallic surfaces is presented in this work. The coatings were deposited using a modified asymmetrical bipolar pulsed-DC PECVD system, gas acetylene, and an active screen. A cathodic grid was designed to act as an additional cathode in order to accomplish plasma densification, while the active screen and the cathode were subjected to the same bias voltage. [4], [5]. A photograph of the acetylene plasma into the active screen is presented in Fig. 1.

With the aim of increasing adherence of DLC coatings on several metallic surfaces, a thin amorphous hydrogenated silicon (a-Si:H) interlayer was used as interface. a-Si:H interlayer produces a gradual change in the thermal expansion coefficients and contributes to reduce stress in the coatings.

In many mechanical and tribological applications, coatings with higher thickness ($\geq 5 \mu\text{m}$) are necessary. In order to obtain adherent DLC protective coatings with thicknesses of about $5 \mu\text{m}$, a multilayer structure of DLC films were deposited. The silicon interlayer and DLC coating thickness values were measured using a high resolution scanning electron microscopy (HR SEM). A HR SEM micrograph of the multilayer (five layers) DLC coating on silicon surface shows in Fig. 2.

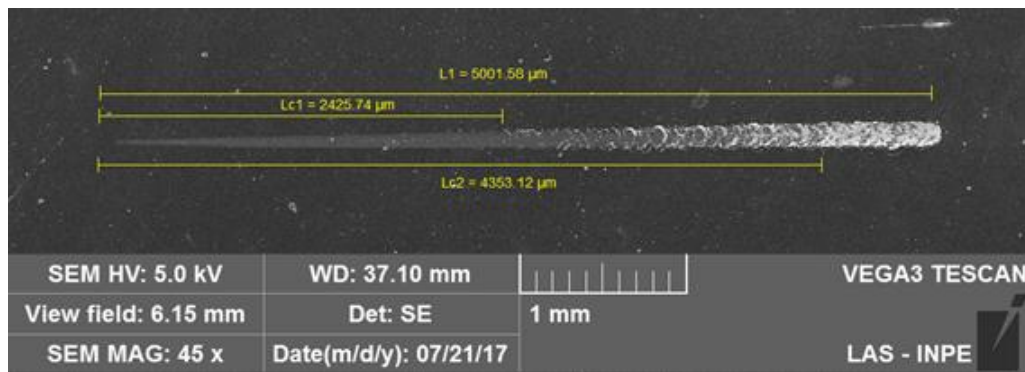


Fig. 3. HR SEM micrograph of the DLC surface deposited on steel substrate after the scratch test

The monolayer and multilayer coatings were analyzed according to their microstructural, mechanical, tribological, and wear resistant properties, as well as their degree of adhesion onto used metallic substrates. The adhesion was analyzed using a conventional scratch test through a critical load measurement, using the Rockwell-C indenter. The applied load varied from 1 to 50 N, with a sliding distance of 5 mm and speed of 0.1 mm/s. The Lc1 and Lc2 critical load values were determined. HR SEM micrograph of the DLC surface deposited on steel substrate after the scratch test is presented in Fig. 3. From the figure, it can see that high value of Lc1 of about 25 N and Lc2 approximately of 44 N were measured.

The corrosion resistance of the DLC coatings was evaluated by electrochemical potentiodynamic polarization techniques. The reference electrode was a saturated Ag/AgCl electrode. The electrolyte solution was a 3% sodium chloride (NaCl) aqueous solution with pH of 5.8. The obtained results show a high corrosion resistant of the DLC coatings. A HR SEM micrographs of DLC surface (a) and steel surface (b) after the corrosion tests are shown in Fig. 4, where the DLC surface is observed without any damage [Fig. 4 (a)]. On the other hand, the steel surface was highly corroded [Fig. 4 (b)].

This modified pulsed-DC PECVD system with an active screen represents a step forward for DLC coating growth by using very lower pressure in almost collision less regime and

higher plasma density than the conventional PECVD system. The used methodology allowed depositing a multilayers structures, reaching coating thicknesses of about 5 μm , maintaining good coating's adhesion on metallic surfaces and growing the silicon interlayers and the DLC coatings with high thicknesses precision. These results are important, once coatings with higher thickness are necessary in many industries where mechanical and tribological applications are required.

