# 5th International Workshop and Exhibition on Plasma Assisted Combustion (IWEPAC)

**15-18 September 2009**
**Hilton Alexandria Mark Center**
**Alexandria, Virginia, USA**

**Applied Plasma Technologies**
**1729 Court Petit, McLean, Virginia 22101, USA**
**www.plasmacombustion.com**

# General Chair

**Dr. Igor Matveev**
Applied Plasma Technologies
USA
i.matveev@att.net

# Steering Committee

**Dr. Louis Rosocha**
Applied Physics Consulting
USA
plasmamon@msn.com

**Professor Homero Maciel**
Instituto Tecnologico de Aeronautica
Brazil
homero@fis.ita.br

**Dr. Myoungjin Kim**
USA
Kim_myoungjin@cat.com

**Evgeniy Kirchuk**
Ukraine
evgeniy.kirchuk@gmail.com

**Professor Larry Moody**
USA
moodyla5@yahoo.com

Designed and printed by Applied Plasma Technologies

# Contents

Synopsis 5
Tentative Agenda 6

## ABSTRACTS

## PLASMA IGNITION AND FLAME CONTROL

Preliminary Test Results and Modeling of Spark and Plasma Ignition Processes in the Internal Combustion Engines 13
System for Plasma Assisted Combustion in Air-Hydrocarbon Mixtures Based on Non-steady State Plasma 16
Development of Cross-flow Plasma Fuel Nozzles 18
Classification of the Plasma Assisted Combustion Systems 21
An Overview of Plasma Assisted Combustion: History and Applications 24
Near-Zero Emissions Combustor System for Syngas and Biofuels 25

## PLASMA FLOW DYNAMICS AND KINETICS

Complex Improvement of the Gas Turbine Plasma Assisted Combustor Characteristics 27
Theoretical and Experimental Investigations of the Working Processes in a Plasma Assisted Combustor with Spatial Arc 32
Chemical Kinetic Modeling in Coal Gasification Overview 37
On Application of Non-Equilibrium Plasma to Pulverized Coal Conversion 44
Modeling of Plasma Impact on Propane-Air Mixture 46
Features of a Plasma Coal Combustion and Gasification Mathematical Model 49

## FUEL REFORMATION AND ACTIVATION

The Role of in Situ Reforming in Plasma Enhanced Ultra Lean Premixed Methane / Air Flames 53
Non-Thermal Plasma Effects on Coal Gasification 55
A Comparison of Plasmatron and Small Thermal Fuel Reformers 57
Gasification of Oil Shale from Aleksinac Using Plasma Technology. Plasma-Allo-Autothermal Gasification and Plasma Steam Gasification Process Simulation Results 58
Coal Fired Thermo Electric Power Plants without Hazardous Emissions 61
Plasma Coal Gasification Pilot Plant 63
CAT Gas Engines and Challenges for Syngas Application 65

## PLASMA GENERATION, DIAGNOSTICS, AND MODELING

Development and Experimental Investigations of High Power Hybrid Plasma Torches 66

Arc Plasma Torches for RF Plasma Ignition and Other Technological Processes 69

Cavity Ringdown Spectroscopy -- a New Tool to Study Mechanisms of Plasma-Assisted Combustion through Measuring Absolute Number Densities 72

## NEW PLASMA EFFECTS AND PROSPECTIVE APPLICATIONS

Application of Thermal Plasma to Waste Treatment and Energy Recovery 75

High Power Microwave Devices and Their Applications for Solving Technological Problems 76

System for Hydrocarbon Decomposition and Generation of Carbon Nano Tubes Based on Non-self Sustained Microwave Discharge 80

Flame Electrodes for Various Technological Applications 82

Report From the INTAS Project: Hydrogen Production and Safety Promotion by Innovative Processes 83

## BUSINESS FORUM

Cities Without Garbage – Industry Without Waste 84

Journal Publication 86

Plasma Assisted Combustion – 2010 Special Issue Announcement 87

# Synopsis

Among about 110 Plasma Conferences to be held in 2009, IWEPAC is the only one devoted to the field of Plasma Assisted Combustion (PAC), combining an exhibition of operating plasma prototypes and market products, and business forum for industry experts and investors.

Established in 2003, IWEPAC provides a specialized forum for researchers, industry experts and venture capitalists to present and discuss scientific, engineering and marketing aspects of PAC, thereby advancing the field to help address critical energy, propulsion, pollution, and climate issues of the $21^{st}$ century.

IWEPAC-5 will have seven separate sessions: (1) plasma ignition and flame control; (2) plasma generation, diagnostics, and modeling; (3) fuel reformation, activation and gasification; (4) plasma flow dynamics and kinetics, (5) new plasma effects and perspective applications, (6) waste-into-energy processing; and (7) business forum. Each section will be followed by a round table session to facilitate discussions on prospective directions of activity and the creation of international research collaborations for joint project development and implementation, including coal and waste gasification, national plasma centers organization, etc.

IWEPAC-5 is expected to have from 30 to 35 oral presentations (30 minutes in duration, including questions and answers), a half-day exhibition of PAC technology and hardware, and also a half-day Coal Gasification Meeting with at least 10 talks related to the problem of partial and complete coal gasification. The exhibition is a very attractive event within IWEPAC. Participants will be encouraged to demonstrate the operation of technical and engineering prototypes and commercial equipment. Several operating plasma devices, including nano-second rise-time discharge spark plugs, subsonic and supersonic plasma igniters, multi-mode plasma pilots and plasma fuel nozzles, microwave and the $2^{nd}$ generation high power ICP/hybrid type plasma torches with reverse vortex flows, plasma assisted "Tornado" combustors, fuel reformers, and power supplies will be demonstrated at the exhibition area of the IWEPAC-5.

IWEPAC-5 will be held September 15 to 18, 2009 in Hilton Alexandria Mark Center, Juniper Room, 5000 Seminary Road, Alexandria, Virginia 22311, U.S.A. (Washington, D.C. area). During the workshop, we plan to honor new members of the International Council of Experts in the field of PAC, announce new International projects and research teams, provide support to junior scientists, and select papers for publication in the *IEEE Transactions on Plasma Science* Special Issue on Plasma-Assisted Combustion.

IWEPAC-5 proceedings will be available in two formats: color booklet with abstracts and after-meeting DVD. The cost is included in the registration fee.

# IWEPAC – 5
# Tentative Agenda

## Monday, 14 September

| | |
|---|---|
| 16.00 – 18.00 | Registration, Hilton Alexandria Mark Center Lobby<br>5000 Seminary Road, Alexandria, VA 22311, USA<br>Phone: (1-703) 845-1010, fax: (1-703) 845-2610 |

## Tuesday, 15 September

| | |
|---|---|
| 8.30 – 9.00 | Registration, Juniper Room |
| 9.00 – 9.30 | **IWEPAC-5 OPENING**<br>Welcome remarks from:<br>*Dr. Igor Matveev* (Applied Plasma Technologies)<br>*Dr. Louis Rosocha* (Los Alamos National Laboratory, DOE and Applied Physics Consulting)<br>*Dr. Selahaddin Anach* (Turkish Coal Enterprises)<br>Announcements |
| 9.30 – 9.45 | Break |
| 9.45 – 15.00 | **PLASMA IGNITION AND FLAME CONTROL**<br>Chaired by *Dr. Igor Matveev*, Applied Plasma Technologies, USA |
| 9.45 – 10.15 | **Preliminary Test Results and Modeling of Spark and Plasma Ignition Processes in the Internal Combustion Engines**<br>*Dr. Albina Tropina* (Princeton University, USA)<br>*Lonnie Lenarduzzi* (Plasmatronics, LLC, USA) |
| 10.15 – 10.45 | **System for Plasma Assisted Combustion in Air-Hydrocarbon Mixtures Based on Non-steady State Plasma**<br>*Prof. Yu. D. Korolev, O.B. Frants, N.V. Landl, V.G. Geyman, I.A. Shenyakin, A.A. Enenko* (Institute of High Current Electronics, Russia)<br>*Dr. Igor Matveev* (Applied Plasma Technologies, USA) |
| 10.45 – 11.00 | Break |
| 11.00 – 11.30 | **Development of Cross-flow Plasma Fuel Nozzles**<br>*Dr. Igor Matveev, S. Matveyeva, E. Kirchuk* (Applied Plasma Technologies, USA) |

| | |
|---|---|
| 11.30 – 12.00 | **Classification of the Plasma Assisted Combustion Systems**<br>*Dr. Igor Matveev* (Applied Plasma Technologies, USA) |
| 12.00 – 13.30 | Lunch |
| 13.30 – 14.00 | **An Overview of Plasma Assisted Combustion: History and Applications**<br>*Dr. Louis A. Rosocha* (Applied Physics Consulting, Los Alamos, USA) |
| 14.00 – 14.30 | **Near-Zero Emissions Combustor System for Syngas and Biofuels**<br>*Dr. Yong Ho Kim, Dr. Louis Rosocha, Darin Westley* (Los Alamos National Laboratory, DOE, USA)<br>*Prof. Yuri Korolev* (Institute of High Current Electronics, Russia)<br>*Dr. Igor Matveev* (Applied Plasma Technologies, USA)<br>*Craig Cassarino, Ted Frambes* (Leonardo Technologies, Inc., USA) |
| 14.30 – 15.00 | Round Table on Plasma Ignition and Flame Control |
| 15.00 – 15.15 | Break |
| 15.15 – 18.30 | **PLASMA FLOW DYNAMICS AND KINETICS**<br>Chaired by *Prof. Serhiy I. Serbin*, National University of Shipbuilding, Ukraine |
| 15.15 – 15.40 | **Complex Improvement of the Gas Turbine Plasma Assisted Combustor Characteristics**<br>*Prof. Serhiy Serbin, Dr. Anna Mostipanenko* (National University of Shipbuilding, Ukraine )<br>*Dr. Igor Matveev* (Applied Plasma Technologies, USA) |
| 15.40 – 16.05 | **Theoretical and Experimental Investigations of the Working Processes in a Plasma Assisted Combustor with Spatial Arc**<br>*Dr. Igor Matveev, E. Kirchuk* (Applied Plasma Technologies, USA)<br>*Prof. Serhiy Serbin* (National University of Shipbuilding, Ukraine )<br>*Ivan Moralev* (High Temperatures Institute of the Russian Academy of Sciences, Russia) |
| 16.05 – 16.30 | **Chemical Kinetic Modeling in Coal Gasification Overview**<br>*Dr. Nadezhda A. Slavinskaya, D.M. Petrea, U. Riedel* (German Aerospace Agency, Germany) |

| | |
|---|---|
| 16.30 – 16.45 | Break |
| 16.45 – 17.10 | **On Application of Non-Equilibrium Plasma to Pulverized Coal Conversion**<br>*Dr. Sci. Nikolay Ardelyan, Dr. Konstantin Kosmachevskii* (Moscow State University, Russia)<br>*Dr. Sci. Vladimir Bychkov, S.V. Denisiuk, Dr. I.I. Esakov, Prof. K.V. Khodataev, L.P. Grachev, A.A. Ravaev* (Moscow |
| 17.10 – 17.35 | **Modeling of Plasma Impact on Propane-Air Mixture**<br>*Dr. Sci. Nikolay Ardelyan, Dr. Konstantin Kosmachevskii* (Moscow State University, Russia)<br>*Dr. Sci. Vladimir Bychkov, Dr. Dmitri Bychkov, S.V. Denisiuk* (Moscow Radio-Technical Institute, Russia)<br>*Dr. Igor Kochetov* (Troitsk Institute for Innovation and |
| 17.35 – 18.00 | **Features of a Plasma Coal Combustion and Gasification Mathematical Model**<br>*Prof. Serhiy Serbin* (National University of Shipbuilding, Ukraine) |
| 18.00 – 18.30 | Round Table on Plasma Flow Dynamics and Kinetics |
| 18.30 – 20.30 | Welcome Reception (Great Hall) |

Wednesday, 16 September

| | |
|---|---|
| 9.00 – 11.30 | **EXHIBITION**<br>5408 Port Royal Rd., Unit S, Springfield, VA 22151<br>APT Laboratory<br>http://www.plasmacombustion.com/directions.htm<br><br>Transportation from Hilton Alexandria Mark Center provided<br>8.45 – shuttle departure from the hotel to laboratory<br>11.30 – shuttle departure from the laboratory to hotel |
| 12.00 – 13.00 | Lunch |
| 13.00 – 17.15 | **FUEL REFORMATION AND ACTIVATION**<br>Chaired by *Dr. Louis A. Rosocha*, Los Alamos National Laboratory, DOE and Applied Physics Consulting, USA |
| 13.00 – 13.25 | **The Role of in Situ Reforming in Plasma Enhanced Ultra Lean Premixed Methane / Air Flames**<br>*Dr. Wookyung Kim, Dr. M. Godfrey Mungal, Prof. Mark A. Cappelli* (Stanford University, USA) |

| | | |
|---|---|---|
| 13.25 – 13.50 | **Non-thermal Plasma Effects on Coal Gasification**<br>*Dr. Yongho Kim, Dr. Louis Rosocha, Graydon Anderson, Hans Ziock* (Los Alamos National Laboratory, DOE, USA) |
| 13.50 – 14.15 | **A Comparison of Plasmatron and Small Thermal Fuel Reformers**<br>*Prof. V. Yu. Plaksin, O.V. Penkov, S.B. Joa, Prof. H.-Ju Lee* (Jeju National University, South Korea) |
| 14.15 – 14.30 | Break |
| 14.30 – 14.55 | **Gasification of Oil Shale from Aleksinac Using Plasma Technology. Plasma-Allo-Autothermal Gasification and Plasma Steam Gasification Process Simulation Results**<br>*V.E. Messerle* (Ulan-Ude Branch of the Institute of Thermophysics of SB Russian Academy of Sciences, Russia)<br>*A.B. Ustimenko* (Research Department of Plasmotechnics, Kazakhstan)<br>*Z.N. Dragosavljevich* (Serbia)<br>*Dr. Petar Rakin* (IHIS Science & Technology Park Zemun, Belgrade, Serbia) |
| 14.55 – 15.20 | **Coal Fired Thermo Electric Power Plants Without Hazardous Emissions**<br>*V.E. Messerle* (Ulan-Ude Branch of the Institute of Thermophysics of SB Russian Academy of Sciences, Russia)<br>*A.B. Ustimenko* (Research Department of Plasmotechnics, Kazakhstan)<br>*Dr. Petar Rakin* (IHIS Science & Technology Park Zemun, Belgrade, Serbia)<br>*Dejan P. Rakin* (IHIS Science & Technology Center, Belgrade, Serbia) |
| 15.20 – 15.45 | **Plasma Coal Gasification Pilot Plant**<br>*Dr. Igor Matveev* (Applied Plasma Technologies, USA) |
| 15.45 – 16.10 | **CAT Gas Engines and Challenges for Syngas Application**<br>*Dr. Myoungjin Kim* (Caterpillar Inc., USA) |
| 16.10 – 16.25 | Round Table on Fuel Reformation and Activation |
| 16.25 – 16.40 | Break |

| | | |
|---|---|---|
| 16.40 – 18.30 | **PLASMA GENERATION, DIAGNOSTICS, AND MODELING**<br>Chaired by *Prof. Vladimir L. Bychkov*, Moscow State University, Russia |
| 16.40 – 17.10 | **Development and Experimental Investigations of High Power Hybrid Plasma Torches**<br>*Dr. Igor B. Matveev, S. Matveyeva, E. Kirchuk* (Applied Plasma Technologies, USA)<br>*Dr. Sergey Zverev* (Saint-Petersburg State Polytechnic University, Russia) |
| 17.10 – 17.40 | **Arc Plasma Torches for RF Plasma Ignition and Other Technological Processes**<br>*Prof. Vladimir Frolov, Dr. Boris Ushin, Dr. Georgy Petrov, Dr. Sergey Zverev, Dr. Dmitry Ivanov* (Saint-Petersburg State Polytechnic University, Russia) |
| 17.40 – 18.10 | **Cavity Ringdown Spectroscopy -- a New Tool to Study Mechanisms of Plasma-Assisted Combustion through Measuring Absolute Number Densities**<br>*Dr. Chuji Wang* (Mississippi State University, USA) |
| 18.10 – 18.30 | Round Table on Plasma Generation, Diagnostics, and Modeling |

## Thursday, 17 September

| | |
|---|---|
| 9.00 – 12.00 | **PARTIAL AND COMPLETE PLASMA COAL GASIFICATION PILOT PROJECTS**<br>**CONCEPTS, OBJECTIVES, MAIN PARAMETERS, PARTNERS AND COOPERATION**<br>**Open Discussion**<br>Speaker: *Dr. Igor Matveev* (Applied Plasma Technologies, USA)<br>Co-speakers: *Prof. Serhiy Serbin* (Ukraine), *Prof. Vladimir Bychkov* (Russia), *Dr. Albina Tropina* (Ukraine), *Dr. Nadezhda Slavinskaya* (Germany), *Kris Livermore* (USA), *Dr. Myoungjin Kim* (USA), *Dr. Louis Rosocha* (USA)<br>Attendees:<br>The Turkish Coal Enterprises (TKI, Turkey), the Deep Coal Mining Enterprise (Serbia), PyroGenesis Canada Inc. (Canada), the German Aerospace Agency (Germany), Siemens Energy, Inc.(Germany-USA), GE Global Research (USA), Caterpillar Inc. (USA), ICARE-CNRS (France), Princeton University (USA), Moscow State University (Russia), the National University of Shipbuilding (Ukraine), |

| | |
|---|---|
| | Thermatool, Corp. (USA), Los Alamos National Laboratory (USA), Leonardo Technologies, Corp. (USA), the US Department of Energy DOE (USA), Science and Technology Park Zemun (Serbia), St.-Petersburg State Polytechnic University (Russia), LP Amina (USA), Technologia Omega C.A. (Venezuela), Lynntech, Inc. (USA), Allied Grude Purchasing, Inc. (USA), State Enterprise “TORIY” (Russia), Jeju National University (Korea). |
| 12.00 – 13.30 | Lunch |
| 13.30 – 17.15 | **NEW PLASMA EFFECTS AND PROSPECTIVE APPLICATIONS**<br>Chaired by *Dr. Myoungjin Kim*, Caterpillar, Inc., USA |
| 13.30 – 14.00 | **Application of Thermal Plasma to Waste Treatment and Energy Recovery**<br>*Pierre Carabin* (PyroGenesis Canada, Inc., Canada) |
| 14.00 – 14.30 | **High Power Microwave Devices and Their Applications for Solving Technological Problems**<br>*Prof. Oleg Yu. Maslennikov, I. Guzilov, P. Kruglenya* (Federal State Unitary Enterprise “Research and Production Corporation TORIY”, Russia)<br>*J. Gulaev, V. Cherepenin* (Institute of Radiotechnics and Electronics, Russia) |
| 14.30 – 15.00 | **System for Hydrocarbon Decomposition and Generation of Carbon Nano Tubes Based on Non-self Sustained Microwave Discharge**<br>*Prof. Yuriy D. Korolev, O.B. Frants, N.V. Landl, V.G. Geyman* (Institute of High Current Electronics, Russia)<br>*A.G. Zerlitsyn, V.P. Shiyan, Yu.V. Medvedev* (Institute of Nuclear Physics, Russia) |
| 15.00 – 15.15 | Break |
| 15.15 – 15.45 | **Flame Electrodes for Various Technological Applications**<br>*Prof. V. Yu. Plaksin, O.V. Penkov, S.B. Joa, Prof. H.-Ju Lee* (Jeju National University, South Korea) |
| 15.45– 16.15 | **MicGAS Biotechnology - a holistic approach of converting coals for economical clean fuels, safer foods, pollution filter while reducing carbon foot print**<br>*Dr. Daman Walia* (ARCTECH, Inc., USA) |
| 16.15 – 16.45 | **Report From the INTAS Project: Hydrogen Production and Safety Promotion by Innovative Processes**<br>*Dr. Iskender Gokalp* (ICARE-CNRS, France) |

| | |
|---|---|
| 16.45 – 17.15 | Round Table on New Plasma Effects and Perspective Applications |
| 17.15 – 18.30 | Meetings, discussions, negotiations, entertainment |

Friday, 18 September

| | |
|---|---|
| 9.00 – 11.00 | **BUSINESS FORUM**<br>Chaired by *Dr. Louis A. Rosocha*, Los Alamos National Laboratory, DOE and Applied Physics Consulting, USA |
| 9.00 – 9.30 | **Cities Without Garbage – Industry Without Waste**<br>*Dr. Petar Rakin* (IHIS Science & Technology Park Zemun, Belgrade, Serbia)<br>*Dejan P. Rakin* (IHIS Science & Technology Center, Belgrade, Serbia)<br>*Dr. Igor Matveev* (Applied Plasma Technologies, USA) |
| 9.30 – 10.00 | **Future of High Power Plasma Generation Systems**<br>*Dr. Igor Matveev* (Applied Plasma Technologies, USA) |
| 10.00 – 10.30 | **Benefits and Market for the Plasma Assisted Combustion Systems**<br>*Dr. Igor Matveev* (Applied Plasma Technologies, USA) |
| 10.30– 11.00 | Round Table<br>Conference Closing |
| 11.00 – 16.00 | **DISCUSSIONS, NEGOTIATIONS, OPTIONAL ADDITIONAL PROTOTYPES DEMONSTRATION AT THE APT LABORATORY** |

# Preliminary Test Results and Modeling of Spark and Plasma Ignition Processes in the Internal Combustion Engines

*Albina Tropina, Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, USA*

*Lonnie Lenarduzzi, Chief Scientist Plasmatronics, LLC, USA*

The optimization of internal combustion engine operation including the efficiency increase as well as toxicity reduction strongly depends on the combustion process. On its turn the proper organization of ignition process as the first step in a combustion process has great impact on the flame kernel development and as a consequence on the whole combustion process. As an alternative to spark ignition the plasma ignition systems based on pulsed corona discharge [1] or nanosecond discharge [2] are used. Previous studies of nanosecond discharge based ignition system "Plasma Drive" showed that it considerably reduced tailpipe emissions compared with the standard spark-ignition system. This study presents the results of pressure measurements in 1.3 liter 4-cylinder engine operating natural gas and gasoline and equipped by the standard spark-ignition system and the plasma ignition system (the PDI) for different engine load conditions (100% load corresponds to M=96 N×m at n=3000 RPM and M=101 N×m at n=3500 RPM). The indicator diagrams measured for engine operation on natural gas, for n=3500 RPM and for one and multi-electrode spark plugs are presented in Fig. 1.

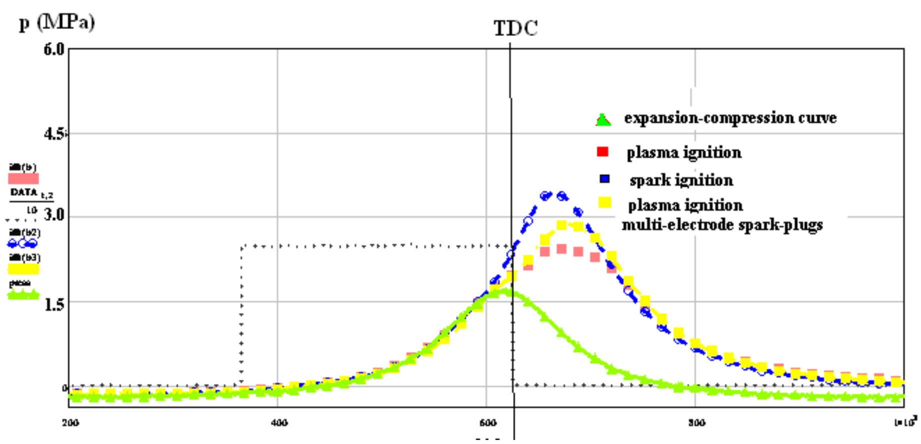



*Fig. 1. The indicator diagrams measured for engine operation on natural gas, n=3500 RPM*

It was obtained that the ignition delay time increased with the PDI used and as a consequence of non-optimal ignition timing the maximum pressure values in the combustion chamber decreased. The situation is improved by using the multi-electrode spark-plugs but anyway to improve engine performance using nanosecond discharge based ignition system the necessity of varying the standard computer ignition timing is indicated. Due to limited literature data of the nanosecond discharge ignition properties at high pressures typical for the internal combustion engines the chemical mechanisms of ignition delay increase obtained are not quite clear and need additional investigations.

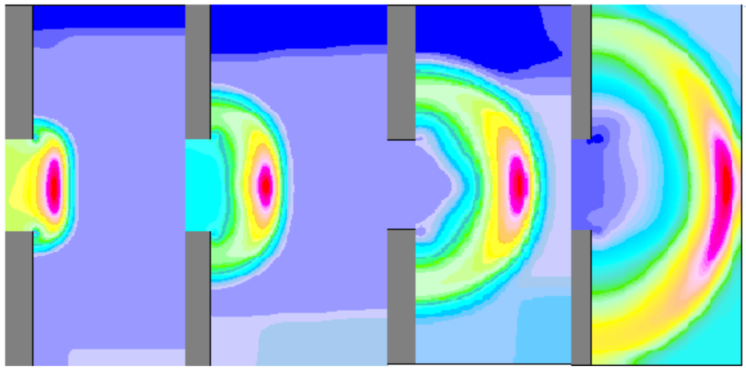


*Fig. 2. The pressure traveling wave at different moments* $t = 1 \div 6 \mu s$

The coupling between gas-phase processes and discharge was modelled by joule heating source term with the electric conductivity as the function of gas temperature. Detailed reactions mechanism for methane-air mixture consisting of 53 species and 325 elementary reactions according to GRI-MECH 3.0 mechanism of high temperature methane oxidation [3] was used. The initial properties of plasma channel shortly after breakdown was used. The calculations have been carried out for the conditions corresponding to an ignition process initiation in the internal combustion engines operating on natural gas accordingly to the indicator diagrams measured. The details of calculation procedure based on the conjugate problem solution when the calculation domain includes as anode, cathode, plasma channel with the zones of effective conductivity adjacent to electrodes and surrounding neutral gas mixture have been presented in [4]. Shortly after breakdown the properties of plasma channel and flow field are determined by pressure wave formed. The development of pressure wave is presented in Fig. 2, where transition of the expanding channel from cylindrical to spherical configuration is clearly visible. The pressure maxima decreases very fast that is typical for cylindrical expanding waves. The intensity of such pressure decrease is higher and the wave velocity is lower that for the case of spark ignition at atmospheric pressure and for laminar gas flow [5]. Due to plasma channel cooling process the kinetic energy of the radial flow transforms into the energy of turbulent pulsations, except the part of energy that transforms into heat due to dissipation processes. Such turbulence generated can cause the flame extinction especially for the case of lean mixture combustion. It was obtained that the main reasons of such extinction are as low spark energy as well as intensive turbulent vortices formed near electrodes edges. The delay time obtained was compared with the data of the experimental indicator diagrams and has shown good agreement.

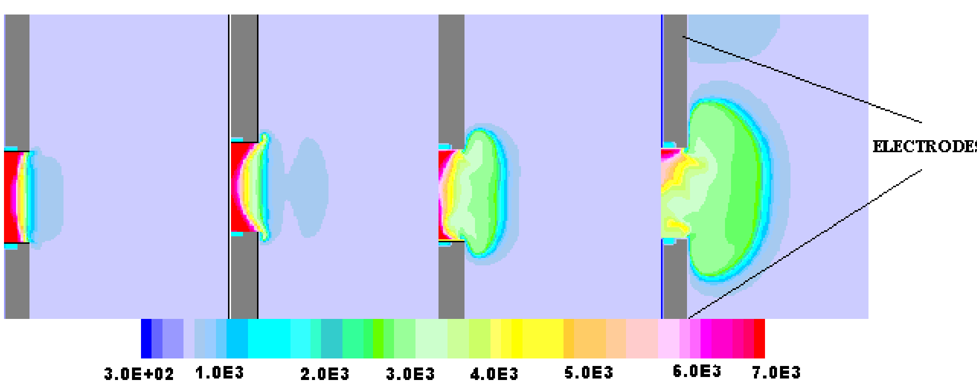



*Fig. 3. The temperature distribution at different moments*

**Acknowledgments.** This work has been supported by the Fulbright grant of U.S. Department of State.

**References**

1. Memarzadeh S., Colgrove J., Ronney P.D. *Transient plasma discharge ignition for internal combustion engines.* Abstracts of IWEPAC-3, 18-21 Sept. 2007, Falls Church, USA, p.47.
2. Lenarduzzi L. *Plasma ignition system for internal combustion engines "Plasma Drive".* Abstracts of IWEPAC-4, 16-19 Sept. 2008, Falls Church, USA, p.13.
3. Smith G.P., Golden D.M., Frenklach M., et al. *GRI-MECH 3.0 mechanism of high temperature methane oxidation*, http://www.me.berkeley.edu/gri_mec.
4. Matveev I., Tropina A., Serbin S., Kostyuk V. *Arc modelling in a plasmatron channel*.- IEEE Trans. on Plasma Sci. .- 2008. - vol. 36. - pp. 293-298.
5. Thiele M., Selle S., Riedel U., Warnatz J., Mass U. *Numerical simulation of spark ignition including ionization.* - Proc. of the Comb. Institute. – 2000. - vol. 28 .- pp. 1177-1185.

***Albina A. Tropina** graduated from the Kharkov National University (Ukraine), the Mathematical and Mechanical faculty and received the Ph.D. Degree in Mechanics of liquids, gas and plasma in 1999. From 1990 to 1999 she was a Researcher, an Assistant Professor with Kharkov National University. Since 2000 she has been working with Kharkov National Automobile and Highway University as Senior Lecturer, Associate Professor on the department of mechanics and hydraulics. She is currently a Fulbright Scholar in the Department of Mechanical and Aerospace Engineering at Princeton University. Her research interests are focused on the theoretical investigation of plasma-assisted combustion and combustion processes in engines.*

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

# System for Plasma Assisted Combustion in Air-Hydrocarbon Mixtures Based on Nonsteady State Plasma Torch

*Yu. D. Korolev, O. B. Frants, N. V. Landl, V. G. Geyman, I. A Shemyakin, A. A. Enenko, Institute of High Current Electronics, Tomsk, Russia*

*Dr. Igor Matveev, Applied Plasma Technologies, McLean, USA*

This paper describes the experiments with the plasma assisted combustion systems as applied to gaseous hydrocarbons. The system is based on nonsteady-state gas-discharge plasmatron with a low average current [1, 2]. The schematic of an experimental installation is shown in Fig. 1. The air/fuel composition is used up partly as a result of burning directly in the plasmatron nozzle. The rest of the composition burns in the combustion chamber 3. In case of necessity, we can add an air or air/fuel mixture directly into the chamber as Fig. 1 shows. Then the torch flame forms in the chamber. An inner diameter of the combustion chamber is 78 mm and its length is 300 mm. The total expenditure of air/fuel composition in the system is up to 5 g/s.

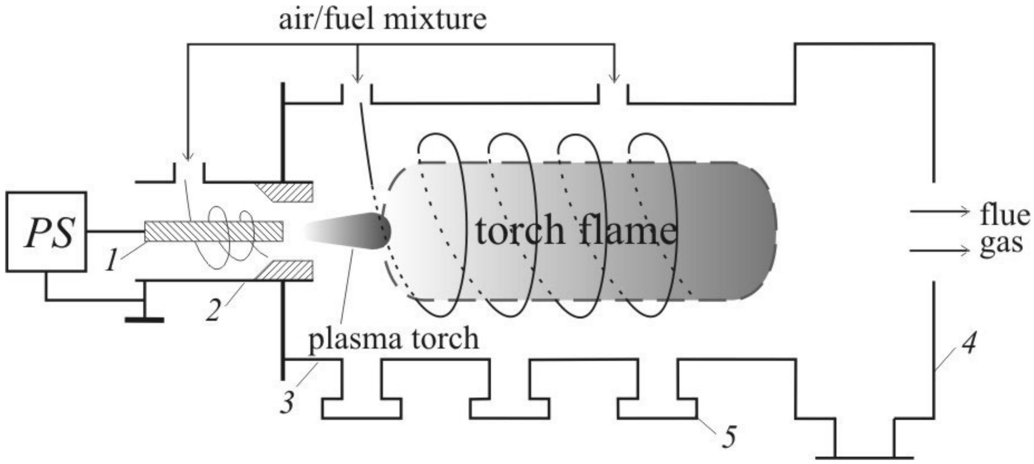



*Fig. 1. Schematic of a system for plasma assisted combustion.*
*1 - inner electrode of a nonsteady-state plasmatron (cathode); 2 - grounded outer electrode of plasmatron (anode); 3 - combustion chamber; 4 - unit for flue gas diagnostics; 5 – auxiliary windows*

Depending on the gas discharge regimes and plasmatron design, the conditions of complete hydrocarbons combustion and partial oxidation have been demonstrated. The regions of external parameters that characterize different regimes of the propane burning are shown schematically on diagram in Fig. 2. Correspondingly, Fig. 3 shows the photographs of the plasma torch at different conditions of the propane oxidation.

The area *1* spans the conditions of high propane or high air percentage in mixtures. The discharge is sustained mainly in air ($\alpha >> 1$) or mainly in propane ($\alpha << 1$). In both cases, we can speak of a non-complete propane oxidation here. As for the area *2*, the process of partial propane oxidation in the plasma torch takes place and this process determines the torch surface appearance. However, the propane combustion is sustained if only the discharge exists in plasmatron. If we switch the plasmatron power supplier off, the burning process ceases.

The area *3* is distinctive due to the following reason. The propane completely burns in the plasma torch in these conditions. The torch has a surface appearance shown in Fig. 3 for α ≈ 1. When we switch off the plasmatron power supplier, the burning process does not stop and the green color flame at the exit is running in a regime of self-sustaining.

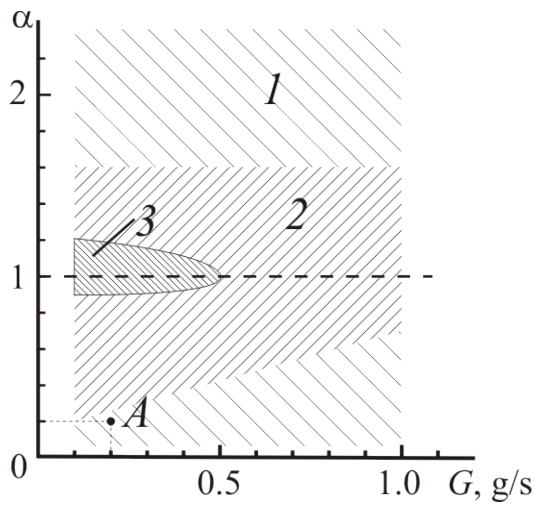



*Fig. 2. Schematic diagram demonstrating different regimes for sustainment of the plasma torch at plasmatron exit*

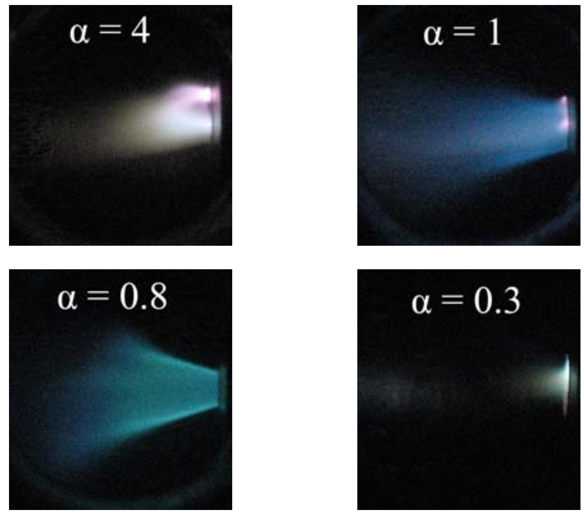



*Fig. 3. Photographs of plasma torch generated by plasmatron for G = 0.2 g/s. Voltage of power supplier $V_0$ = 3 kV, ballast resistor $R_b$ = 13.5 kΩ*

The photographs of the torch flame are shown in Fig. 4. Most illustrative case if the mixture that flows across the plasmatron nozzle has an excess of propane. In particular, the point *A* in Fig. 2 is related to the conditions of α = 0.2. It is evident that there is a shortage of air for propane oxidation. When airflow is additionally delivered via the feedpipe on the chamber wall, the torch flame arises inside the chamber 3. With total a value close to stoichiometric blend, the complete oxidation of propane is provided. It is also remarkable that at α ≈ 1 it becomes possible to switch the power supplier off and the burning process in the torch flame continues to be sustained.

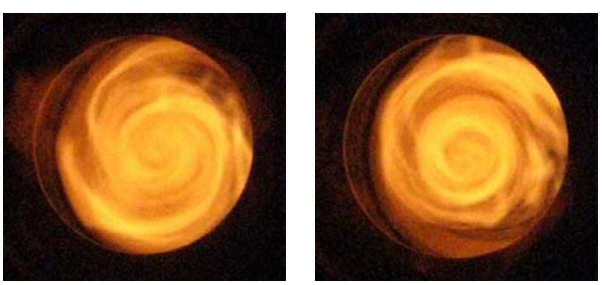


*Fig. 4. Photographs of the torch flame in the coditions when the air is additionally delivered via the chamber wall. The total α value takes into account the airflow across the plasma-tron nozzle and the feedpipe in the chamber wall α= 1.3 (left), α = 0.95 (right)*

**References**


1. Ombrello, T, Qin, X., Ju, Y., Gutsol, A., Fridman, A. and Carter, C., *Combustion Enhancement via Stabilized Piecewise Non-equilibrium Gliding Arc Plasma Discharge*, AIAA Journal, Vol. 44, No. 1, 2006, pp. 142-150.
2. Ombrello, T., Ju, Y., and Fridman, A., *Kinetic Ignition Enhancement of Diffusion Flames by Non-Equilibrium Magnetic Gliding Arc Plasma*, AIAA Journal, accepted, in

# Development of Cross-flow Plasma Fuel Nozzles

*Dr. Igor Matveev, S. Matveyeva, E. Kirchuk,*
*Applied Plasma Technologies, McLean, USA*

Gaseous and liquid feedstock gasification technologies require development of new atomizing and mixing devices with preferably integrated ignition and flame control options [1 - 2]. The report of some results of engineering and experimental investigations of such three-in-one units named plasma fuel nozzles (PFN), is a subject of this presentation.

Fuel atomizers for the fuel rich reactors operate in some cases in environment with relatively low process pressure and the reagents flow velocities. This leads to difficulties with mixing, cooling, and process sustaining, and results in higher residence time, and the final products insufficient uniformity. So, nozzles for the gasifiers, and particularly with liquid feedstock, should differ from nozzles for conventional gas turbines and burners [3]. Among the main requirements for the PFN could be the follows:

- Low input fuel pressure – by 5 to 10 bar (72 to 145 psig)
- Fuel flexibility – operation on both gaseous and liquid fuels
- Presence of the atomizing media channel (air, fuel gas, steam, etc.)
- Fine atomizing – droplet sizes ≤ 30 μm
- Efficient atomizing – supporting air to fuel ratio ≤ 3
- Integrated low temperature and low power plasma source (Ne ≤ 500 W) with affordable life time (over 1,000 running hours)
- Total number of independent channels ≥ 3.

The developed variety of the PFN prototypes could be divided onto two groups: (1) with direct fuel injection into the plasma channel and (2) with independent fuel injection. The first group demonstrates relative design simplicity and efficiency, i.e. less electric power per unit of the fuel flow rate, but in some cases needs more precise pressure and flow control and distribution. The second group could be also divided into sub-groups depending on the fuel atomizer design, as: (a) centrifugal, (b) air supported, (c) with porous atomizer, and (d) cross flow atomizer. This group looks more promising for the liquid fuel gasifiers and chemical reactors due to the almost independent operation of each channel, wider operation range by the reagents flow, composition, and plasma power.