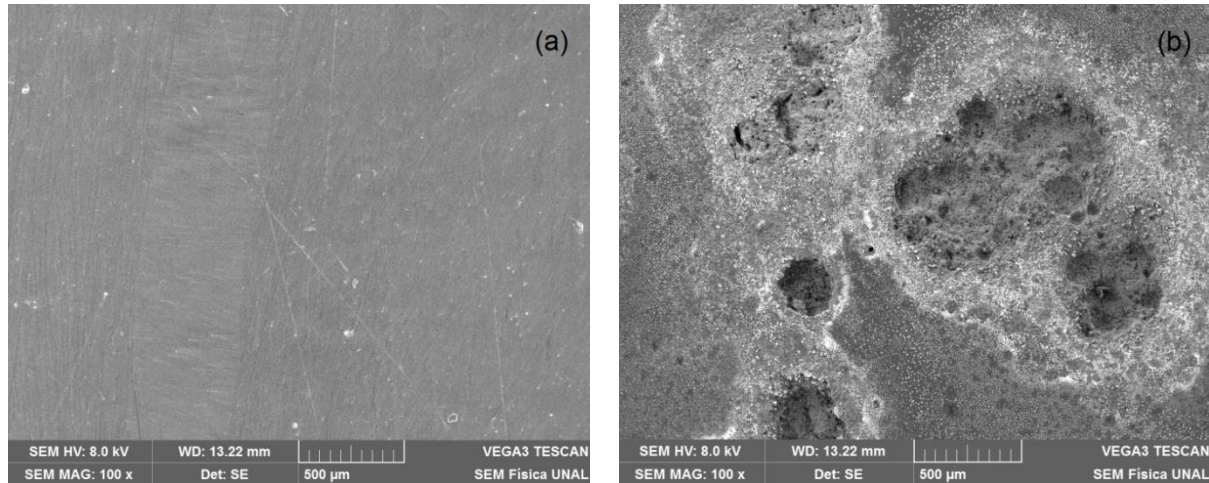


Fig. 4. HR SEM micrographs of DLC surface (a) and steel surface (b) after the corrosion test

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Surface Modification of Vegetable Fibers for use as Reinforcement in the Manufacture of Bio-Composites

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The application of new treatment methods to perform the surface modification of the vegetal fibers is a fast and safe alternative. Plasma treatments are clean processes, which do not use pollutants. They contribute to mitigate the environmental impact generated by chemical treatments traditionally used for the conditioning of the vegetable fibers to be used as reinforcement in composites materials [1]–[12].

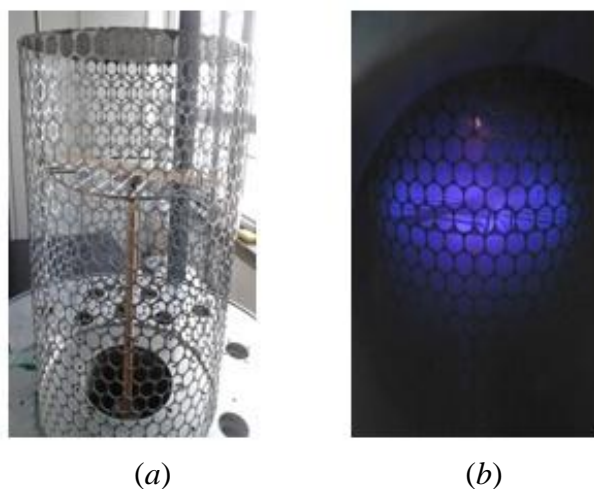


Fig. 1. Plasma treatment:

(a) placement of the fibers inside the deposition camera; (b) Methane plasma

In this work, the effect of plasma surface modification in vegetal fibers on the mechanical behavior of bio-composites is presented. A methane plasma was used to increase the roughness and hydrophobicity of the fiber surfaces. The vegetal fibers were treated with cold methane plasma for 10 minutes, using a working pressure of 27 Pa, a DC applied voltage of -700 V, and a gas flow of 10 sccm. Temperature during the treatment was kept of about 26 °C. Fig. 1 shows the methane cold plasma treatment.

In order to determine the physical properties of the fibers, two fiber groups were prepared according to their initial condition: untreated and treated with

methane cold plasma. Each group was conformed by 50 fiber bundles, composed by ten fibers of 5 cm of length. Moisture content, the effective absorption, and the density of the fibers were evaluated according to the specifications of the standards ASTM D 4442-16 [13], ASTM D5229-14 [14] and ASTM D3800-16 [15], respectively. Results of the physical properties of the fibers are presented in Table 1.

Table 1. Physical properties of vegetal fibers.

Properties	Untreated fibers	Treated with methane plasma
Moisture content (%)	7.6	8.5
Effective absorption (%)	62.5	28.0
Density (g/cm^3)	0.75	0.58

Composite panels were manufactured following the methodology described in the molding manual and using compaction by pressing. The molding process consisted of the application of successive layers of fibers in a square mold, impregnating the fibers with a vegetal resin and making an initial compaction for each layer.

Mechanical characterization was focused in the realization of axial tensile, compression and static bending tests. For the accomplishment of the tests the specifications of the ASTM 1037-12 were followed [16]. The results are compared with those obtained for panels made with modified fibers using an alkaline treatment. Mechanical properties of the vegetal fibers measured for both treatments are presented in Table 2.

The obtained results allowed concluding that it was possible to produce a decrease of the effective absorption of the fibers and an increase of their roughness when the fibers had been treated by plasma. These modifications had a favorable effect on the fiber-matrix interface and contributed to the dimensional stability of the bio-composite. Fibers treated with methane cold plasma showed a greater adhesion in the matrix, causing an increase in the mechanical properties of the composite.

Table 2. Mechanical properties of vegetal fibers.

Properties	Alkaline treatment	Methane cold plasma
Tensile stress (MPa)	8	15
Compressive Stress (MPa)	14	20
Rupture Modulus (MPa)	27	35

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Her current research interests include composite materials and the use of natural fibers for structural applications in the construction industry.

Comparisons Between TiO₂/Al₂O₃ Nano-Laminates Grown by Thermal and Plasma Enhanced Atomic Layer Deposition

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The properties of atomic layer deposited (ALD) nanolaminates depend on their compositions, stacking sequences and thicknesses. The key of successful application of these materials is a detailed understanding of its growth mechanism and controlling of their properties. Herein, we report the growth mechanism and material properties of TiO₂/Al₂O₃ nanolaminates grown on silicon (100) and glass substrates by plasma enhanced atomic layer

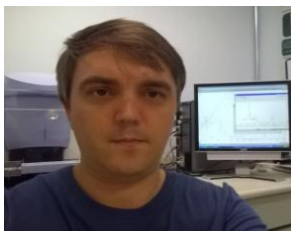
deposition (PEALD) and compare them with thermal ALD nanolaminate structures of our previous work [1]. For the purpose of comparison of synthesis methods, the same structure concept was used i.e., each $\text{TiO}_2/\text{Al}_2\text{O}_3$ nanolaminate incorporates a certain number of Al_2O_3 partial-monolayers (between 10 and 90) during 2,700 total reaction cycles of TiO_2 under temperature of 250 °C. As precursors, in thermal mode, we used titanium tetraisopropoxide (TTIP) and water vapor (H_2O) to deposit TiO_2 layers and trimethylaluminum (TMA) and H_2O to deposit Al_2O_3 layers. In plasma mode, an O_2 plasma was used instead of H_2O . Results obtained from the characterization of the nanolaminates evidenced that the model proposed for thermal ALD $\text{TiO}_2/\text{Al}_2\text{O}_3$ nanolaminate is valid for PEALD, however it was necessary a higher number of Al_2O_3 layers to stop the TiO_2 crystallinity. This allows obtaining a nanolaminate with improved properties in comparison with thermal ALD, as for example higher transmittance, lower band gap (near the value of 3.2 eV), low resistivity, and higher hardness and Young's modulus. The properties indicate that UV detection is an interesting potential application for the PEALD $\text{TiO}_2/\text{Al}_2\text{O}_3$ nanolaminates.