The authors present results of engineering and experimental investigations of over 10 PFN modifications with flow rates 0.2 – 4 g/s per channel for both gaseous and liquid fuels. These PFN were tested with plasma gas air, oxygen, and air/propane/methane blends; such fuels as methane, propane, and diesel; with atomizing media as air, water steam, and fuel gas. The PFNs with cross flow channels are shown in Fig. 1. The tests have been performed in open air, as in several modifications of the reverse vortex combustor with total air flow by 20 g/s (see Fid. 2). They showed that the developed line of the PFN satisfies major initial requirements, could be further scaled up, and adjusted to a variety of commercial applications, including chemical reactors, gasifiers, special burners, propulsion systems, and prospective gas turbines.

*Fig. 1. PFN modifications with the cross flow channels*

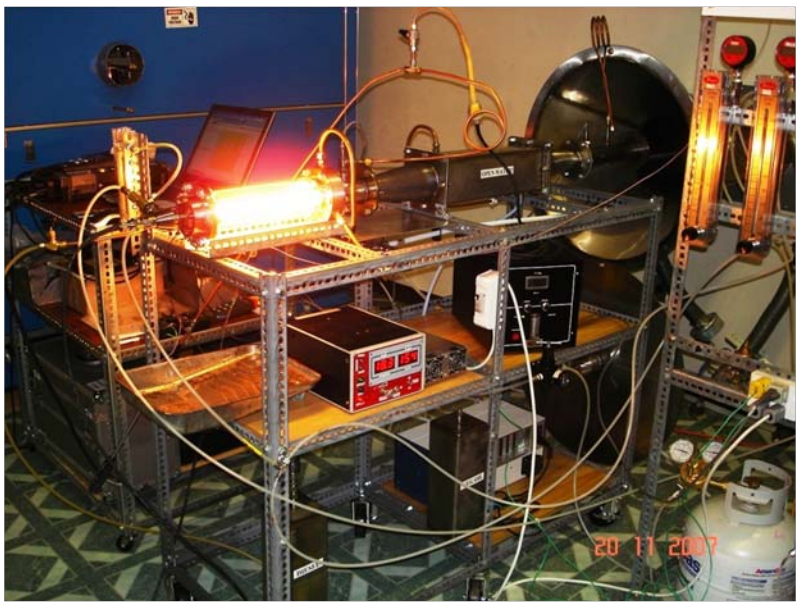
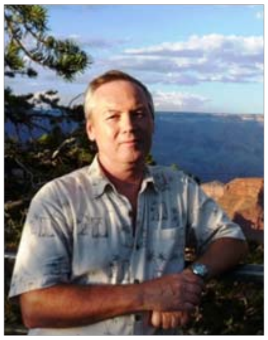



*Fig. 2. Diesel fuel reactor operation with a cross flow PFN*

**References**


1. I. Matveev, S. Serbin, *Experimental Investigation of the Hybrid Type Plasma Assisted Combustion and Reformation System*, *4*-th Int. Workshop and Exhibition on Plasma Assisted Combustion, Falls Church, Virginia, 2008, pp. 61–63.
2. I. Matveev, S. Serbin, K. Serbina, *Theoretical Investigation of the Physical and Chemical Processes in a Liquid Fuel Plasma Assisted Reformer*, 4-th Int. Workshop and Exhibition on Plasma Assisted Combustion, Falls Church, Virginia, 2008, pp. 64–67.
3. I. Matveev, S. Serbin, S. Lux, *Efficiency of a Hybrid-Type Plasma-Assisted Fuel Reformation System,* IEEE Trans. Plasma Sci., vol. 36, no. 6, pp. 2940-2946, Dec. 2008.



***Igor Matveev** was born in Russia on February 11, 1954. He earned his Master of Science degree in mechanical engineering from Nikolaev Shipbuilding Institute, Nikolaev, Ukraine, in 1977 and his Ph.D. degree in 1984. His Ph.D. thesis was entitled "Development and Implementation of The Plasma Ignition Systems for Naval Gas Turbines." From 1977 to 1990 he was a Researcher, Teacher and Associate Professor with the Nikolaev Shipbuilding Institute. In 1990 Dr. Matveev established a privately owned company Plasmatechnika (Ukraine) for development and mass production of plasma systems. Over 1,200 plasma systems developed under his supervision are in operation worldwide. In 1996 he was awarded the title "Citizen of the Year" in his native city. From 2000 to 2002 he served as an international consultant for the UN Economic Commission for Europe in energy and water conservation. During that time the UN project established the Energy and Water Conservation Zones in Ukraine, Kazakhstan, and Kyrgyzstan. Since 2003 he is with Applied Plasma Technologies, McLean, VA, as President and CEO. Since 2004 Dr. Matveev has been a guest editor for the IEEE Plasma Assisted Combustion special issue and the organization committee chair for the 2$^{nd}$, 3$^{rd}$, 4$^{th}$, and 5$^{th}$ International Workshop and Exhibition on Plasma Assisted Combustion (IWEPAC).*

***Svetlana Matveyeva** – MS in mechanical engineering, graduated from the Moscow Technical University named after Bauman. Specialized in robotics design including electric, hydraulic, pneumatic, and mechanical systems. Also studied manufacturing of specialized aircraft and space systems. Has over 25 years of intensive expertise in development of the plasma assisted combustion systems, including plasma torches, plasma pilots and nozzles, and reverse vortex combustors.*

***Evgeniy Kirchuk** was born in Ukraine on July 2, 1977. He earned his Master of Science degree in electrical engineering from Nikolaev Shipbuilding Institute, Nikolaev, Ukraine, in 2000.*

*Since 2003 he has been a manager of Plasma Technika Consult – the APT strategic partner in Ukraine. He served as a technical secretary for the 2$^{nd}$, 3$^{rd}$, 4$^{th}$, and 5$^{th}$ International Workshop and Exhibition on Plasma Assisted Combustion (IWEPAC).*

# Classification of the Plasma Assisted Combustion Systems

*Dr. Igor Matveev,*
*Applied Plasma Technologies, McLean, USA*

Recent progress in research and development of the plasma based technologies for ignition and combustion enhancement in propulsion, power generation, and gasification systems has led to the formation of a new field of science known as the plasma assisted combustion (PAC). With the first known practical efforts in the early 60-s of the 20-th century the PAC systems' developers and investigators have engineered a list of technologies, which could be divided onto several groups, including the following:

- Plasma igniters;
- Plasma pilots and flame sustainers;
- Plasma fuel nozzles;
- Fuel reformers and gasifiers.

*Fig. 1. Plasma Igniter*

**Plasma igniters** are the most developed units for short-term operation (up to several minutes) mainly based on thermal DC torches, RF and MW initiators for sub- and supersonic flows [1-2]. Over 1,200 plasma ignition systems are in operation worldwide, including land-based gas turbines and furnaces. They normally replace spark plugs and have power consumption from 500W to 1 kW, plasma gas flow rate of up to 1 g/s and a lifetime up to 4,000 operating cycles. The main advantage of a plasma igniter in comparison to a conventional spark plug is in the much bigger plasma plume volume and velocity. This allows deeper penetration of a highly reactive plasma plume into a combustion zone for more reliable ignition. One of the plasma igniters for industrial gas turbines in operation is demonstrated in Fig. 1.

There are several known approaches for ignition in high-speed cross flows specifically for the aerospace propulsion systems and scramjets. Among the perspective solutions are radiofrequency (RF) and microwave (MW discharges, as far as non-thermal torches with a fuel feeding into the arc chamber. Recently developed by Applied Plasma Technologies (APT) the supersonic torch based on transient glow to spark discharge is shown in Fig. 2.

*Fig. 2. Supersonic Plasma Igniter*

**Plasma pilots and flame sustainers** are in the second group of the plasma devices with two main functions – ignition and continuous flame control. The market requirements of continuously operating in a high temperature environment with variable pressure pilots and flame holders have moved researches to development of non-thermal plasma sources with a significantly extended lifetime and less power consumption, pulse power devices, direct arc initiators, and MW initiators. Known plasma pilots operate within the average powerrange of up to 300-500 W, at pressure by 10-15 bar, and provide continuous operation by 1,000 running hours. One of the most perspective MW systems for

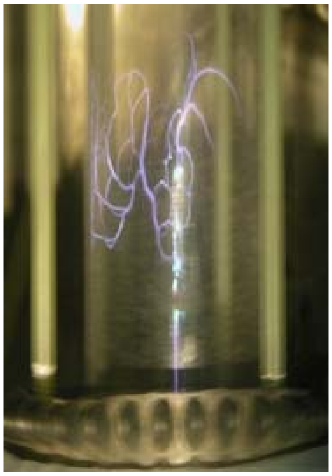


*Fig. 3. Subcritical streamer MW discharge in a reverse vortex combustor*

ignition and flame control in a reverse vortex combustors has been developed by Moscow Radio Technical Institute and is presented in Fig. 3.

Spatial arc is one of the recently patented by APT applications of a non-thermal high voltage discharge in a form of orbiting inside a combustion chamber source of ignition and flame control. Employing the combustor walls as the electrodes, this arc with average power consumption from 10 W to 1 kW provides simple and energy efficient solution for gas fired furnaces and combustors, particularly lean-burned ones. A photo of one of the lab-scale combustor prototypes with low power spatial arc is provided in Fig. 4.

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

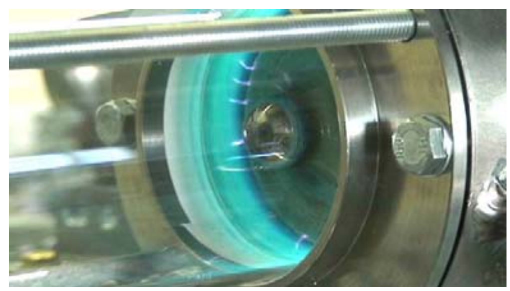


*Fig. 4. Reverse vortex combustor with 10W spatial arc*

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

*Fig. 5. Appearance of a plasma fuel nozzle for gaseous fuels*

**Fuel reformers and coal gasifiers.** There are numerous publications devoted to fuel reformation, waste and coal gasification. It could be seen from the published manuscripts that the main obstacle in the way of the full-scale gasification technologies development and implementation is the absence of the energy efficient plasma sources with affordable lifetime and operation costs. For example, existing coal ignition and partial gasification technology employs 100-200 kW DC torches limited by 200 running hours of a cathode lifetime. A similar situation occurs with all other plasma torches on the market. This means that any progress in this direction will be caused by the development of a new generation of high power atmospheric pressure plasma sources and power supplies. Based on known plasma generation solutions the authors have selected for further development and implementation a hybrid type (RF + DC) plasma torch with reverse vortex flow [3], which could provide the atmospheric pressure plasma reactors operation in supplies. Such a solution allows an unlimited lifetime of both electrical and plasma generation modules and a high caloric value of a syngas as a final product based on oxygen gasification process also based on recently developed air separation technology. The maximum achieved power level per unit is 1.8 MW and expected 10 MW.

### References


1. I. Matveev, S. Matveeva, E. Kirchuk, *Plasma Assisted Combustion Technologies*, 4-th European Combustion Meeting, Vienna, 14-17 April 2009, p. 22.
2. I. Matveev, S. Matveeva, E. Kirchuk, *Non-thermal Plasma Igniter for High-Speed Flow*, 47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition, 5 - 8 January 2009, Orlando, Florida, AIAA-2009-1556.
3. I. Matveev, S. Serbin, *Preliminary Design and CFD Modeling of a 1 MW Hybrid Plasma Torch for Waste Destruction and Coal Gasification*, 2-nd Int. Workshop and Exhibition on Plasma Assisted Combustion, Falls Church, Virginia, pp. 43–44, 2006.


***Igor Matveev*** *was born in Russia on February 11, 1954. He earned his Master of Science degree in mechanical engineering from Nikolaev Shipbuilding Institute, Nikolaev, Ukraine, in 1977 and his Ph.D. degree in 1984. His Ph.D. thesis was entitled "Development and Implementation of The Plasma Ignition Systems for Naval Gas Turbines." From 1977 to 1990 he was a Researcher, Teacher and Associate Professor with the Nikolaev Shipbuilding Institute. In 1990 Dr. Matveev established a privately owned company Plasmatechnika (Ukraine) for development and mass production of plasma systems. Over 1,200 plasma systems developed under his supervision are in operation worldwide. In 1996 he was awarded the title "Citizen of the Year" in his native city. From 2000 to 2002 he served as an international consultant for the UN Economic Commission for Europe in energy and water conservation. During that time the UN project established the Energy and Water Conservation Zones in Ukraine, Kazakhstan, and Kyrgyzstan. Since 2003 he is with Applied Plasma Technologies, McLean, VA, as President and CEO. Since 2004 Dr. Matveev has been a guest editor for the IEEE Plasma Assisted Combustion special issue and the organization committee chair for the 2nd, 3rd, 4th, and 5th International Workshop and Exhibition on Plasma Assisted Combustion (IWEPAC).*

# An Overview of Plasma Assisted Combustion: History and Applications

*Louis A. Rosocha, Applied Physics Consulting &*
*Los Alamos National Laboratory, Los Alamos, USA*

The application of electric fields to flames has been studied at least as far back as 1814, was applied to flame combustion in the 1920's and was further developed into several applications in the last half of the 20th Century. When the electric field strength is sufficient to cause electrical breakdown of a fuel or fuel/air mixture, plasma effects will dominate. Plasma effects can increase electron and ion temperatures and promote combustion through the formation of 'active' species (such as free radicals) or the dissociation of fuel molecules into smaller, more-easily combusted fragments.

Plasma-assisted combustion (PAC) is now a timely topic worldwide, possibly having applications that can allow more efficient fossil-fuel usage, the conversion of low-grade fuels into higher-grade fuels, and the reduction of pollution through ultra-lean burn combustion. This presentation focuses on non-equilibrium ("cold" or "non-thermal") plasma applications to combustion, particularly for enhancing combustion stability, efficiency, and reducing undesirable emissions. This is in contrast to equilibrium ("hot" or "thermal") plasmas (e.g., spark plugs, plasma jets/torches). However, a brief overview of a subset of thermal plasmas will be briefly discussed, mainly in connection with a joint project between the Los Alamos National Laboratory and the Institute of High Current Electronics in Tomsk, Russia.

This talk will present a brief historical background on electric field and plasma effects on combustion and will then discuss non-equilibrium plasmas, as mainly applied to combustion stability, efficiency, and pollution reduction in more detail. Plasma-based ignition will be covered to a lesser extent because it is considered a specialized, although important, topic within the PAC field. This presentation is not meant to be a detailed review of the subject of plasma-assisted combustion, but will present selected examples from the literature and will primarily focus on work carried out by the author and collaborators that will provide examples of non-equilibrium plasma applications to combustion enhancement.

***Louis A. Rosocha*** *received the B.S. degree in physics from the University of Arkansas (Fayetteville) in 1972. He received the M.S. and Ph.D. degrees in physics, with a minor in chemistry, from the University of Wisconsin (Madison) in 1975 and 1979, respectively. From 1978-1981, he was with the National Research Group of Madison, Wisconsin, where he assisted in the development of pulsed ultraviolet lasers and fast pulsed- power switchgear, and lead a project on the modeling of commercial ozone generators. From October 1981 – January 2008, he was a technical staff member and manager at the Los Alamos National Laboratory. Over the course of his career, he has worked on plasma chemistry, large inertial fusion gas laser systems, relativistic electron beam sources, pulsed power, and non-thermal plasma processing. His current research interests are focused on plasma-assisted combustion and pollution abatement and chemical synthesis using plasmas.*

*He organized the 1st International Workshop on Plasma-Assisted Combustion in 2003, and co-organized the 2nd event in 2006.*

*Dr. Rosocha is now an independent consultant and his current R&D interests are focused on two of the most important problems of our time: $CO_2$ sequestration/global warming and national energy security (improving combustion, the efficiency of engines/fuels, and the conversion of trash into 'green' energy).*

# Near-Zero Emissions Combustor System for Syngas and Biofuelds

*Yongho Kim, Louis A. Rosocha, Darin Westley,*
*Los Alamos National laboratory, Los Alamos, USA*

*Yuri Korelev, Institute of High Current Electronics, Tomsk, Russia*

*Igor Matveev, Applied Plasma Technologies, McLean, USA*

*Craig Cassarino, Ted Frambes, Leonardo Technologies, Inc., USA*

Recently, a multi-institutional plasma combustion team was awarded a research project from DOE/NNSA GIPP (Global Initiative for Proliferation Prevention) office. The Institute of High Current Electronics/Tomsk (based in Russia); the Leonardo Technology LLC (an American-based USIC partner), in conjunction with the Los Alamos National Laboratory participate in the project to develop novel plasma assisted combustion technologies. The purpose of this project is to develop prototypes of marketable systems for more stable and cleaner combustion of syngas/biofuels and to demonstrate that this technology can be used for a variety of combustion applications – with a major focus on contemporary gas turbines. The research team's ultimate goals are to adapt and commercialize their novel, Plasma-Assisted Tornado Combustion system technology for use on contemporary gas-turbine engines operating on syngas/biofuels.

The project covers the following interrelated tasks.

**Task 1.** Investigation of non-steady state gas discharge in the systems for ignition and flame stabilization: The subject of this Task is the investigation of high-pressure gas discharges in air-hydrocarbon, air-biofuel mixtures in the systems for ignition and flame stabilization. The experiments will be carried out with a use of installations based on different type of plasmatrons for combustion sustainment and on Tornado chambers.

**Task 2.** Development and construction of power supplies for driving non-steady state discharges: The main direction of activity in the framework of Task 2 is to develop and construct the power supplies for the plasmatrons that are will be used in the Tornado combustion systems.

**Task 3.** Investigation of a high-frequency one-electrode torch discharge as applied to the combustor systems: This task is concentrated on a usage of a special type of gas discharge for sustainment the combustion (so called one-electrode high-frequency torch discharge). This discharge is capable to generate both equilibrium and non-equilibrium plasma torch in a rather high range of average power (from hundred of watts to tens of kilowatts).

**Task 4**. Computer modeling of the gas dynamic and plasma chemical processes in the systems for ignition and flame stabilization: The computer simulation of the gas discharge and plasma chemical processes will cover the main units of the systems for plasma assisted combustion, namely: the plasmatrons, the tornado chambers, the unit for generation of one-electrode high-frequency torch discharge, and the output unit of the system (pyrolysis chamber).

The research team anticipates the development of plasma assisted high pressure multi-fuel turbine technology for electricity generation. The technology to be developed is intended to promote cleaner, more energy-efficient synthesis gas and biofuel utilization, thereby benefiting the environment and national energy security.

***Yongho Kim*** *Dr. Kim is a technical staff member in Plasma Physics Group (P-24) at LANL. He has been at P-24 for the past five years working on nuclear fusion and plasma technology, which both are directed to national energy and homeland security. Nuclear fusion technology includes 1) fusion gamma-ray detector development for National Ignition Facility and 2) neutron generator development for detecting special nuclear materials. Plasma technology includes 1) plasma assisted combustion, 2) plasma catalyzed coal gasification, and 3) atmospheric pressure plasma jet. Dr. Kim, the winner of a 2005 Distinguished Performance Award at LANL for novel applications of atmospheric-pressure, non-thermal plasmas, received the B.S., M.S., and Ph.D. degrees in nuclear engineering from Seoul National University, Seoul, Korea, in 1994, 1996, and 2002, respectively. He was awarded the Best Student Prize at $4^{th}$ Asia-Pacific Conference on Plasma Science and Technology held in Sydney in 1998. In 2002, he joined with Korea Institute of Machinery & Materials, where he worked on the plasma-SCR system for after-treatment of 300-hp diesel engine exhaust. Since 2003, he has been worked for the P-24 in Los Alamos. He has written twelve first-authored papers in peer-reviewed journals and one US patent. He has been a member of the Institute of Electrical & Electronics Engineers (IEEE). He serves as a reviewer for the IEEE Transactions on Plasma Science.*

# Complex Improvement of the Gas Turbine Plasma Assisted Combustor Characteristics

*Serhiy Serbin and Anna Mostipanenko*
*National University of Shipbuilding, Mikolayiv, Ukraine*

*Igor Matveev, Applied Plasma Technologies, McLean, USA*

The main requirements for combustors of the modern gas turbines are effectiveness, reliability, affordable life time, low emission, and high stability of operation. We believe in the possibility to satisfy these restrictions for toxic components emission by the development of low-emission combustors, in which burning of lean fuel-air mixtures occurs. This lean burn combustion provides a decrease of the flame temperature up to 1950-1970 K, a reduction of the chemical reacting zone, and accordingly a decrease of $NO_x$ emission. The essential disadvantage of such a combustor type is the limited air access coefficient operation range. It is possible to eliminate this imperfection by using either an additional diffusion jet-flame, which could support combustion, or by using plasma assisted combustion systems [1-4]. A 25 MW gas turbine combustor was chosen as a subject for investigation. In this device the principle of the partially premixed lean gas-air mixture burning is realized [5-8]. It is known for this gas turbine that the uniformity of a temperature field in the output combustor cross section at a full load operation reaches 22 %, and values of the $NO_x$ emission 20-36 ppm. Besides, lack of effective cooling of the outlet flame tube mixer and a high temperature level near the walls may lead to the appearance of the combustion instabilities.