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Development and application of thermal plasma torches for materials processing: surface coating and solid waste vitrification

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Plasma technologies can be used in a wide range of applications being highlighted, among them, those based on thermal plasma torches which are capable of supplying the

necessary energy for materials processing and melting, along with numerous advantages including: high temperature, high enthalpy, non-ionizing radiation and high energy density. The heat source and the thermal gradients can be controlled independently of chemistry. Whereas an upper temperature limit of 2,000 °C can be achieved by burning fossil fuels, electrically generated thermal plasmas can reach temperatures up to 20,000 °C or more[1]. The research group at Laboratory of Plasmas and Processes (LPP) of the Technological Institute of Aeronautics (ITA), by taking advantage of these characteristics, has developed equipments aiming applications of thermal plasma torches for growing ceramic coatings and for solid waste treatment, as described below.

A High Velocity Plasma Spray (HVPS) torch was developed for materials processing (Fig. 1), which has the capacity to process solid materials (powders), or liquid (solution or suspension). The spray system has the following characteristics: axial injection, high particles velocities (800 m/s), high voltage (240 ~ 380) V and low operating current (54 ~ 140)A.

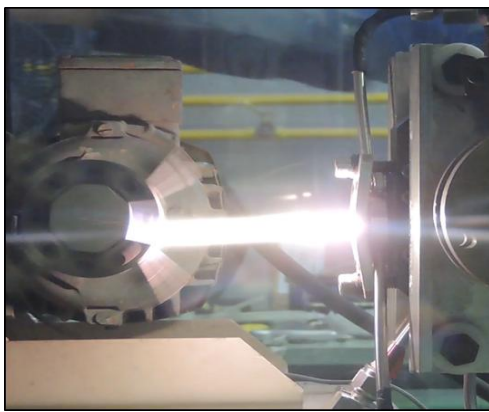


Fig. 1. HVPS torch in deposition process of TBC (CoNiCrAlY)

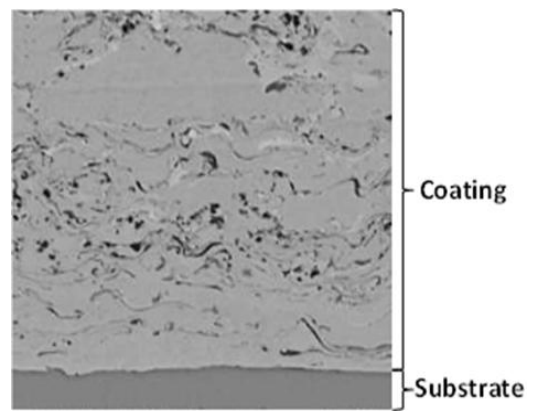


Fig. 2. CoNiCrAlY Thermal Barrier Coating on Substrate Ti-6Al-4V

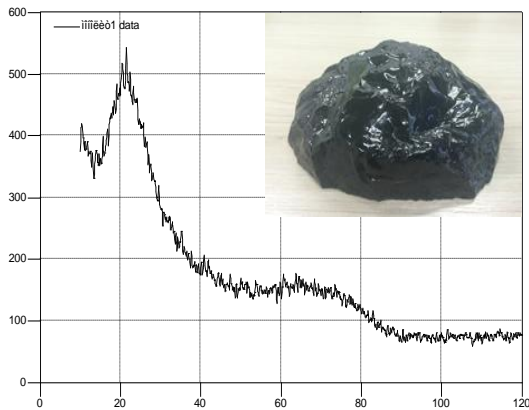


Fig. 3. X-ray powder diffraction analysis of vitrified ash from sugarcane bagasse with amorphous microstructure

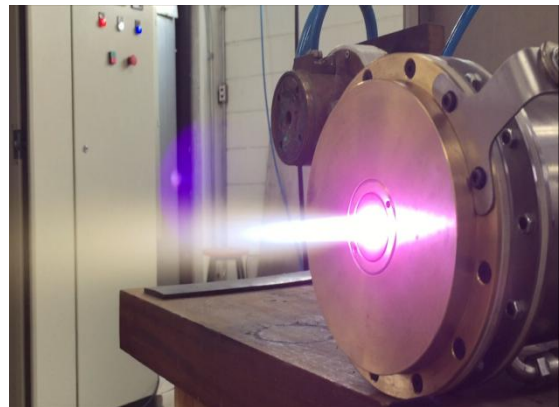


Fig. 4. Tornado II plasma torch in operation test

A Plasma based Reactor/Furnace was also developed using a Tornado II plasma torch (Fig. 4) to provide efficient heating for melting solid waste materials, after a short time of interaction of the plasma with the solids. Vitrification tests ($T > 1,600$ °C) were performed using two types of materials. First material used was ash from sugarcane bagasse, a waste produced in large amount in industrial plants of ethanol in Brazil. Moreover, its processing is

somehow a means to simulate the vitrification of fly ash which is a hazardous material produced in MSW incinerators. The resulting melted material, after cooling, forms a chemically and physically durable vitreous rock. Depending on the original mineralogy, the final product consists of an amorphous glassy material (Fig. 3). The second vitrification test was performed using sewage sludge. In both cases the vitrification process was able to promote the inertization and considerable reduction (mass and volume) of the residues. Feasibility studies and costs related to the process have also been carried out.

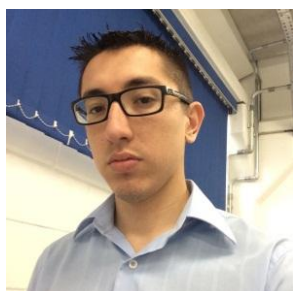
Finally, we point out some innovative aspects regarding the performance of the two plasma based equipments. The equipment for deposition process called HVPS uses plasma torch which has efficiency around 75–80%, high deposition rate of 15 μm when processing liquid materials and 30 μm for solid materials (powders). Due to axial injection, all material injected is processed under the same energy dose, reducing the occurrence of unmelted particles, which compromise the final coating. The versatility of this plasma torch enables the processing of solids (powders) or liquids (solutions or suspensions) materials. This is due to the large operating range that allows the power adjustment according to the material to be sprayed. The final coatings have low porosity, consequently high density and excellent adherence due to the supersonic regime of the plasma torch. The coatings obtained are used for Thermal Barrier Coatings (TBC) or/and Environmental Barrier Coatings (EBC) (Fig. 2). The other equipment, the vitrification Furnace, operating with Tornado II plasma torch of about 88–94% efficiency, was able to process waste material at a rate 100 kg / h. The results of the analysis of vitrified materials show that the process is capable of reducing by 95% the volume of residues and makes them inert. The obtained vitreous material can be reused for useful applications. In relation to the sewage sludge, the process costs were estimated: for processing 1kg of dry sewage sludge, having typically moisture up to 10%, the cost is about US\$ 0.13, whereas for a ton of wet sludge, which leads to 200 kg of dry waste, the cost of vitrification would be about US\$ 26.00 / ton.

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thermal plasmas , processes of gasification and combustion to thermal and non-thermal plasmas.

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barrier coatings and functional coatings, Mechanical and Thermal Properties

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NANO STRUCTURES PRODUCTION

RF Plasma Systems for Material Processing

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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 8,000 to 12,000 K. The advantages of ICP torches are well known and described elsewhere. Non-equilibrium plasma is mostly used in the semiconductor industry and for some special applications, such as plasma synthesis of fine powder and bio-material surface treatment. We will focus on the present situation in this field by discussing the commercial and R&D efforts related to RF plasma technology for material processing.

1. Powder Processing. This technology refers primarily to the densification, spheroidization and purification of metal, ceramic and inter-metallic powders. 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 materials and a wide range of particle size.

1.1. RF-Plasma treatment (RFPT) of spray materials. The potential for this market is based on exploiting the well-known advantages of inductive coupled plasma (ICP) system. 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 efficiency and flexibility of RFPT provide the opportunity for the economically viable production of powders with the high degree of densification, spheroidization and purity. RFPT is based on RF power used to create ICP at atmospheric

pressure. Advanced schemes have been developed to increase the heat transfer from the plasma stream to particles by up to 35%. Some of the materials processed include: ZrO_2 , W_2C , WC and WC–Co combinations. Full or partial spheroidization of powders can be achieved by the process. RFPT improves the working characteristics of cermet and coatings such as: hardness, density, bond strength, and wear and corrosion resistance. A typical layout of a basic RFPT installation include: the RF generator, RF plasma torch, reactor and quenching device. The following gases having rates G_p ranging from 0.2 to 5 m^3/Hr has been employed: Ar, O_2 , Air, $\text{Ar} + \text{H}_2$, $\text{N}_2 + \text{H}_2$. 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. An important factor for the thermal treatment of materials is the heat transfer coefficient. For instance, due to high heat transfer, W_2C powder can be spheroidized by RFPT for particle size of 400 microns and higher. A 10 kW RF plasma unit produces dense $\text{W}_2\text{C}/12\%\text{Co}$ at a rate of about 50 lbs per hour. The first commercial RF Plasma Powder Processing plant was designed, manufactured and tested. The plant includes: four industrial 300 kW RF Plasma units, gas and water supply systems. Each plasma unit produces more