The analyses of these phenomena were carried out using the 3D-computational modeling of the combustion processes.

The results of numerical experiments show:

- Lack of secondary air in the combustor's mixing zone. As a result the secondary streams do not provide effective and uniform dilution of the combustion products and do not penetrate enough into the hot flame cone in radial direction;
- The air excess coefficient for the inner swirler of the flame tube is 1.39. This increases maximum mixture temperature in the combustor up to 2340 K, and creates favorable conditions for the formation of thermal nitric oxides and hot flame cone in the flame tube;
- The air excess coefficient for the peripheral swirler of the flame tube is 2.3. This value in combination with a barrier cooling system may have a negative impact on the carbon monoxide emission rate and stability of the burning process, and lead to the appearance of the pulsations;
- A cooling system of the investigated chamber was not designed rationally, and this leads to increased temperature of the flame tube mixer wall.

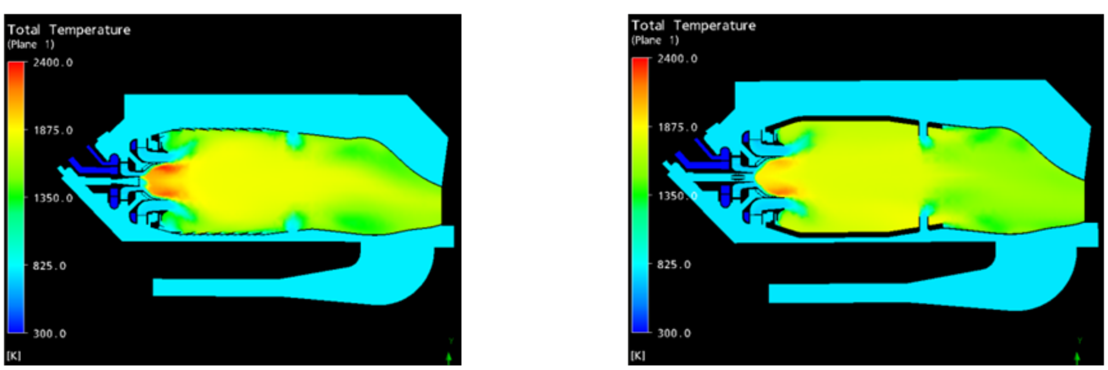
The results of the 3-D numerical experiments were used to offer directions of the combustor improvements, including the following:

- Simultaneous decrease of the air excess coefficient for the peripheral swirler up to 2.1 and increase of the air excess coefficient for the inner swirler up to 1.6-1.7. This allows reduce maximum temperature of the working medium inside the combustor and nitric oxides emission, and enhances the combustor's stability;

• Optimization of the wall cooling system with the aim of the air mass flow rate reduction up to 10 %;
• Decrease of the secondary air mass flow rate and provide it's rational supply into the mixing zone;
• Application of a plasma assisted system for the combustion processes stabilization in the flame tube for the entire range of operating conditions.
• To implement the proposed improvements the following changes in the basic serial flame tube design were suggested:
• Increase cross section of the secondary air orifices. This will allow to increase the relative secondary air mass flow rate from 15.7 up to 19.4 %;
• Place special liners in the secondary air holes to enhance the air streams penetration into the mixing zone;
• Replace the barrier cooling system of the flame tube on the convective one. This could allow to reduce the relative cooling air mass flow rate from 11.4 up to 10.2 %;
• Redirect air flow from annular channel of the convective cooling system into the flame tube through a butt aperture behind the first raw of the secondary air holes and through the gaps around the liners placed on the secondary air holes;
• Increase cross area of the peripheral swirler vane channel by increasing height of the swirler blades and their rotation on 1.5° Similarly increase cross area of the peripheral swirler exit cross section;
• Place a plasma pilot into the central channel of the inner swirler for additional flame stabilization in the combustion zone.

Three-dimensional calculations of the processes in a modified gas turbine combustor gave a number of results and showed significant improvements of the combustor's temperature distributions and ecological characteristics.

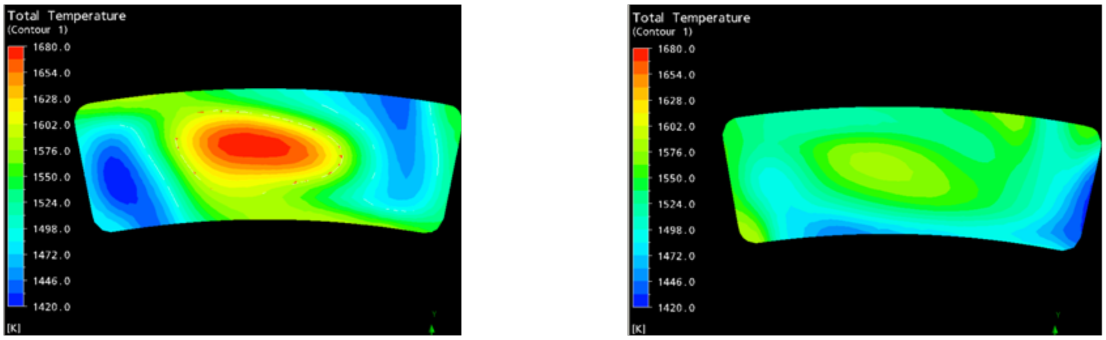
1. The maximum temperature level of the combustion products (Fig. 1) decreased by 190 degrees (from 2340 up to 2150 K), and as the result the calculated $NO_x$ emission reduced from 16 to 1 ppm with the conservation of the carbon monoxide emission. Note that the experimental value of the nitric oxides emission for the base operation mode was 20 ppm. Conformity of the numerical and experimental data may prove that the emission of harmful components will significantly decrease in real conditions. It is possible to reduce the nitric oxides emission by the factor of two with keeping CO on the same level.




*a)* *b)*

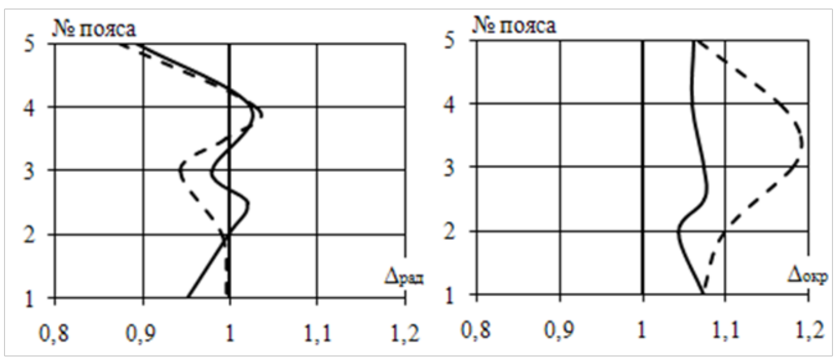
*Fig. 1. Temperature field in the combustor: a – basic case; б – modification*

2. The total air flow rate for the flame tube cooling could be reduced by the application of the convective cooling system. As a result of the secondary air flow rate increase and its deeper penetration into the flame tube by using of special liners in conjunction with reduction of the temperature level, the tangential temperature variation in the outlet cross section decreases from 19 up to 8.6 % (Fig. 2, 3).



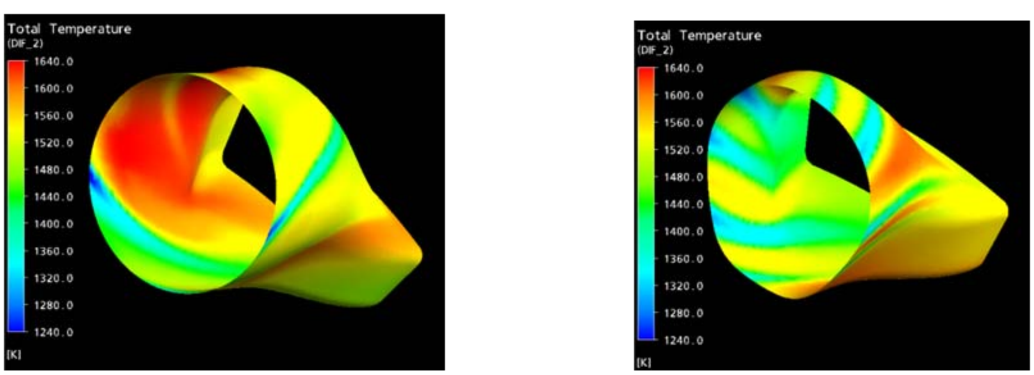

*a)* *b)*

*Fig. 2. Temperature field in the combustor outlet cross section :*
*a – basic case; b – modified*




*a)* *b)*

*Fig. 3. Temperature field variation in the combustor outlet cross section :*
*a – radial (average); b – tangential (maximum);* ——— *- basic case;* - - - *- modified*




*a)* *b)*

*Fig. 4. Temperature field near the inner wall of the outlet mixer: a – basic case; б – modified*

3. The combustor's stability thresholds expand considerably due to a plasma pilot stabilization in the lean fuel-air mixture burning conditions.
4. The temperature field near the walls of the flame tube mixture becomes more favorable as the result of dividing of the secondary air holes onto two rows and cooling air redirect from the convective cooling system annular channel (Fig. 4).
5. Total pressure losses in a modified combustor slightly decreased to 5.72 % for improved design from 6.11 % in the basic case.

**References**

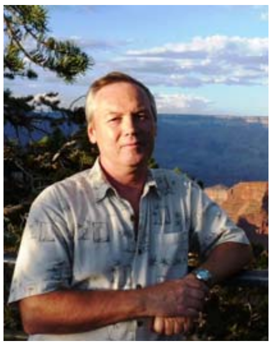

1. Matveev, I., Serbin, S., *Experimental and Numerical Definition of the Reverse Vortex Combustor Parameters*, 44th AIAA Aerospace Sciences Meeting and Exhibit, 9-12 January 2006, Reno, Nevada, AIAA-2006-0551.
2. Matveev, I., United States Patent 7,452,513 B2 "Triple Helical Flow Vortex Reactor", issued Nov. 18, 2008.
3. Matveev, I., *United States International Publication Number WO 2008/122849 A2 for "Powerplant and Method Using a Triple Helical Vortex Reactor",* 16.10.2008.
4. Matveev, I., Serbin, S., Mostipanenko, A., *Numerical Optimization of the "Tornado" Combustor Aerodynamic Parameters*, 45th AIAA Aerospace Sciences Meeting and Exhibit, 8-11 January 2007, Reno, Nevada, AIAA 2007-391.
5. Bondin, J.I., Michajlov, A.B., *The main results of the pilot exploitation of GTE DN80L on "Sofievskaja" Compression Station*, Marine and energetic gas turbine building, Vol. 1, GTR&PC "Zorya-Mashproekt", 2004, Nikolaev, p. 7–16.
6. Mostipanenko, A.B., *Ecological safety increasing of the gas turbine units by means of technology of low-emission fuel combustion technology*, Scientific study collection of NUS, №1 (412), 2007, Mykolayv, p. 100-108.
7. Budanova, N.A., Vantsovskiy, V.G., Korotich, E.V., *Development of the low-emission combustion chambers for the gas turbine engines DN70, DN80, DB90,* Marine and energetic gas turbine building, Vol. 1, GTR&PC "Zorya-Mashproekt", 2004, Nikolaev, p. 31-35.
8. Serbin, S.I., Mostipanenko, A.B., *Development of the mathematical model of toxic components formation in combustors of the stationary gas turbine units*, Scientific studies of MSHU, № 49(36), 2006, Mykolayv, p. 38-44.


***Serhiy Serbin*** *was born on April 29, 1958, in Mykolayiv, Ukraine. He received his M.S. (Dipl. Mech. Eng.) and Ph.D. (Cand. Sc. Tech.) degrees in mechanical engineering from the Mykolayiv Shipbuilding Institute, Ukraine, in 1981 and 1985, respectively, and the Dipl. D. Sc. Tech. and Dipl. Prof. degrees from the National University of Shipbuilding, Ukraine, in 1999 and 2002, respectively.*

*Since 1984, he has been working with the Ukrainian State Maritime Technical University as an Assistant Professor, Senior Lecturer, and Associate Professor. Since 1999, he has been working with the National University of Shipbuilding as a Professor of Turbine Units Department. His research interests are plasma-chemical combustion, the techniques of intensifying the processes of hydrocarbon-fuels ignition and combustion in power engineering, combustion and plasma processes modeling.*

*Dr. Serbin is the Academician of the Academy of Shipbuilding Sciences of Ukraine and International Academy of Maritime Sciences, Technologies and Innovations.*

***Anna Mostipanenko** was born on August 13, 1981, in Mykolayiv, Ukraine. She received her M.S. (Dipl. Mech. Eng.) degree in mechanical engineering from the Ukrainian State Maritime University, Ukraine, in 2004.*
*Since 2004, she has been working in the National University of the Shipbuilding as an Assistant of Turbine Units Department. At the same time she had been a postgraduate student until June 2009.*
*Her research interests are combustion and plasma processes modeling, the techniques of intensifying the processes of hydrocarbon-fuels ignition, and combustion in power engineering.*



***Igor Matveev** was born in Russia on February 11, 1954. He earned his Master of Science degree in mechanical engineering from Nikolaev Shipbuilding Institute, Nikolaev, Ukraine, in 1977 and his Ph.D. degree in 1984. His Ph.D. thesis was entitled "Development and Implementation of The Plasma Ignition Systems for Naval Gas Turbines." From 1977 to 1990 he was a Researcher, Teacher and Associate Professor with the Nikolaev Shipbuilding Institute. In 1990 Dr. Matveev established a privately owned company Plasmatechnika (Ukraine) for development and mass production of plasma systems. Over 1,200 plasma systems developed under his supervision are in operation worldwide. In 1996 he was awarded the title "Citizen of the Year" in his native city. From 2000 to 2002 he served as an international consultant for the UN Economic Commission for Europe in energy and water conservation. During that time the UN project established the Energy and Water Conservation Zones in Ukraine, Kazakhstan, and Kyrgyzstan. Since 2003 he is with Applied Plasma Technologies, McLean, VA, as President and CEO. Since 2004 Dr. Matveev has been a guest editor for the IEEE Plasma Assisted Combustion special issue and the organization committee chair for the 2nd, 3rd, 4th, and 5th International Workshop and Exhibition on Plasma Assisted Combustion (IWEPAC).*

# Theoretical and Experimental Investigations of the Working Process in Plasma Assisted Combustor with Spatial Arc

*Igor B. Matveev, Applied Plasma Technologies, McLean, USA*

*Serhiy Serbin, National University of Shipbuilding, Mikolayiv, Ukraine*

*Ivan Moralev, Institute for High Temperature of the Russian Academy of Sciences, Moscow, Russia*

*Evgeniy Kirchuk, Plasma-Technika-Consult, Mikolayiv, Ukraine*

There is an opportunity to improve dramatically a combustor's parameters by employing several innovations. They are as follows: 1) reverse-vortex flow, which provides cold walls and eliminates the compressed air need for their cooling, significantly widens flammability limits, and provides more options for fuel selection [1-5]; 2) plasma arc (initiated inside a combustor in the form of spatial arc) for energy efficient and reliable ignition and continuous flame control [1-4]. A reverse-vortex plasma assisted combustor (RVPAC) has been developed and preliminary tested on the basis of the Applied Plasma Technologies patents and patent applications [1, 6, 7].

The scheme of the RVPAC system is presented in Fig. 1. It consists of a quarts combustor with an internal diameter of 73 mm and length of 300 mm providing optical access to the process, the primary and auxiliary bottom swirlers, and the exhaust tube. The main air is supplied through the primary swirler with a constant flow rate. A spatial arc plasma generator is installed on the bottom part of the combustor. The air-fuel mixture is injected directly through

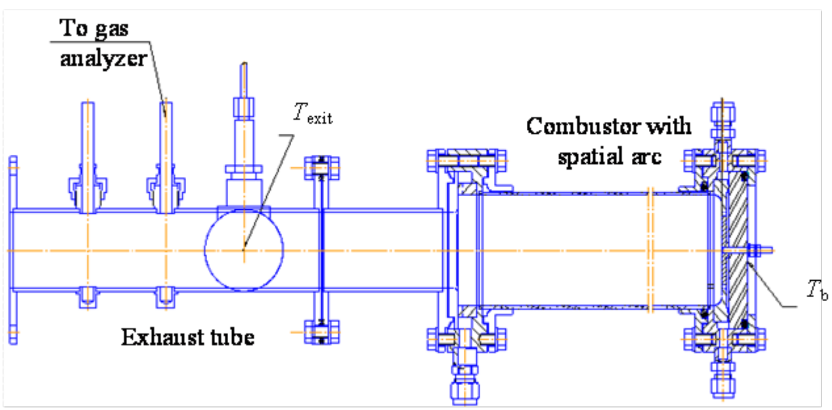



*Fig.1. Plasma assisted combustion system*

For this design excitation of a rotating spatial arc in a fuel feeding zone ensures conditions for thermal, kinetic, and turbulent influence of plasma discharge on the processes of mixing, ignition and burning. Excitation of the spatial arc is provided by a high-voltage (up to 30 кV) power supply having a capability for power control from 10 to 200 W. Because of the low power arc, no visible erosion of electrodes was observed (central cathode and casing), even after several hours of operation.

Passive optical spectroscopy was used to study the features of the combustion processes. Spectra were acquired by 3-channel Avantek spectrometer with spectral resolution 0.2-0.4 nm.

The fiber optic tip was mounted on a 2D moving stage. Spatial resolution was varied in different experiments from 0.25 to 1 cm. The following parameters were extracted from spectra: average gas temperature (from continuous spectra fitting), peak flame temperature (from molecular bands fitting), average air excess coefficient in the flame (from relative intensity of molecular bands), and combustion zone length (from OH band intensity distributions).

A number of numerical simulations for the RVPAC were made to investigate the influence of electric arc on chemical processes inside the combustor. In the 3D CFD-calculations the RNG $k$-$\varepsilon$-model of turbulence, multistage reactions of propane burning, segregated solver, steady formulation, pressure-velocity coupling are used taking into consideration the influence of the turbulent pulsations on kinetics within the framework of Eddy Dissipation Concept (EDC).

The EDC combustion model was chosen for the prediction of chemical species distribution inside the RVPAC. The EDC model is an extension of the eddy-dissipation model to include detailed chemical mechanisms in turbulent flows. It assumes that reaction occurs in small turbulent structures, called the fine scales. Species are assumed to react in the fine structures over a time scale. Combustion at the fine scales is assumed to occur as a constant pressure reactor, with initial conditions taken as the current species and temperature in the cell. The reactions proceed over the time scale governed by the Arrhenius rates of equation for the molar rate of creation/destruction of species and are integrated numerically using the ISAT algorithm.