1.2. Effect of modulated RF Plasma for powder treatment. One of the important factors to increase the heat transfer between plasma and particles is the modulation of plasma parameters. The modulation of plasma parameters is realized by modulation of the plasma current. RF modulated plasma has been successfully applied to the spheroidization and densification of molybdenum and tungsten. Efficiency of the plasma system was a major subject of research. Frequency and amplitude modulations were optimized for the plasma process. The efficiency of the heating process with modulated plasma is 30% higher.

1.3. RF Plasma technology for densification of Palladium powder. Significant quantities of palladium are consumed in the form of dispersed powder used for the manufacture of conducting or resistive paste for electronics. RF plasma is used to convert a regular palladium powder into a new product with reduced grain boundaries and increased resistance to oxidation. The starting material enters the plasma zone, where the particles are heated. After quenching with liquid argon, the treated powder was collected under the reactor on the surface of the metal-ceramic filter. Sixty particles were analyzed to provide statistically significant measurement. The average particle size for four different samples are: $0.92 \pm 0.25 \mu\text{m}$; $0.93 \pm 0.17 \mu\text{m}$; $0.95 \pm 0.15 \mu\text{m}$; $1.04 \pm 0.3 \mu\text{m}$; some samples included particles greater than $2 \mu\text{m}$. XRD crystalline size is more than 4,000 Angstroms. The dynamics of oxidation when heating in air is an important parameter for Pd powder. Oxidation starts at low temperature (around 250–300 °C) and the Pd starts to transform into PdO. Above 800 °C the PdO dissociates back to Pd metal. The RFPT decreases the TGA by about 36%.

1.4. Nano-powder production.. Using conventional thermal or milling methods to produce nano-powders is technically difficult and economically unattractive. Arc plasma technology due to the erosion of the electrodes results in unacceptable level of impurities. High purity powders with a narrow PSD in the nano-size range are produced by RFP technology. The synthesis of high purity oxides (SiO_2 , TiO_2) and nitrides (Si_3N_4 , TiN) is done by using tetraethylorthosilicate and tetrabutyltitanium as an initial material. The plasma gases used were air, ammonia, oxygen or nitrogen. To synthesize TN and Si_3N_4 powders of Ti and Si are used as the raw material. The process is based on the interaction of vaporized Ti or Si with the ionized nitrogen plasma gas. The purity of the initial materials and the RFP are assured by the content of admixtures less than $10^{-5}\%$. The contaminations are most evident at the filter and packaging stages. The most common impurity is carbon. The TEM results showed the shape of the 70 to 200 nm powder is spherical. The specific surface area (measured by BET) is in the range of 15 to 45 m^2/g . X-ray diffraction shows that TiO_2 is produced in two phases: anatase (30%) and rutile (70%). It is worth noting that only harmless gases are generated in the process, which results in an environmentally clean process.

1.5. Plasma processing of aluminum nano-fuel. Ultrafine aluminum powder with the size range of 300 to 15,000 Angstrom may be produced by electrical explosion of aluminum wire in the hydrogen and argon containing media. However, the electrical explosion procedure of Al powder is not applicable for industrial production of such powder. The powder produced by using RF plasma process has a similar size range, but narrower particle size distribution. Plasma processed aluminum powder can contain approximately 2.2 times more hydrogen than chemically obtained AlH_3 . Oxidation of this hypothetical substance is as follows: $2(\text{AlH}_{6.7}) + 4.85\text{O}_2 = \text{Al}_2\text{O}_3 + 6.7 \text{H}_2\text{O}$. Molecular hydrogen is absorbed on the surface of the melted aluminum particles. The hydrogen then dissociates into atoms and diffuses into the depth of the metal. The atomic nature of hydrogen diffusion in metals was experimentally verified during the research of hydrogen diffusion in a deuterium mixture. A hydrogen saturated aluminum powder with the formula of $(\text{AlH}_{6.7})$, has a theoretical Specific Calorific Power (SCP) more than 20,000 kcal/kg. The technology is based on direct vaporization of powdered aluminum in a RF hydrogen plasma discharge at atmospheric pressure. The resulting matrix is rapidly quenched into ultra-fine aluminum powder. Typical plasma sample content: Al = 51.4%; Total Al = 69.5%; free carbon = 2.15%. SCP for all combustible components is about 21,888 BTU/lb. In order to produce Al particles saturated with hydrogen and interrupt the increase of particle size (i.e. to fix the particle in its meta-stable form) the quenching procedure is required. The A-type samples were obtained as a consequence of quenching of Al powder on a cooled surface. The B-type samples were obtained by volume liquid argon quenching of Al particles. Rapid solidification can be achieved by imposing a high cooling rate ($10^3 - 10^9 \text{ C}^0/\text{sec}$) for the layer thickness not more than 10 microns. The average quantity of captured hydrogen was about 1% to 3.2%.