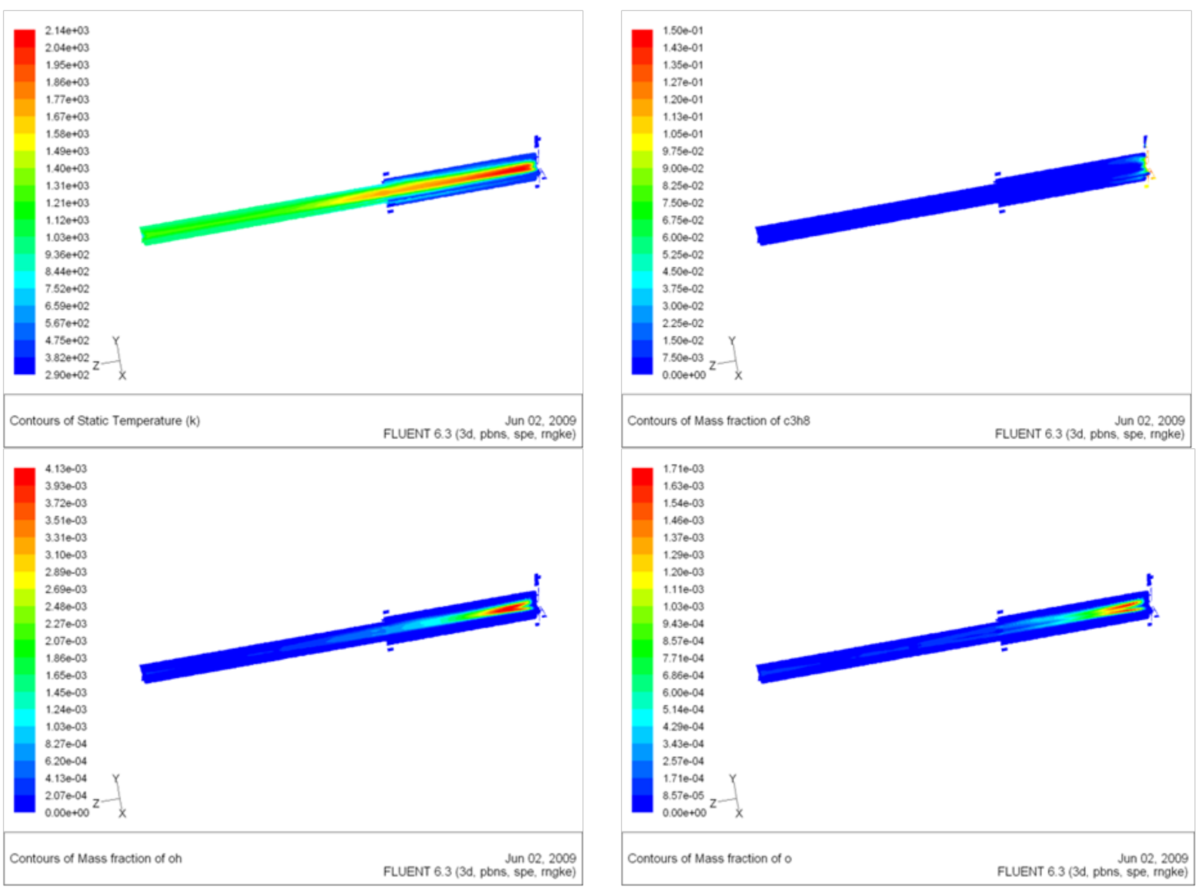



*Fig. 2. Contours of temperature and species mass fractions*

For the comparison of theoretical and experimental data numerical simulations of the RVPAC with spatial arc are carried out. The operating conditions are the following: primary air mass flow rate through the tangential swirler 18.202 g/s, air mass flow rate through the auxiliary bottom swirler 2.791 g/s, propane consumption 0.3938 g/s.

Fig. 2 shows the contours of static temperature, $C_3H_8$, OH and O mass fractions in the combustor volume. Note that gaseous propane was injected into spatial arc channel together with plasma feedstock air**.** Therefore their preliminary mixing has been ensured.

During the conducted experimental tests primary (ensuring a reverse stream inside a combustor) air flow rate was kept constant and equal to 18.3 g/s, air flow rate through the bottom vortex generator varied from 0 to 4.6 g/s, and propane consumption changed from 0.31 to 0.56 g/s, spatial arc power was nearly 156 W.

OH intensity distributions were measured at 3.5 cm combustor radius with a spatial resolution of 1 cm. Typical curves are presented in Fig. 3, where $\lambda_b$ is the air excess coefficient in the bottom swirler. A significant shortening of the combustion zone is obtained only for regimes with rich mixture in the vicinity of the combustor bottom.

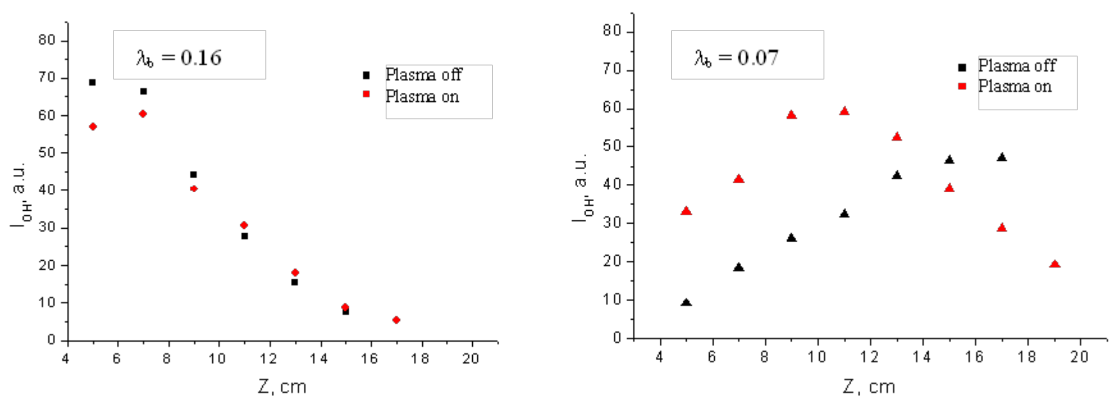



*Fig. 3. OH intensity distributions along the flame (total air excess coefficient $\lambda_\Sigma$ = 2.5)*

Air excess coefficients λ in the combustion zone were measured by means of passive spectroscopy. Results are presented in Fig. 4. It can be seen that mixture in combustion zones become lean in the observable region with $\lambda_b = 0.35$.

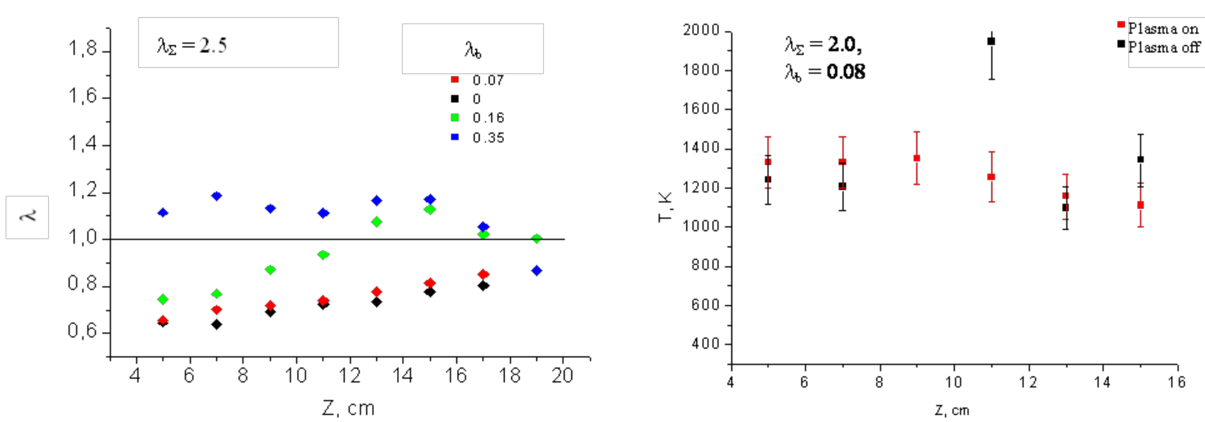



*Fig. 4. Air excess coefficient and average plume temperature along the combustor axis*

It is revealed that a spatial arc inside combustor allows the rich flame to stabilize. It leads to a shortening of the combustion zone, a slight decreasing of CO emission and an increasing of the combustion completeness up to several percents. Plasma assistance in this case allows to retard the rich blowout inside the combustor.

**References**


1. Matveev, I., *United States Patent 7,452,513 B2 "Triple Helical Flow Vortex Reactor",* issued Nov. 18, 2008.
2. Matveev, I., Matveeva, S., Gutsol, A., Fridman, A., *Non-Equilibrium Plasma Igniters and Pilots for Aerospace Application,* 43d AIAA Aerospace Sciences Meeting and Exhibit, 10- 13 January 2005, Reno, Nevada, AIAA-2005-1991.
3. Matveev, I., Serbin, S., *Experimental and Numerical Definition of the Reverse Vortex Combustor Parameters,* 44th AIAA Aerospace Sciences Meeting and Exhibit, 9-12 January 2006, Reno, Nevada, AIAA-2006-0551.
4. www.plasmacombustion.com
5. Matveev, I., Serbin, S., Butcher, T., Tutu, N., *Flow Structure investigation in a "Tornado" Combustor*, 4th International Energy Conversion Engineering Conference and Exhibit (IECEC), 26-29 June 2006, San Diego, California, AIAA 2006-4141.
6. Matveev, I., *United States Patent Application Publication for a "Triple Helical Flow Vortex Reactor Improvements"*, US 2009/0050713 A1, Feb. 26, 2009.
7. Matveev, I., *Applied Plasma Technologies, International Publication Number WO 2008/122849 A2 for "Powerplant and Method Using a Triple Helical Vortex Reactor",* 16.10.2008.


***Igor Matveev*** *was born in Russia on February 11, 1954. He earned his Master of Science degree in mechanical engineering from Nikolaev Shipbuilding Institute, Nikolaev, Ukraine, in 1977 and his Ph.D. degree in 1984. His Ph.D. thesis was entitled "Development and Implementation of The Plasma Ignition Systems for Naval Gas Turbines." From 1977 to 1990 he was a Researcher, Teacher and Associate Professor with the Nikolaev Shipbuilding Institute. In 1990 Dr. Matveev established a privately owned company Plasmatechnika (Ukraine) for development and mass production of plasma systems. Over 1,200 plasma systems developed under his supervision are in operation worldwide. In 1996 he was awarded the title "Citizen of the Year" in his native city. From 2000 to 2002 he served as an international consultant for the UN Economic Commission for Europe in energy and water conservation. During that time the UN project established the Energy and Water Conservation Zones in Ukraine, Kazakhstan, and Kyrgyzstan. Since 2003 he is with Applied Plasma Technologies, McLean, VA, as President and CEO. Since 2004 Dr. Matveev has been a guest editor for the IEEE Plasma Assisted Combustion special issue and the organization committee chair for the 2nd, 3rd, 4th, and 5th International Workshop and Exhibition on Plasma Assisted Combustion (IWEPAC).*

***Serhiy Serbin*** *was born on April 29, 1958, in Mykolayiv, Ukraine. He received his M.S. (Dipl. Mech. Eng.) and Ph.D. (Cand. Sc. Tech.) degrees in mechanical engineering from the Mykolayiv Shipbuilding Institute, Ukraine, in 1981 and 1985, respectively, and the Dipl. D. Sc. Tech. and Dipl. Prof. degrees from the National University of Shipbuilding, Ukraine, in 1999 and 2002, respectively.*

*Since 1984, he has been working with the Ukrainian State Maritime Technical University as an Assistant Professor, Senior Lecturer, and Associate Professor. Since 1999, he has been working with the National University of Shipbuilding as a Professor of Turbine Units Department. His research interests are plasma-chemical combustion, the techniques of intensifying the processes of hydrocarbon-fuels ignition and combustion in power engineering, combustion and plasma processes modeling.*

*Dr. Serbin is the Academician of the Academy of Shipbuilding Sciences of Ukraine and International Academy of Maritime Sciences, Technologies and Innovations.*

***Ivan Moralev*** *was born on 12 February 1985 in Moscow, Russia. He graduated from Moscow Institute of Physics and Technology (MIPT) in 2007.*
*Since 2004 he has been working at the Institute for High Temperatures RAS on the problems of PAC and discharge flow control. Recently he became a PhD student of IHED RAS.*
*His recent main interests are discharge-based flow control, vortical flows and laser-based diagnostics in aerodynamics and combustion.*

***Evgeniy Kirchuk*** *was born in Ukraine on July 2, 1977. He earned his Master of Science degree in electrical engineering from Nikolaev Shipbuilding Institute, Nikolaev, Ukraine, in 2000.*
*Since 2003 he has been a manager of Plasma Technika Consult – the APT strategic partner in Ukraine. He served as a technical secretary for the 2nd, 3rd, 4th, and 5th International Workshop and Exhibition on Plasma Assisted Combustion (IWEPAC).*

# Chemical Kinetic Modeling in Coal Gasification Overview

*Dr. Nadezhda A. Slavinskaya, Dr. D. M. Petrea*
*German Aerospace Agency, Institute of Combustion Technology, Stuttgart*

Coal gasification (partial coal combustion), Fig. 1, is rather a complicated process coupled with two-phase turbulent flow, heat transfer, combustion and gasification. Next physical and chemical processes occur in the coal gasifier: heating and evaporation of coal particles; devolatilization of volatile material; the char combustion (heterogeneous/porous oxidation) or gasification; the gas phase reaction/oxidation (homogeneous oxidation) of gaseous products from coal particles. Heterogeneous/ homogeneous oxidation is described with reaction models according to the surrounding environment (air, $O_2$, $CO_2$, $H_2O$, $H_2$) used in the coal gasifier.

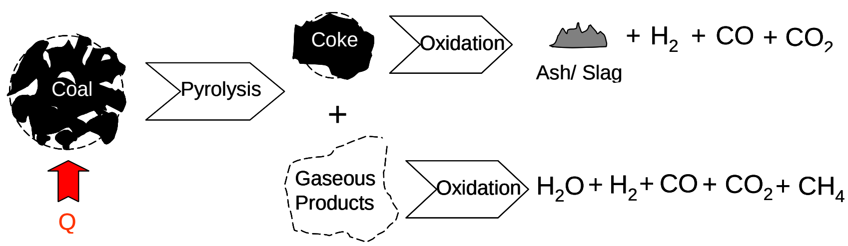



*Fig. 1. Principal scheme of coal gasification*

A complete description of coal gasification is not possible, due to the complexity of interaction of physical and chemical processes. At plasma assisted coal gasification the modeling becomes even more complicated. However, based on experiments and simplified mechanisms, this process can be divided into several sub-models, which can be studied separately, Fig. 2.

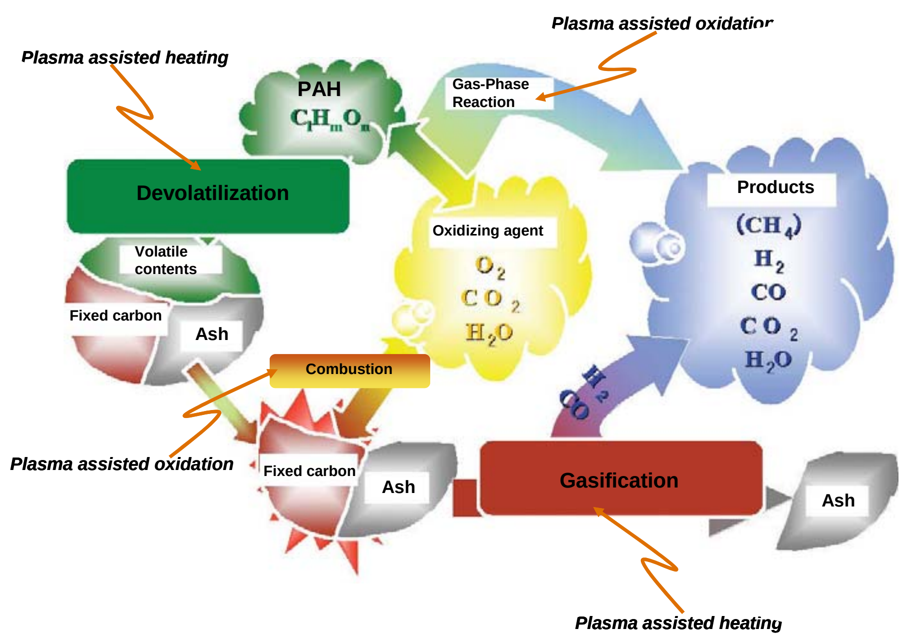



*Fig. 2. Principal scheme of physical and chemical processes by coal gasification to be modeled (used design of [1])*

Processes of coal devolatilization and gasification of carbon have been discussed widely in the literature for many years. Plasma applying in this case is less investigated and is associated mostly with the heating of coal particles, [2, 3]. These two physical processes strongly influence the chemical heterogeneous/homogeneous reactions which are main topic of presented overview.

Coal reactivity is affected by different variables which involve the coal properties that can not just be related to coal physical structure or to process parameters. These variables are: coal rank, thermal history of the char (pyrolysis), pore structure, chemical structure of coal. In contrast to reactivity, some factors that are solely related to the physical structure of coal or to the conditions in which reactions take place are said to affect the reaction rate: reactive gases concentration, pressure, sample size [4, 5].

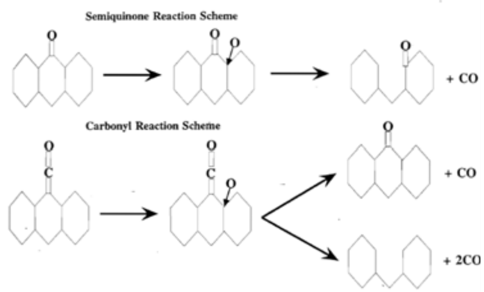



*Fig. 3. Reaction schemes for carbon removal by oxygen [7]*

Different models have been proposed to describe the char gasification reaction. The analysis of most simple models (homogeneous models, and unreacted core models), which do not consider coal structural changes during process and any chemical reactions, can be found in [6]. These models do not distinguish the heterogeneous or homogenous reactions describing coal gasification with empirical overall reaction constants. They are preferred if the main intention for studying coal reactivity is just to describe the relation between time and conversion.

One of more recent and wide used studies of ***heterogeneous reaction*** with carbon was published by Chen et al. [7]. He suggested the main heterogeneous reaction passes for oxygen, Fig.3, carbon dioxide, steam and hydrogen gasification.

In [6] the entire course of carbon gasification, from 0 to 100% conversion, was simulated for the first time using molecular orbital theory, Fig. 4. This method could simulate the following commonly observed features in actual gasification: (1) gasification starts at edge carbon atoms; (2) zigzag sites are more reactive than armchair sites; (3) specific rate increases monotonically with conversion. Furthermore, this simulation predicted that the specific rate depends on crystallite size, but is insensitive to crystallite shape.

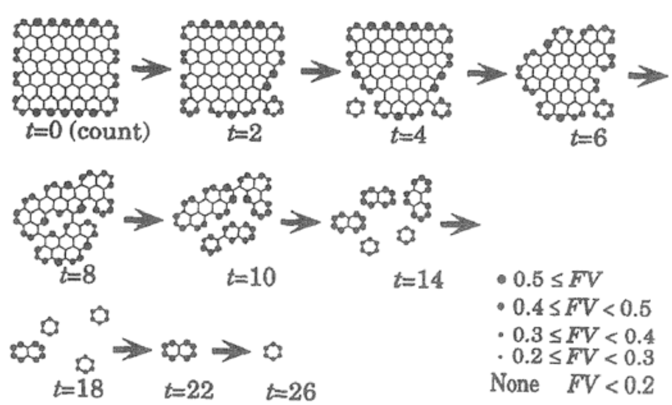



*Fig. 4. Carbon gasification process from [8]. FV-free valence at a carbon atom, t- uncalibrated gasification time*

More simple reaction sets of the carbon heterogeneous reactions can be found in [6, 9-13]:

$$C+CO_2 = 2CO$$

$$C + H_2O = CO + H_2$$

$$C + 2H_2O = CO_2 + 2H_2$$

$$C + 2H_2 = CH_4$$

The investigations of plasma influence on carbon gasification were not found in the literature.

The simple set of ***gas – phase reactions*** also can be found in [9-13]:

$$H2+1/2O2 = H2O$$

$$CO + 1/2O2 = CO2$$

$$CH4 + 2O2 = CO2 + 2H2O$$

$$H2O + CO = H2 + CO2$$

$$CO + 3H2 = CH4 + H2O$$

$$CO + H2 = H2O + C$$

$$CO2 + 4H2 =2H2O + CH4$$

Well developed gas-phase reaction model was used in [3, 14-16] by coal plasma gasification. This mechanism of 51 chemical reactions and 25 chemical species represents 3 different kinetic processes. The first 6 reactions describe the initialisation stage of coal conversion in the PFS and devolatilisation. The second set of 4 reactions represents the carbon gasification and combustion. Finally, the third sub mechanism contents the radical reactions of volatiles and gasification products with their further transformations. Hence this model was used for plasma assisted coal gasification and it does not have plasma chemical reactions. Through investigations [3, 14-16] the electric arc plasma is considered as an internal heat source with a presumed temperature profile. In [17] measurements of polycyclic aromatic hydrocarbons (PAHs) resulting from coal combustion under different ambient gas properties are presented and also a global kinetic model of PAH formation is proposed. The PAH measurements were performed at different ambient atmosphere, air temperatures and oxygen concentration. It has been shown that the maximal PAH production appeared at 600 $^{o}C$ from pyrolysis and at 800 $^{o}C$ from combustion. With increasing oxygen concentration, PAH formation from coal combustion decreased significantly. So, from this investigation it follows, that reaction models for coal gasification have to have the sub model of PAH formation and oxidation.

***Plasma-assisted combustion*** replaces catalysis and accelerates chemical reactions through high temperature effect (thermal plasma) or through active species generation by fast electrons (non equilibrium plasma). The key element in the research work of modern experimentalists and engineers in plasma-chemistry is setup design through qualitative understanding of input of principal plasma and chemical phenomena in behavior of complex plasma systems. The principal aim here is the construction of a physicochemical kinetic mechanism for process modeling, i.e. the determination and description of the necessary set of substances and reactions, which can be integrated in the detailed mechanism in frame work of simplified model of plasma reactors- “partial modeling”. In this approach, simulation precedes the prototyping, so that the researcher can significantly reduce the amount of experimental tests. In addition, it becomes possible to fully exploit abundant information of processes gained in basic research.

The main experimental and numerical investigation of plasma combustion can be found in [18-20]. The influence of plasma on the chemical process, first of all the active species formation, is determined with the type and parameters of plasma, i.e. with plasma production devises, and with system parameters (pressure, density, etc.).

The main species present in an air plasma are $N_2$, $O_2$, N, O, NO (neutral species) and $NO^+$, $N_2^+$, $O_2^+$, $O^+$, e (charged species). The concentrations of negative ions and doubly charged ions are negligible [21]. Oxygen atoms and nitrogen atoms can be produced by electron impact:

$$O_2 + e = O + O + e$$

$$N_2 + e = N + N + e$$

At high temperature, the formation of N, O, and NO in air occurs through the well-known Zeldovich mechanism:

$$O + N_2 = NO + N$$

$$N + O_2 = NO + O$$

In air plasmas, excited states of dinitrogen, $N_2 (X, v)$ are present and produce a reaction with a higher rate:

$$O + N_2(X, v) = NO + N.$$

Water vapour in the mixture gives several important pathways for OH production: direct electron impact disassociation of water vapour and the creation of $O(^1D)$, which reacts with water vapor to produce OH [22]:

$$e + H_2O \rightarrow H + OH + e$$

$$e + O_2 \rightarrow O(^1D) + O + e$$

$$O(^1D) + H_2O \rightarrow 2OH$$

To calculate the densities of electrons and active particles, one has to determine electron energy distribution function (EEDF) by solving Boltzmann equation for electrons [23].

Kinetic schemes to simulate the production of active particles during the discharge and in its afterglow and then plasma-assisted combustion for $H_2$, $CH_4$, $C_2H_6$ were developed in [24-28]. These works establish the main principals of the plasma-assisted ignition modelling and investigate properties of hydrocarbon combustion with the plasma applying. In [29] the kinetics of alkane oxidation has been measured from methane to decane in stoichiometric and lean mixtures with oxygen and air at room temperature under the action of high-voltage nanosecond uniform discharge. How it follows from presented investigations there is enough information to develop detailed reaction model for plasma-assisted coal gasification. Simultaneously, all investigators note the high level of uncertainty in chemical-kinetic data both for heterogeneous and homogeneous reaction. That can be concluded from comparison of kinetic data used in different models. Especially is that actual for plasma chemistry.

The lack of the necessary physicochemical data and the well-known difficulties with their experimental and theoretical recovery hase recently limited the practical use of predictive modeling. But, the progress in theoretical methods, application of state-of-art electronic structure methods, theory of elementary processes and progress in computers science permits us to generate complete set of data for plasma chemical process simulation.

**References**


1. *Basic Technologies for Advanced Coal Utilization, NEDO-commissioned project, FY2000-FY2004*, Japan Coal Energy Center.
2. Messerle, V.E. and Peregudov, V.S., 1995. *Ignition and Stabilisation of Combustion of Pulverised Coal Fuels by Thermal Plasma. Investigation and Design of Thermal Plasma Technology*, Cambridge Interscience Publishing, London, 2, 323–343.
3. Gorokhovski, M. A., Jankoski, Z., Lockwood, F. C., Karpenko, E. I., Messerle, V. E. and Ustimenko, A. B., 2007. *Enhancement of pulverized coal combustion by plasma technology*. Combustion Science and Technology 179, 10, 2065 – 2090.
4. Lemaignen, L., Zhuo, Y., Reed, G.P., Dugwell, D.R., Kandiyoti, R., 2002. *Factors governing reactivity in low temperature coal gasification. Part II. An attempt to correlate conversion with inorganic and mineral constituents.* Fuel 81, 315-325.
5. Liu G., Benyon P., Benfell K.E., et al., 2000, *The porous structure of bituminous coal chars and its influence on combustion and gasification under chemically controlled conditions,* Fuel 79 , 617–626
6. Molina A. and Mondrago N.F., 1998. *Reactivity of coal gasification with steam and CO2,* Fuel 77, 15, 1831–1839.
7. Chen, S.G., Yang, R.T., Kapteijn F., Moulijn J.A., 1993. *A new surface oxygen complex on carbon: toward a unified mechanism for carbon gasification reaction*. Ind.Eng.Che.Res., 32, 2835.
8. Kyotani T., Ito K., Tomita A., Radovic L. R., 1996. *Monte Carlo Simulation of Carbon Gasification Using Molecular Orbital Theory*. AIChE Journal, 42, 8, 2303-2307.
9. Choi, Y.C., Li, X.Y., Park, T.J., Kim, J.H., Lee, J.G., 2001. *Numerical study on the coal gasification characteristics in an entrained flow gasifier*. Fuel 80, 2193-2201.
10. Biba, V., Macak, J., Klose, E., Malecha, J., 1978. *Mathematical Model for the Gasification of Coal under Pressure*. Ind. Eng. Chem. Process Des. Dev., 17, 1,92-98.
11. Beath, A.C., 1996. *Mathematical modelling of entrained flow coal gasification*. PhD Thesis, University of Newcastle, Australia.
12. Norman, J. J., Pourkashanian M., Williams, A., 1997. *Modelling the formation and emission of environmentally unfriendly coal species in some*. Fuel 76, 13, 201-1216.
13. Kerinin, E.V., Shifrin, E.I., 1993. *Mathematical model of coal combustion and gasification in a passage on a underground gas generator*.Translation from Fizika Goreniya 29, 2, 21-28.
14. Kalinenko, Kuznetsov, A.P., Levitsky, A.A., Messerle, V.E., 1993. *Pulverized Coal Plasma gasification*. Plasma Chemistry and Plasma Processing 13, 1, 141-167.
15. Gorokhovski, M., Karpenko, E. I., Lockwood, F. C., Messerle,V. E., B. Trusov, G., Ustimenko, A. B., 2005. *Plasma technologies for solid fuels:experiment and theory*. Journal of the Energy Institute 78, 4, 157-171.
16. Matveev, I.B., Messerle, E.V., Ustimenko, A.B., 2009-in press, *Plasma Gasification of coal in Different Oxydants*, IEEE Transactions of plasma science.

17. You, X. F., Gorokhovski, M. A., Chinnayya, A., Chtab, A., Cen, K. F., 2007- *Experimental study and global model of PAH formation from coal combustion*. Journal of the Energy Institute 80, 1, 12-23.
18. Starikovskaia, S. M., 2006, *Plasma assisted ignition and combustion*, J. Phys. D: Appl. Phys. 39 , R265–R299.
19. Gleizes, A., Gonzalez J. J., Freton, P., 2005. *Thermal plasma modelling*, J. Phys. D: Appl. Phys. 38, R153–R183.
20. Fridman, A., Chirokov, A., Gutsol, A., 2005. *Non-thermal atmospheric pressure discharges*, J. Phys. D: Appl. Phys., 38, R1–R24.
21. Andari, J. AI., Diamy, A. M., Legrand, J. C., Ben-Aim R. I., 1993. *Air Microwave-Induced Plasma: Relation between Ion Density and Atomic Oxygen Density*, Plasma Chemistry and Plasma Processing 13, 1, 103-116.
22. Cathey, C., Cain J., Wang H., Gundersen M. A., Carter C., Ryan M., 2008. *OH production by transient plasma and mechanism of flame ignition and propagation in quiescent methane–air mixtures*, Combustion and Flame 154, 715–727.
23. Starikovskaia, S. M., Anikin, N. B., Pancheshnyi, S. V., Zatsepin, D. V., Starikovskii, A. Yu., 2001. *Pulsed breakdown at high over voltage: development, propagation and energy branching.* Plasma Sources Sci. Technol. 10, 344–355.
24. Bozhenkov, S.A., Starikovskaia, S.M., Starikovskii, A.Yu, 2003. *Nanosecond gas discharge ignition of H2- and CH4-containing mixtures,* Combustion and Flame 133, 133–146.
25. Stariskovskaia, S.M., Starikovskii, A.Yu., Zatsepin, D.V., 2001. *Hydrogen oxidation in stoechiometric hydrogen-air mixture in the fast ionization wave*. Combustion Theory and Modelling 5, 1, 97-129.
26. Kosarev, I.N., Aleksandrov, N.L., Kindysheva, S.V., Starikovskaia, S.M., Starikovskii, A.Yu., 2008. *Kinetics of ignition of saturated hydrocarbons by nonequilibrium plasma: CH4-containing mixtures***.** Combustion and Flame 154, 569–586.
27. Deminsky, M., Jivotov, V., Potapkin, B., Rusanov, V., 2002. *Plasma-assisted production of hydrogen from hydrocarbons*. Pure Appl. Chem. 74, 3, 413–418.
28. Deminsky, M., 2009. *Plasma chemical mechanism understanding via partial modelling*, Invited lecture, ISPC-19, Bochum, Germany.
29. Starikovskii, A.Yu., Anikin, N. B., Kosarev, I. N., Mintoussov, E. I., Starikovskaia, S. M., Zhukov, V. P., 2006. *Plasma-assisted combustion*, Pure Appl. Chem. 78, 6, 1265–1298.

***Dr. Nadezhda Slavinskaya*** *was born in Russia. M.S degree in thermophysik in Moscow Power Engineering Institute (TU),* **1985,** *Ph.D. degree in the field of chemical physics, including physics of combustion and explosion in* ***1991. 2002 – present*** *Senior research fellow, Institute of Combustion Technology, Division of High Temperature Kinetics, German Aerospace Center (DLR), Stuttgart ;* ***1999 – 2002*** *- Senior research fellow, Central Institute of Aviation Motors (CIAM), Moscow;* ***1994 – 1999*** *– Senior research fellow, Institute of High Temperatures of Russian Academy of Sciences (IVTAN), Moscow ;* ***1991 – 1994*** *– Professor, Kishinev Polytechnic Institute (TU);****1987 – 1991*** *- Assistant professor, Kishinev Polytechnic Institute (TU);* ***1985 – 1987*** *– Engineer – researcher, Institute of Applied Physics of Moldavian Academy of Sciences, Kishinev.*

***Monica Petrea*** *was born in Romanian, in September 19, 1967. She received the MSc. Degree in environmental engineering from "Gh. Asachi" Technical University, Faculty of Industrial Chemistry, Iasi, Romania in 2001 and the PhD degree with a thesis entitled "Emissions of Non-Methane Volatile Organic Compounds (NMVOC) from Vehicular Traffic in Europe", at Bergische Universität Wuppertal, Germany in 2007.*

*From 1998 to 2001 she worked as a reasearcher at the "Al.I.Cuza" University of Iasi, Romania. From 2001 she worked in Dept. of Physical Chemistry, the at the Bergische Universität Wuppertal, Germany.*

*Since 2007 she is a Research Scientist, DLR/ VT- Stuttgart, Germany. During the last years she performed various studies in the area of fuels research, influence of various fuels on the vehicles emissions.*

# On Application of Non-Equilibrium Plasma to Pulverized Coal Conversion

*N.V. Ardelyan, K.V. Kosmachevskii, Department of Computational Mathematics and Cybernetics, M.V.Lomonosov Moscow State University, Moscow, Russia*

*V. L. Bychkov, S.V. Denisiuk, I.I. Esakov, K.V. Khodataev, L.P. Grachev, A.A. Ravaev, Moscow Radiotechnical Institute Russian Academy of Sciences MRTI RAS, Moscow, Russia*

Main feature of non-equilibrium low temperature plasmas is that they can reach high temperatures (2000-3000 K) at simultaneous presence of high concentrations of active particles in them. This leads to highly active impact of the plasmas on reacting substances. Typical feature of substances transformation in these plasmas is difference of products and components types in these plasmas from those realized in thermodynamically equilibrium [1-3]. Another advantage of non-equilibrium plasma sources with respect to equilibrium plasma generators is their smaller weight-size characteristics which are important at development of movable installations for coal conversion.

Investigations with the non-equilibrium plasmas were made in the microwave and glow corona discharges have shown that obtained products are analogous to those obtained at temperatures of several thousands degrees [2]. However conditions of these discharges realization required low pressure and high power parameters. Investigations with the corona discharge [3] at U=20 kV have shown that cost of transformation of coal into liquid and gaseous products under impact of atoms H and radicals $CH_3$ in it is smaller than in other sources of electric energy. Output of liquid products were the same as in thermal processes but there were no resin. Breakdown and short circuit over coal particles lead to decay of the corona discharge. By opinion of [2] creation of continuous corona discharge could create most effective plasma chemical reactor for coal processing.

Development of new sources of non-equilibrium plasmas that took place during last decades lead to creation of combined plasma sources consisting of electron-beam, gas-flow and external electric field [1]; non-self-maintained gas discharges including electron beams and external electric fields [4]; subcritical streamer microwave discharge in reverse-vortex combustion chamber [5]; atmospheric-pressure vortex microwave plasma generator [6]. These plasma sources realize plasma at high levels of electric field that allows to exceed parameters of corona discharges at acceptable power characteristics far below electric arc parameters and they can be realized free from short circuit of the plasma systems.

In the report are presented schemes and parameters of these plasma sources.

Presented calculations for plasmas of these parameters show high level of non-equilibrium at temperatures in the range 1000-3000 K, that makes these plasma generators attractive for pulverized coal conversion applications.

**Acknowledgment** Authors acknowledge AFOSR and EOARD for financial support in frames of the Project ISTC #3775p.

## References


1. *Basic Technologies for Advanced Coal Utilization, NEDO-commissioned project, FY2000-FY2004*, Japan Coal Energy Center.
2. Ardelyan N.V., Bychkov V.L., Kosmachevskii K.V. *Features of Combined Plasmas*. IEEE Trans on Plasma Science. 2008. December. V.36. N.6.P.2892-2897.
3. Zhukov M.F., Kalinenko R.A., Levitsky A.A., Polak L.S. *Plasma-Chemical Processing of Coal*. Nauka Publishers. Moscow. 1990.
4. Dibelius N.R., Fraser J.C., Kawahafa M., Dyle C.D. *Corona processing of coal*. Chem. Eng. Process. 1964. V.60. N.6. P.41-44.
5. Ardelyan N., Bychkov V., Kosmachevskii K., Denisiuk S., Gudovich V., Bychkov D., Kochetov I. *Electron-beams for Plasma Impact on Gas Flammable Mixtures*. AIAA-2009-0693. $47^{th}$ AIAA Aerospace Sciences Meeting. 5-8 January 2009. Orlando World Center Marriott. Orlando. Florida.
6. Aleksandrov K.V., Bychkov V.L., Grachev L.P., Esakov I.I., Khodataev K.V., Ravaev A.A. and Matveev I.B. *Subcritical streamer microwave discharge in reverse-vortex combustion chamber*. 4-th Intern. Workshop and Exhibit. On Plasma assisted Combustion (IWEPAC) 16-19 September 2008. Best Western Falls Church Inn, VA, USA. P.22-25.
7. Lavrov B.P., Lavrov P.B., Ravaev A.A., Khodataev K.V., Bychkov V.L., Grachev L. P. and Matveev I.B. *Atmospheric-Pressure Vortex Microwave Plasmatron*. 4-th Intern. Workshop and Exhibit. On Plasma assisted Combustion (IWEPAC) 16-19 September 2008. Best Western Falls Church Inn, VA, USA. P.34-36.

# Modeling of Plasma Impact on Propane-Air Mixture

*N.V. Ardelyan, K.V. Kosmachevskii, Department of Computational Mathematics and Cybernetics, M.V.Lomonosov Moscow State University, Moscow, Russia*

*I.V. Kochetov, State Research Center of Russia Troitsk Institute for Innovation and Thermonuclear Research, Troitsk, Moscow region, Russia*

*V. L. Bychkov, D.V. Bychkov, S.V. Denisiuk, Moscow Radiotechnical Institute Russian Academy of Sciences MRTI RAS, Moscow, Russia*

A problem of optimal plasma systems creation for inflammation and combustion of hydrocarbon gaseous mixtures requires a development of physical and chemical models of processes in the mixture under impact of different type plasmas and mathematical models assisted with corresponding numerical codes. This problem consists in solution of several connected sub-problems such as: determination of electron-molecule collision rate constants in the given plasma, determination of main ion-molecule, atom-molecule and molecule-molecule reactions in conditions of the gas plasma heating, corresponding solution of plasma-chemical kinetics with equations for gas and electron temperatures, and in case of high energy release – joint solutions of equations of kinetics and gas dynamics.

The present work is devoted to analysis of electron-beam, non-self-maintained and self-maintained gas discharge plasma models in propane-air gaseous mixture and is connected with experiments with non-self-maintained gas discharges in this mixture [1]. In the work [2] main rate constants of electron-molecule processes in this mixture in gas discharges were obtained; it was shown there that electron energy balance in propane-air mixtures at propane concentrations below 8% practically coincides with those in air. Thus in the given work we use for electrons parameters of air electric discharge and electron-beam plasmas obtained in [3, 4]. For the plasma model in the propane-air mixture we have applied two approaches: according to the first one we took a short propane-air chemical kinetics from [5], which reliably describes a propane-air mixture self ignition, and detailed air plasma chemical kinetics from [1, 3, 4]; according to the second one we added to the previous system the detailed reaction system typical for water-air gaseous mixtures. Total number of chemical and plasma chemical reactions is 768, components 68. The system includes equations for electron and gas temperatures.

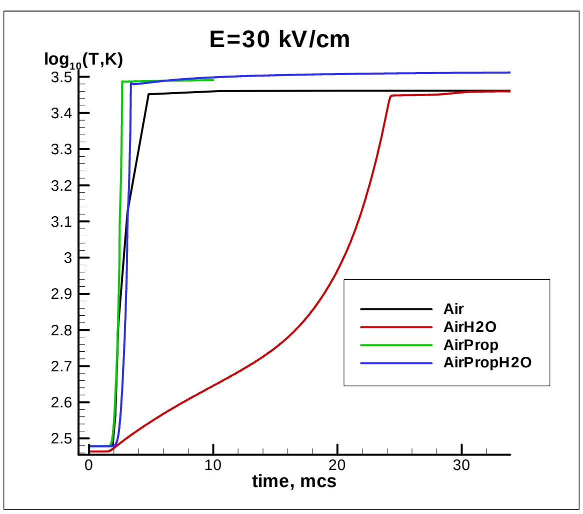



*Fig. 1*

In Fig. 1 one can see the temperature evolution in discharge plasma at external field strength of E=30 kV/cm at initial gas temperature T=300 K and normal pressure in dry air, air-water (1%) mixture; Air-Propane stoichiometric mixture with detailed air and shortened propane and water (1%) reaction system; and detailed air and water, at shortened propane reaction system.