2. Plasma Sintering. Our interest is especially focused to zirconia nano-crystalline structure modification. It is shown that RF plasma technology is capable to process (sinter) partially and fully stabilized Zirconia in flight without grain growth and binders. Plasma processed Zirconia has a nearly 100% theoretical density. Pre-existing oxidation and contaminants are evaporated during plasma process. This method is especially useful for sintering ceramic dental appliances in minutes, which lead to in-situ fabrication of such appliances directly in dental office.

3. Plasma sterilization of dispersed material. Current methods of decontamination must weigh the level of microbial reduction with the amount of acceptable product degradation. Some current methods affect detriment upon the substrate. For instance, substances with heat-labile active ingredients are prone to degradation when exposed to high heat; the active element in dry and steam is heat treatments. Oxidizing agents, such as, ethylene oxide or sodium hypochlorite can either be reactive toward or be absorbed into the processed material. Cold, low pressure RF plasma (CLPP) was modeled for decontamination of powdered botanicals, such as: hydrilla, stinging nettle leaf, organic wheat grass powder and saw palmetto. Chia seeds were tested as a coarse-material out-group.

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.

Boron Particles Behavior in ICP/RF Plasma

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Existence of boron nitride nanotubes (BNNT) was first predicted back in 1994, but it took another year before first samples were produced [1]. In addition to being a value in fundamental science, BNNT have a wide range of practical applications: adding them to metals, ceramics, polymers, textiles drastically change properties of the composite materials.

Many methods of BNNT synthesis have already been established including, but not limited to: (1) ball-milling annealing methods; (2) catalyst-based chemical vapor deposition (CVD); (3) arc-discharge; (4) laser vaporization.

The perspective method of BNNT production was introduced by Prof. A. Zettl from University of California Berkeley. His recently issued patent [2] offers high temperature plasma application. Zettl group reports production of high-quality boron nitride nanotubes (BNNTs) at continuous production rates of 35 g/h under suitable conditions. The EPIC system immediately generates a fibrous, light-colored, cotton-candy web-like material, which soon occupies the entire cross-sectional area of the synthesis chamber [3]. The EPIC system displays great versatility for tuning synthesis conditions.

In 2012 Applied Plasma Technologies has developed the plasma system APT-60, based on a high-pressure inductively coupled plasma (ICP) or radio-frequency (RF) torch. This patented torch [4]–[6] operated on pure nitrogen at pressures from 1 bar to 7 bar. It's obvious that high-pressure RF plasma has at the moment priority for development of larger scale production units. Similar unit (Fig. 1), based on the APT-100 plasma system with up to 50 kW power in plasma has been developed and successfully tested.



Fig. 1. High-pressure RF plasma system APT-100-2 for BNNT production and new materials synthesis.

Before BNNT synthesis in a high pressure reactor, boron particles should be warmed up and melted in nitrogen plasma inside a special mixing chamber installed right after the torch. The boron heating characteristics will largely depend on aerodynamic structure of the flows in the mixing chamber and on the plasma torch parameters.

For the purpose of a qualitative estimation of a boron particle behavior in nitrogen plasma, we will make the following simplifying assumptions: 1) the processes of phase changes, including sublimation, are not observed; 2) there are no chemical reactions inside the mixing chamber; 3) the plasma-chemical reactions occur in a special reactor after the mixture chamber.