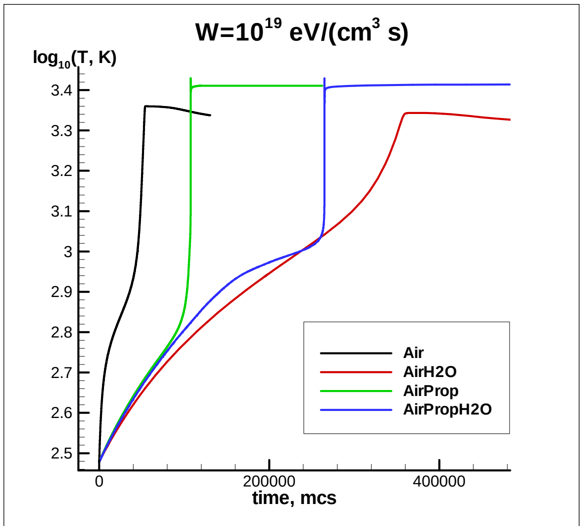



*Fig. 2*

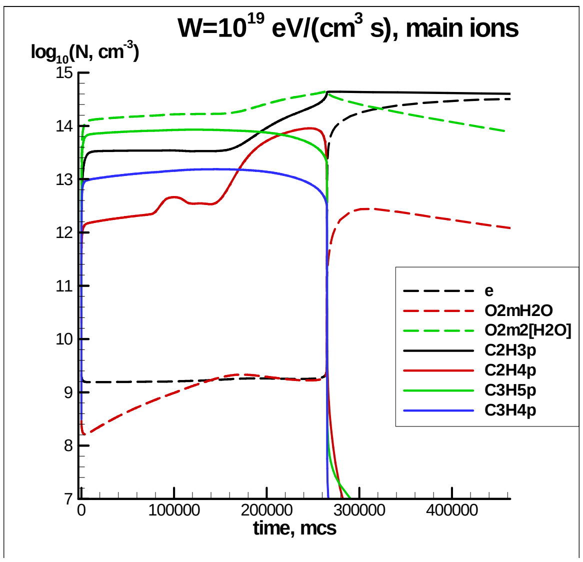



*Fig. 3*

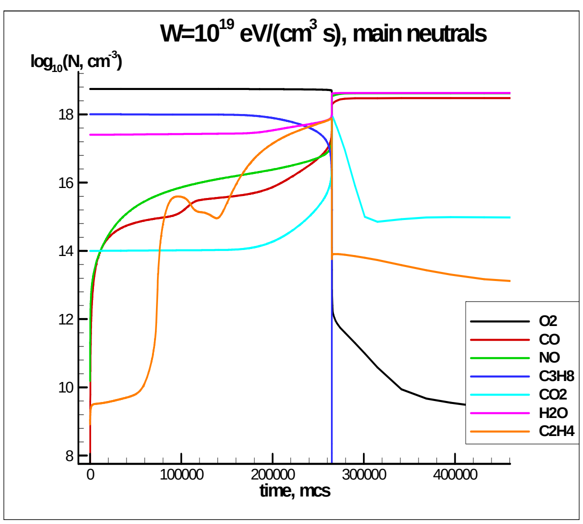



*Fig. 4*

In Fig. 2 one can see temperature evolution in the electron beam plasma at electron beam energy E=300 keV/cm, electron beam current density J=1 mA/cm$^2$ (W=36 eV×2.8×10$^{20}$×$J_b$ eV/(cm$^3$s); $J_b$, A/cm$^2$), at initial gas temperature T=300 K and normal pressure in dry air, air-water (1%) mixture; Air-Propane stoichiometric mixture with detailed air, shortened propane and water reaction system; and at detailed air, water, and shortened propane reaction system.

In Fig. 3, 4 one can see evolution of main ions and neutrals Air-Propane stoichiometric mixture at detailed air, water (1%), and shortened propane reaction system.

From Fig. 1 one can see that ignition with application of the discharge in propane-air stoichiometric mixture can be realized during 2-3 ms due to quick heating of the mixture by Joule heating of the gas discharge.

Fig. 2 shows that ignition in propane-air stoichiometric mixture (at 1% of $H_2O$) in the electron beam plasma takes place between 80 and 280 ms. Detailed description of water components (see Fig. 3, 4) leads to longer heating of the mixture in computations with respect to the non detailed description. It can be connected with longer accumulation of active radicals in ion-ion recombination reactions due to presence of heavy ions in the mixture with water components. At calculated times the system is non-equilibrium and concentrations of CO are greater that of $CO_2$. Plasma sources for some time heat the mixture and create active radicals, then the ignition takes place at temperature T~ 1000 K.

Obtained results show that different plasma sources impact differently on the ignition process. It has to be accounted at their practical application.

**Acknowledgment.** Authors acknowledge AFOSR and EOARD for financial support in frames of the Project ISTC #3775p.

## References


1. Ardelyan N., Bychkov V., Kosmachevskii K., Denisiuk S., Gudovich V., Bychkov D., Kochetov I. *Electron-beams for Plasma Impact on Gas Flammable Mixtures*. AIAA-2009-0693. 47th AIAA Aerospace Sciences Meeting. 5-8 January 2009. Orlando World Center Marriott. Orlando. Florida.
2. Bychkov V. L., Kochetov I.V., Bychkov D.V. *Air-propane mixture ionization processes for optimization of ignition in combustion chambers at application of gas discharges*. 4-th Intern. Workshop and Exhibit. On Plasma assisted Combustion (IWEPAC) 16-19 September 2008. Best Western Falls Church Inn, VA, USA. P.29-31.
3. Ardelyan N., Bychkov V., Kosmachevskii K., Chuvashev S., Malmuth N. *Modeling of Plasmas in Electron Beams and Plasma Jets*. AIAA 2001-3101 Proc. 32-nd AIAA Plasmadynamics and Lasers Conference and 4 th Weakly Ionized gases Workshop 11-14 June 2001, Anaheim, CA.(15 P).
4. Ardelyan N.V., Bychkov V.L., Kosmachevskii K.V. *Features of Combined Plasmas.* IEEE Trans on Plasma Science. 2008. December. V.36. N.6.P.2892-2897.
5. Varatharajan B., Williams F.A. *Reduced Chemistry Descriptions for Ignition and Detonation of Higher Hydrocarbons*. 40-th AIAA Aerospace Sciences Meeting and Exhibit. 14-17 January, 2002, Reno, NV.


*Vladimir Bychkov,*
*Dr. Sci., head of a laboratory*

*Igor Kochetov Ph.D., head of a laboratory*

*Dmitry Bychkov, Ph.D., junior researcher*

*Nikolai Ardelyan Dr.Sci., head of a laboratory*

*Konstantin Kosmachevskii, Ph.D., senior researcher*

# Features of Plasma Coal Combustion and Gasification Mathematical Modeling

*Serhiy Serbin and Anna Mostipanenko*
*National University of Shipbuilding, Mikolayiv, Ukraine*

Plasma gasification offers one of the cleanest ways to convert coal into hydrogen rich gas, electricity, and other energy forms. Obtained refined synthesis gas can be efficiently used in internal combustion engines, gas turbines, boilers, fuel cells, etc. One of the major obstacles in the way of plasma technologies implementation is the limited lifetime of existing plasma torches, which does not exceed 100-150 hours for 300-500 kW DC devices.

Applied Plasma Technologies develops robust, durable and universal hybrid type plasma assisted technology mainly for effective coal combustion and gasification. The new high energy efficient inductive (electrodeless) atmospheric pressure plasma torch will merge several solutions, as innovative reverse vortex reactor, plasma pilot, and plasma chemical reactor [1-4].

The objective of this paper is preliminary the determination of flow dynamics features and selection of corresponding mathematical models for prediction of main plasma coal gasifier parameters. For modeling of physicochemical processes inside a plasma gasifier, a generalized method has been used, based on the numerical solution of the combined conservation and transport equations for turbulent chemically reacting system. The coupled discrete phase model has been used for definition of the trajectory of a discrete phase by integrating the force balance of the coal particles.

The inert heating model is applied when the coal particle temperature is less than the vaporization temperature that define, $T_{vap}$, and after the volatile fraction, $f_{v,0}$, of a particle has been consumed.

These conditions may be written as

$$T_p < T_{vap}, \quad m_p \le (1 - f_{v,0}) m_{p,0},$$

Where $T_p$ is the particle temperature, $m_{p,0}$ is the initial mass of the coal particle, and $m_p$ is its current mass.

The devolatilization model is applied to a combusting particle when the temperature of the particle reaches the vaporization temperature, and remains in effect while the mass of the particle exceeds the mass of the non-volatiles in the particle:

$$T_p \ge T_{vap}, \quad m_p > (1 - f_{v,0})(1 - f_{w,0}) m_{p,0},$$

where $f_{w,0}$ is the mass fraction of the evaporating/boiling material if wet combustion is used.

After the volatile component of the coal particle is completely evolved, a surface reaction begins which consumes the combustible fraction, $f_{comb}$, of the particle. For a combusting particle after the volatiles are evolved:

$$m_p < (1 - f_{v,0})(1 - f_{w,0}) m_{p,0}$$

and until the combustible fraction is consumed:

$$m_p > (1 - f_{v,0} - f_{comb})(1 - f_{w,0}) m_{p,0}.$$

When the combustible fraction has been consumed, the coal particle may contain residual "ash" that reverts to the inert heating model.

Modeling of multiple particle surface combustion and gasification reactions is similar to the wall surface reaction model, where the surface species is now a "particle surface species". The particle surface species constitutes the reactive char mass of the particle, hence, if a particle surface species is depleted, the reactive "char" content of the particle is consumed, and in turn, when a surface species is produced, it is added to the particle "char" mass.

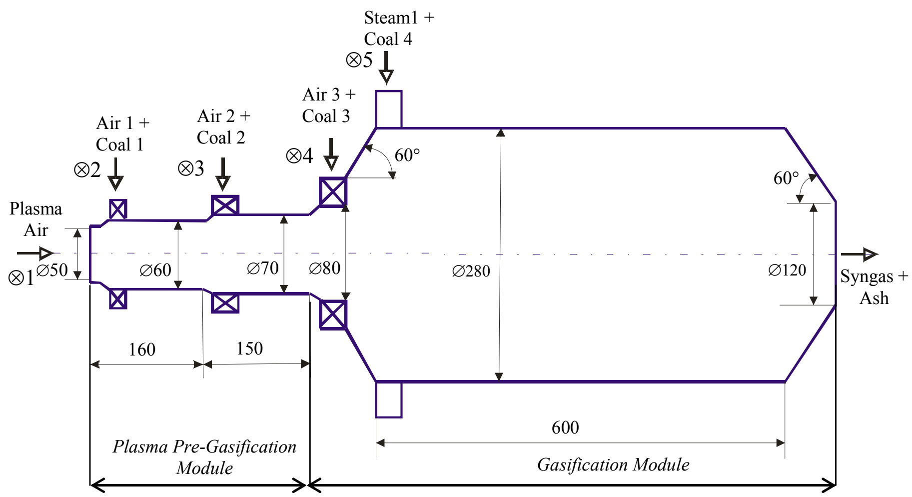


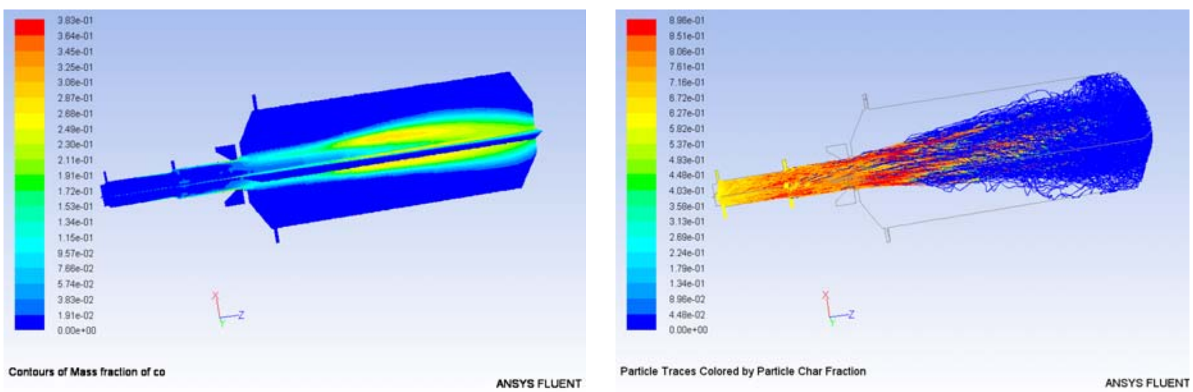

*Fig. 1. Geometrical scheme of plasma gasification system:*
*⊗1 – axial plasma air injection; ⊗2 – tangential (radial) air-coal injection;*
*⊗3 – tangential (radial) air-coal injection; ⊗4 – tangential (axial-radial) air-coal injection;*
*⊗5 – radial steam-coal injection*

Two air-coal streams are injected in series into plasma for prior heating, devolatilization, and combustion (partial oxidation). Next the portion of air-coal mixture (or pure air) is supplied into the gasification module through a special swirler to guarantee stable combustion (partial oxidation) of previously prepared plasma-air-coal mixture. Steam and coal are injected in radial direction for getting of gasification products, including carbon monoxide and molecular hydrogen. Coal particles with release from corresponding air surfaces enter the plasma pre-gasification module with a mass flow rate of 1.0 and 2.0 g/s. For the main gasification process steam and coal are radially injected with a total mass flow rate of 5.0-10.0 g/s. Particle size distribution is defined by fitting the size distribution data to the Rosin-Rammler equation. In a majority of cases the minimum diameter is 5 mkm; maximum diameter is 100 mkm; mean diameter is 40 mkm.

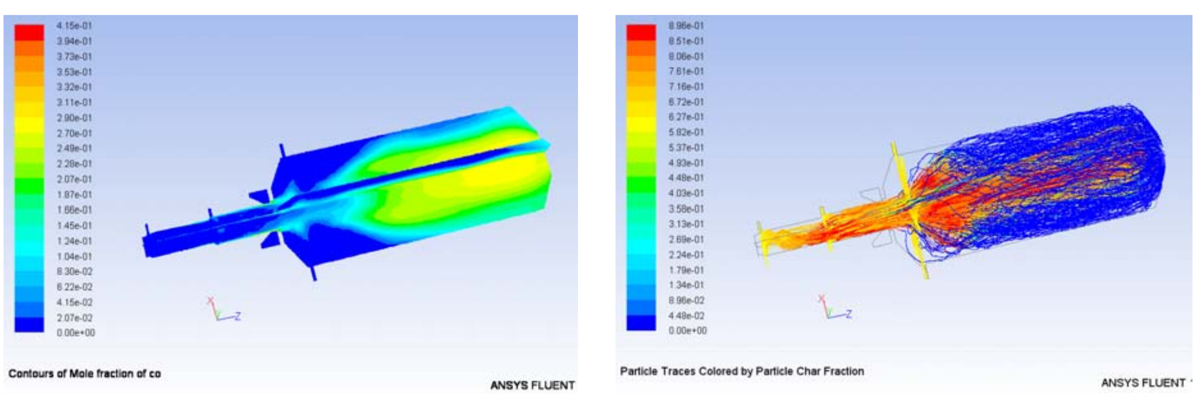
The Powder River Basin bituminous coal was taken for plasma gasification computation (proximate analysis, weight %: volatile = 0.299, fixed carbon = 0.583, ash = 0.068, moisture = 0.050, higher caloric value of the coal = $3.133 \cdot 10^{7}$ J/kg).

The coal vaporization temperature is 400 K, specific heat is 1680 J/(kg·K), density is 1400 $kg/m^3$, thermal conductivity is 0.33 W/(m·K), binary diffusivity is $4 \cdot 10^{-5}$ $m^2/s$, swelling coefficient is 1.4.

Contours of CO mass fraction and particle traces colored by particle char fraction for two (Coal1 + Coal2) and three (Coal1 + Coal2 + Coal4) coal injections are shown in Fig. 2. Case *a)* corresponds to partial oxidation of coal in plasma pre-gasification module, and case *b)* corresponds to coal steam gasification in gasification module.




*a)*




*b)*

*Fig. 2. Contours of CO mass fraction and particle traces colored by particle char fraction: a – two coal injection; b –three coal injection*

Exit component mole fractions in case *a*): CO = 0.0832, $H_2$ = 0.0227, $CO_2$ = 0.1070, $H_2O$ = 0.0593, volatile = 0.0026, $O_2$ = 0.0196, $SO_2$ = 0.0004, char conversion = 99.9 %. Exit component mole fractions in case *b*): CO = 0.2019, $H_2$ = 0.1255, $CO_2$ = 0.0516, $H_2O$ = 0.1346, volatile = 0.021, $O_2$ = $3.01 \cdot 10^{-6}$, $SO_2$ = 0.00061, char conversion = 64.72 %. For ensuring more efficient char conversion in case *b*) it is necessary to increase a particle residence time at the expense of reaction zone extension and steam-coal mixture swirling, or to use oxygen as working medium.

The carried out calculations have proven the principal possibility of using of CFD complexes for prediction and parameter optimization of plasma coal gasifiers. The further improvements of computational procedures are linked, first of all, with development of more detailed kinetic schemes of coals (with different fractional composition) combustion and gasification, amelioration of devolatilization mechanisms, and taking into account radiation heat transfer. Special attention is necessary to devote to verifications of the offered chemical and physical mechanisms that require conducting coordinated experimental and theoretical investigations.

## References


1. Matveev, I., *United States Patent 7,452,513 B2 "Triple Helical Flow Vortex Reactor",* issued Nov. 18, 2008.
2. Matveev, I., *United States International Publication Number WO 2008/122849 A2 for "Powerplant and Method Using a Triple Helical Vortex Reactor",* 16.10.2008.
3. I. Matveev, S. Serbin, *Preliminary Design and CFD Modeling of a 1 MW Hybrid Plasma Torch for Waste Destruction and Coal Gasification*, 2-nd Int. Workshop and Exhibition on Plasma Assisted Combustion, Falls Church, Virginia, pp. 43–44, 2006.
4. Matveev, I., Matveeva, S., Messerle, V., Ustimenko, A., Serbin, S., *Bituminous Coal Plasma Gasification*, 3-nd Int. Workshop and Exhibition on Plasma Assisted Combustion, Falls Church, Virginia, pp. 25-26, 2007.


***Serhiy I. Serbin*** *was born on April 29, 1958, in Mykolayiv, Ukraine. He received his M.S. (Dipl. Mech. Eng.) and Ph.D. (Cand. Sc. Tech.) degrees in mechanical engineering from the Mykolayiv Shipbuilding Institute, Ukraine, in 1981 and 1985, respectively, and the Dipl. D. Sc. Tech. and Dipl. Prof. degrees from the National University of Shipbuilding, Ukraine, in 1999 and 2002, respectively.*

*Since 1984, he has been working with the Ukrainian State Maritime Technical University as an Assistant Professor, Senior Lecturer, and Associate Professor. Since 1999, he has been working with the National University of Shipbuilding as a Professor of Turbine Units Department. His research interests are plasma-chemical combustion, the techniques of intensifying the processes of hydrocarbon-fuels ignition and combustion in power engineering, combustion and plasma processes modeling. Dr. Serbin is the Academician of the Academy of Shipbuilding Sciences of Ukraine and International Academy of Maritime Sciences, Technologies and Innovations.*

# The Role of in Situ Reforming in Plasma Enhanced Ultra Lean Premixed Methane / Air Flames

*Wookyung Kim, M. Godfrey Mungal, Mark A. Cappelli,*
*Mechanical Engineering Department, Stanford University, Stanford, USA*

This presentation describes a mechanism for the stabilization of ultra lean premixed methane/air flames by pulsed nonequilibrium plasma enhancement. It is shown that the pulsed discharge plasma produces a cool (~ 500–600 K) stream of relatively stable intermediate species including hydrogen ($H_2$) and carbon monoxide (CO), which play a central role in enhancing flame stability. This stream is readily visualized by ultraviolet emission from electronically excited hydroxyl (OH) radicals. The rotational and vibrational temperature of this "preflame" are determined from its emission spectrum. Qualitative imaging of the overall flame structure is obtained by planar laser-induced fluorescence measurements of OH. Preflame nitric oxide (NO) concentrations are determined by gas sampling chromatography.