The modeling of physical processes of the boron particles heating up in a mixing chamber is based on solutions of the differential equations of mass, impulse, and energy conservation for a multi-component, turbulent, chemically-reacting system [7]. Coupled discrete phase model (DPM) has been used for two phases calculations. This procedure predicts the trajectory of a discrete phase particle by integrating the force balance on the particle, which is written in a Lagrangian reference frame.

Three-dimensional CFD calculations of the boron particles heating process by nitrogen plasma in the mixing chamber with one and four feeding channels, for different plasma power, boron, and transport gas flow rates have been performed.

The speed and temperature fields in the mixing chamber for plasma power 30 kW (calculated average plasma temperature 6,760 K at nitrogen flow 1.0 g/s) are presented in Fig. 2.

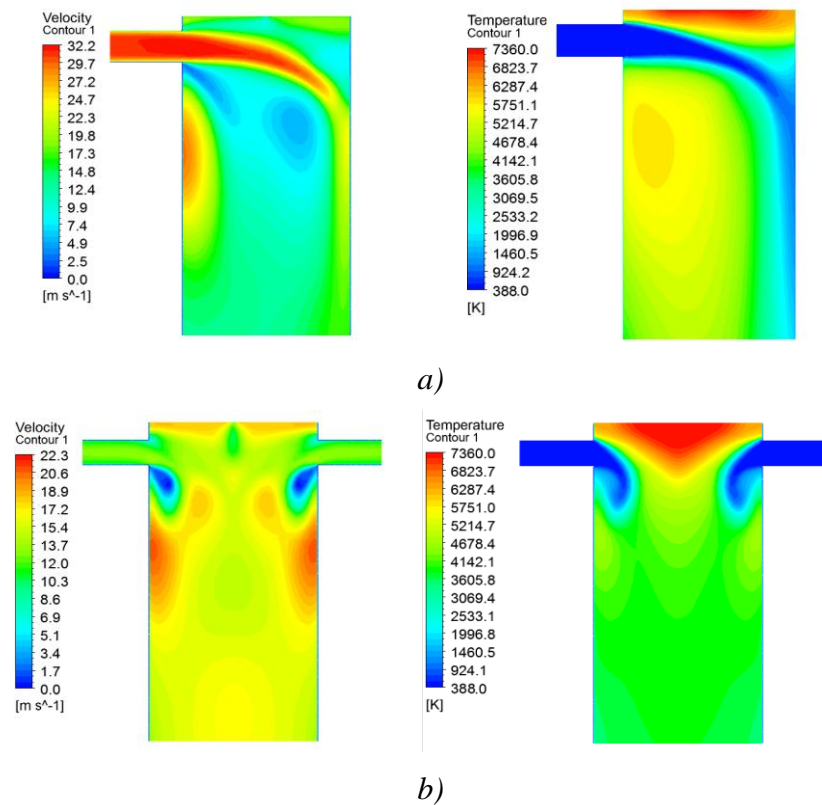


Fig. 2. Speed (m/s) and temperature (K) fields in the mixing chamber (plasma power 30 kW, chamber length 100 mm):

a) – 1 feeding channel; b) – 4 feeding channels

Using of four feeding ports instead of one results in much more uniform distribution of the boron particles inside the mixing chamber volume. The temperature non-uniformity at the mixing chamber outlet could be significantly reduced as well from 33.6-46.7% to 4.6-18.9%.

For plasma gas flow rate of 1 g/s, boron flow of 0.5 and 1.0 g/s the plasma power level of 15 kW does not provide heating of boron particles up to 2,000 K temperature threshold for

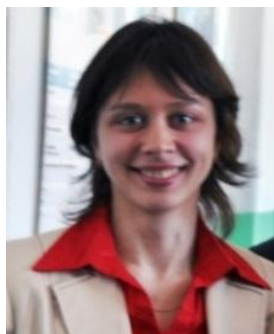
over 55-65% of the particles. It means insufficient treatment mode for boron particles. For uniform particle distribution and operation modes with plasma power 30 kW, plasma gas flow rate of 1 g/s, boron flow of 0.5 g/s and 1.0 g/s, about 90-95% and 86-96% of boron particles, respectively, have temperature over 2,000 K.

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