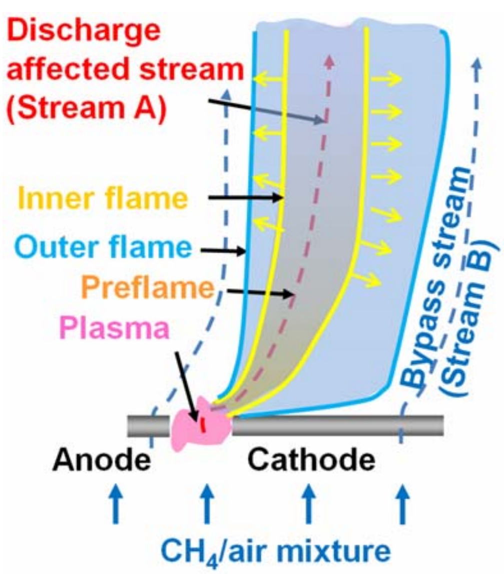



*Fig. 1 A schematic interpretation of the flame structure*

As illustrated in Fig. 1, a simple model of this plasma enhanced premixed flame is proposed that includes the generation of the preflame through plasma activation, and predicts the formation of a dual flame structure that arises when the preflame serves to pilot the combustion of the surrounding non-activated premixed flow. The calculation represents the plasma through its ability to produce an initial radical yield, which serves as a boundary condition for conventional flame simulations. The simulations also capture the presence of the preflame and the dual flame structure, and predict preflame levels of NO comparable to those measured. A subsequent pseudo-sensitivity analysis of the preflame shows that flame stability is most sensitive to the concentrations of $H_2$ and CO in the preflame. As a consequence of the role of $H_2$ and CO in enhancing the flame stability, the blowout limit extensions of methane/air and hydrogen/air mixtures in the absence/ presence of a discharge are investigated experimentally. For methane/air mixtures, the blowout limit of the current burner is extended by ~ 10% in the presence of a discharge while comparable studies carried out in lean hydrogen/air flames fail to extend this limit.

***Wookyung Kim*** *received the B.S. degree in mechanical engineering from Seoul National University, Seoul, Korea, in 1999 and the M.S. and Ph.D. degrees in mechanical engineering from Stanford University, Stanford, CA, in 2002 and 2006, respectively. He is currently with the Department of Mechanical Engineering, Stanford University, as a Postdoctoral Researcher. His research interests include the stabilization of turbulent flames using bluff bodies and plasma discharges, and hydrogen conversion using nonequilibrium gas discharges. Dr. Kim is a member of the American Physical Society, the American Institute of Aeronautics and Astronautics, and the Combustion Institute.*

***M. Godfrey Mungal*** *was born in Trinidad, West Indies. He received the B.A.Sc. degree in engineering science (Hons) from the University of Toronto, Toronto, ON, Canada, in 1975 and the M.S. and Ph.D. degrees in aeronautics from the California Institute of Technology, Pasadena, in 1977 and 1983, respectively. He is currently Dean of Engineering with the Santa Clara University, Santa Clara, CA, and Professor Emeritus of Mechanical Engineering with the Department of Mechanical Engineering, Stanford University, Stanford, CA, where his research efforts have covered supersonic mixing and combustion, turbulent reacting jets in coflow and crossflow, image processing (volume rendering) of turbulent flows, drag reduction of bluff bodies, flame stability, including liftoff and blowout, flow in microchannels, studies of drag reduction in boundary layers with injected polymers, and, most recently, the use of pulsed plasmas to control flame stability. Dr. Mungal is a fellow of the American Physical Society, an Associate fellow of American Institute of Aeronautics and Astronautics, a Fellow of the American Society of Mechanical Engineers, and a member of the American Society of Engineering Education and the Combustion Institute.*


*M**ark A. Cappelli*** *received the B.A.Sc. degree in physics from McGill University, Montreal, QC, Canada, in 1980 and the M.A.Sc. and Ph.D. degrees in aerospace science and engineering from the University of Toronto, Toronto, ON, Canada, in 1983 and 1987, respectively. He is currently a Professor of Mechanical Engineering with the Department of Mechanical Engineering, Stanford University, Stanford, CA. His research includes broad aspects of plasmas and gas discharges as they apply to aerodynamic and space propulsion, combustion, material processing, and biological processes.*

# Non-thermal Plasma Effects on Coal Gasification

*Yongho Kim, Louis Rosocha, Graydon Anderson, Hans Ziock,*
*Los Alamos National Laboratory, Los Alamos, USA*

A new concept for a Zero Emission Coal (ZEC) technology which produces a pure stream of $H_2$ and captures $CO_2$ for sequestration has been proposed by Los Alamos National Laboratory in collaboration with Louisiana State University. A challenge faced by the ZEC technology is carrying out the hydrogasification reaction under a reasonable set of conditions. Although the hydrogasification reaction is exothermic and is thermodynamically favored at ambient conditions, its kinetics are far too slow. Ideally one could use catalysts to enhance the kinetics of the hydrogasification reaction, thereby reducing the required temperatures and pressures, but the hostile environment of coal gasification (abrasion, sulfur poisoning, relatively high temperatures, etc.) create a very hostile environment in which conventional costly catalysts will rapidly degrade. We have attempted to address this issue through the use of a plasma in a catalytic role, where a plasma turns a very small fraction of the coal and reactant gases into highly reactive free radicals and excited species, which are believed to promote gasification reactions.

Two atmospheric pressure plasma sources, a microwave plasma and a dielectric barrier discharge (DBD), have been developed in the mixtures of hydrogen, coal powder, and argon in order to study the hydrogasification of coal. When the activated $Ar/H_2$ gas stream interacted with cold carbon particles downstream of the microwave cavity, $CH_4$ (methane) was the only stable gasification product. However, when carbon particles were injected into the plasma within the microwave cavity, both $C_2H_2$ (acetylene) and $C_2H_4$ (ethylene) were measured in addition to the $CH_4$. Based on UV spectroscopic measurement, the initial reaction step leading to $C_2$ species is thought to be a hydrogen ion reaction with a carbon particle. For the $CH_4$ production, adsorption of neutral species of hydrogen onto the carbon particle is suggested [1]. We also have developed a nonthermal DBD gasifier in order to separate plasma and temperature effects on hydrogasification of coal. The hydrogen gas (no plasma) produced no methane at all temperatures; however, the 10 W hydrogen plasma produced varying concentrations of methane as the system temperature increased to 400 °C. After 500 °C, methane production decreased. Nonthermal plasma effects on the carbon hydrogasification will be discussed at the presentation.

**References**

1. Y. Kim, H. Ziock, S. Abbate, G. Anderson, L. Rosocha, J. O. Lee, and R. Sanchez-Gonzalez, *Experimental Characterization of Carbon Hydrogasification in Atmospheric Pressure Microwave Plasma*, Proceedings of 5th International Symposium on Non-Thermal Plasma Technology, Oleron Island, France, June 19-23 (2006)
2. Y. Kim, S. Abbate, H. Ziock, G. Anderson, and L. Rosocha, *Hydrogasification of Carbon in an Atmospheric Pressure Microwave Plasma*, IEEE Trans. Plasma Sci. **35**, 1677-1681 (2007)

**Acknowledgment** This work was funded by the LANL Laboratory Directed Research and Development Program, using funds from the US Department of Energy/National Nuclear Security Administration.

***Yongho Kim*** *Dr. Kim is a technical staff member in Plasma Physics Group (P-24) at LANL. He has been at P-24 for the past five years working on nuclear fusion and plasma technology, which both are directed to national energy and homeland security. Nuclear fusion technology includes 1) fusion gamma-ray detector development for National Ignition Facility and 2) neutron generator development for detecting special nuclear materials. Plasma technology includes 1) plasma assisted combustion, 2) plasma catalyzed coal gasification, and 3) atmospheric pressure plasma jet. Dr. Kim, the winner of a 2005 Distinguished Performance Award at LANL for novel applications of atmospheric-pressure, non-thermal plasmas, received the B.S., M.S., and Ph.D. degrees in nuclear engineering from Seoul National University, Seoul, Korea, in 1994, 1996, and 2002, respectively. He was awarded the Best Student Prize at 4th Asia-Pacific Conference on Plasma Science and Technology held in Sydney in 1998. In 2002, he joined with Korea Institute of Machinery & Materials, where he worked on the plasma-SCR system for after-treatment of 300-hp diesel engine exhaust. Since 2003, he has been worked for the P-24 in Los Alamos. He has written twelve first-authored papers in peer-reviewed journals and one US patent. He has been a member of the Institute of Electrical & Electronics Engineers (IEEE). He serves as a reviewer for the IEEE Transactions on Plasma Science.*

# A Comparison of Plasmatron and Small Thermal Fuel Reformers

*V. Yu. Plaksin, O. V. Penkov, S.B. Joa, H. J. Lee,*
*Department of Nuclear & Energy Engineering,*
*Jeju National University, South Korea*

A comparison of two types of diesel fuel reformers having partly similar sizes and structure has been made. The first reformer was a plasmatron. In the DC arc plasmatron, a plasma forming gas channel in between cathode and anode filled with argon flow is separated from the technologic channel where an activation of the process gas flow takes place. The gas is excited by a hot arc discharge, flows into the technologic channel through an anode orifice to induce the plasma chemical interaction with the cold process gas consisting of atomized diesel fuel mixed with air. After this interaction the reacting gases are pressing throw an orifice to the pipe, where the reaction accomplishes, and gas is cooling.

Another reformer is a thermal reformer, which consists of three main parts. The first one is the active element – a 100 cell per square inch Si-C filter block which originally has a diameter of 81 mm and length of 103 mm from the Notox company, but we usually used only a cut with a diameter 20-28 mm. The filter was used as a diesel particulate filter (DPF) in origin. The second part is a fuel preparation system. The last part is stainless steel housing, containing a thermal insulation, and electric feed-through. As a fuel preparation system we used spray nozzle or pre-heating with an evaporation of the diesel oil. The fuel reformation reaction goes without supplying the power to the reaction zone. But to ignite the reaction at the start-up we used an electrical heating of the active part in both modifications of fuel supply, and spark ignition of the lean mixture when we worked with the evaporator.

The operation and efficiency comparison was made using the near bands of fuel flow rates (1.5-5.0 ml/min) and O/C ratios (0.8-3.0). The good reformation degrees with a plasmatron were achieved in mixtures reach of oxygen. An amount of CO in the resulting gases reached the theoretical maximum at the O/C ratio about 2. The thermal reformers have maximum efficiencies lower, but they show better performance at stoichiometric ratios of components.

# Gasification of Oil Shale from Aleksinac Using Plasma Technology. Plasma-Allo-Autothermal Gasification and Plasma Steam Gasification Process Simulation Results

*V.E. Messerle, Ulan-Ude Branch of the Institute of Thermophysics of SB RAS, Ulan-Ude, Russia*

*A.B. Ustimenko, Research Department of Plasmotechnics, Research Institute of Experimental and Theoretical Physics of Kazakhstan National University, Almaty, Kazakhstan*

*P.M. Rakin, IHIS Naučno Tehnološki Park ZEMUN, Belgrade, Serbia*

*Z.N. Dragosavljevich, Public Enterprise for Underground Coal Exploitation, Resavica, Serbia*

*D.P. Rakin, IHIS Development & Production Center, Belgrade, Serbia*

The article presents results of developed plasma technology of coal gasification, applied on oil shale of Aleksinac. Results are obtained using a mathematical model and codes for numerical investigation of the processes of plasma-allo autothermal gasification and plasma-steam gasification of oil shale.

Results show full economical and ecological sense to use oil shale for plasma production of synthetic gas which can be used, besides others for production of electric energy.

Based on the results of researching using mathematical modeling of the process of plasma gasification of oil shale from Aleksinac, we propose their use for plasma gasification with air as plasma gas with the goal to produce energy gas from the organic part of the oil shale mass which would be used in boilers as a substitute for heavy oil or natural gas.

The condensed products of the air gasification of oil shale are a mixture of mineral components, released carbons of the following composition (% by weight): $SiO_2$ – 7,2 ; $Al_2O_3$ – 13,5 ; FeS – 5,7 ; $MgSiO_3$ – 11,9 ; $CaSiO_3$ – 54,9 ; $K_2Si_4O_9$ – 6,8. A mixture of this composition can be used for producing cement and as filler for fire proof concrete.

A final analysis of use of condensed products of plasma gasification of oil shale must be carried out in cooperation with cement production experts. This is necessary, on one hand because of the economic side of use of oil shale for plasma gasification and on the other hand because of ecological conditions.

Due to considerably large reserves of mineral raw materials in the mentioned mine near Aleksinac, Serbia alone, a group of authors came to the conclusion that it could be used, by implementing plasma technology and production of synthesis gas, for production of electric energy.

## References

1. M. Gorokhovski, E.I. Karpenko, F.C. Lockwood, V.E. Messerle, B.G. Trusov and A.B. Ustimenko. "Plasma Technologies for Solid Fuels: Experiment and Theory." *Journal of the Energy Institute*, 78 (4), pp. 157-171, 2005.

2. V.E. Messerle, A.B. Ustimenko. *Solid Fuel Plasma Gasification*. In Advanced Combustion and Aerothermal Technologies, N.Syred and A.Khalatov (eds.), Springer, 2007, pp.141-156.
3. V. Galvita, V.E. Messerle, A.B. Ustimenko. *Hydrogen production by coal plasma gasification for fuel cell technology*. International Journal of Hydrogen Energy, 32 (16), pp. 3899-3906, 2007.
4. Matveev I.B., Messerle V.E., Ustimenko A.B. *Plasma Gasification of Coal in Different Oxidants.* // Plasma Science, IEEE Transactions on. V. 36, Issue 6, Dec. 2008 P. 2947 – 2954.
5. M.Khan, L.Khan, V.G.Lukiaschenko, V.E.Messerle, A.B.Ustimenko. *Petrocoke plasma steam gasification.* // Abstracts and full-papers CD of 17th International Symposium on Plasma Chemistry // Toronto, Canada, August 7-12, 2005. – Abstract – p. 1038-1039, CD – Topic 13, P.P.11
6. O.A.Lavrichshev, V.E.Messerle, E.F.Osadchaya, A.B.Ustimenko. *Plasma Gasification of Coal and Petrocoke.* // Contributed papers to the 35th European Physical Society Conference on Plasma Physics, 9-13 June 2008, Hersonissos, Crete, Greece, O2.018.

***Vladimir E. Messerle*** *was born on June 10, 1947 in Alma-Ata, Kazakhstan. In 1970 he graduated from Physical department of Kazakh State University. He received a Candidate Degree on physical and mathematical sciences (equivalent to Ph.D.), Moscow, 1979, a Doctor Degree on technical sciences, Moscow, 1991. He has been a Professor, Moscow, 1997, an academician of the International Energy Academy, Moscow, 1997, and an academician of the International Informatization Academy, Moscow, 2003. He is Professor of the Chair "Thermal Power Plants" of East-Siberian State Technological University, Ulan-Ude, 1998, and Professor of the Chair of Thermal Physics of the Department of Physics of Kazakh National University after al-Farabi, 2002. He is a head of the laboratory of Plasma Chemistry of the Combustion Problems Institute, 2001. Vladimir Messerle is the main author of the technology of electrothermochemical preparation of the solid fuel for burning. Under the direction of Professor Messerle, 11 Ph.D. theses and 2 doctoral theses were prepared and defended.*

***Alexander B. Ustimenko*** *was born on August 24, 1962, in Alma-Ata, Kazakhstan. He graduated from Kazakh State University, Physical department in 1984 and received a Candidate Degree on physical and mathematical sciences (equivalent to Ph.D.) in 1991. The topic of the thesis is "High-Temperature Heating and Gasification of Coal Particles". From 1984 to 2001 he was a researcher of the Kazakh Scientific-Research Institute of Energetics. From 2001 to 2007 he was a leading staff scientist of Combustion Problems Institute at al-Farabi Kazakh National University. Since 1991 he has been with the Research Department of Plasmotechnics (Kazakhstan) as CEO, and since 2002 he has been a leading staff scientist of Research Institute of Experimental and Theoretical Physics at the Physical Department of al-Farabi Kazakh National University.*

***Petar M. Rakin*** *is a Senior Research Scientist, and also the general director of IHIS Science & Technology Park Zemun, Belgrade, Serbia (+381 11 2195 700; mob. +381 63 212 512; e-mail: ihis@eunet.yu).*
*He started (1963) research on kinetics of electrode processes (PhD) and applied electrochemistry and fuel cells at the Faculty of Technology and Metallurgy.*
*He earned his PhD at Belgrade University - Yugoslavia in technical sciences (electrochemistry). He is a founder (1971) of Chemical Power Sources Institute leading many development projects in the same field.*
*He is a founder (1991) of a Technology Park which in 2006 has been registered by the Ministry of Science of Serbia as a Science & Technology Park.*
*He is keen on Renewable energy, Electric Vehicles, Clean technologies and Environment. He is member of Rotary International.*

**Zlatko Dragosavljevich** *has a dipl.ing. in Mining and Economics earned at Belgrade University, Faculty of Mining and Geology and at the European University of Belgrade, Faculty of Service Business, Department of Financial Business Management.*
*Since 1993 he has been employed at the Public Enterprise for underground exploitation of coal starting as a young engineer through all other levels to the General Director of the Enterprise.*
*He started to be very interested in the commercial use of plasma technology in production of electric energy, and is doing research on plasma gasification of oil shale.*

***Dejan P. Rakin*** *has a dipl.ing. in Mechanical Engineering. He earned his diploma at Belgrade University, Faculty of Mechanical Engineering. He is the owner and Director of IHIS Development & Production Center Ltd. (a member of the S&T Park) and at the same time the Manager of IHIS Science & Technology Park Zemun Corp. (Tel. +381-2195-700; Mob. +381-63-445-320; e-mail: dejarak@eunet.rs)*
*He started his research in technical chemistry, but already several years he paid attention to innovation technologies using plasma techniques. He is very familiar with techno-economic studies preparing business plans for different innovation projects.*

# Coal Fired Thermo Electric Power Plants without Hazardous Emissions

*.E. Messerle, Ulan-Ude Branch of the Institute of Thermophysics of SB RAS, Ulan-Ude, Russia*

*A.B. Ustimenko, Research Department of Plasmotechnics, Research Institute of Experimental and Theoretical Physics of Kazakhstan National University, Almaty, Kazakhstan*

*P.M. Rakin, IHIS Naučno Tehnološki Park ZEMUN, Belgrade, Serbia*

*D.P. Rakin, IHIS Development & Production Center, Belgrade, Serbia*

On the basis of research done in Kazakhstan and Russia on gasification of coal of different quality using plasma technologies, it was concluded that plasma-allo-autothermal coal gasification and plasma-steam gasification and complex treatment of coal for getting synthesis gas ($CO+H_2$), hydrogen ($H_2$) and useful byproducts from the mineral components of coal, are economically justified procedures which will enable these 21 century technologies to be used in Serbia today in a commercial sense. For testing of domestic lignite, samples of wet and dried lignite were chosen. In this paper the test results are given for plasma gasification using a combined type plasmatron, in which the heat development space is the same as the space for taking away heat by using exothermal reaction gasification. This way the losses are minimal and the use of electrical energy is very close to the theoretical values of the gasification reaction.

The testing results on a device with power of 100kW showed justification for working on the task of defining the industrial parameters for which building a pilot plant with power of 1.000kW has been suggested which will give us the parameters for building a smaller industrial plant which could process 32 tons of pulverized lignite an hour.

Since large quantities of electrical energy are needed for the gasification process in this paper we discussed conditions for industrial implementation which would enable EPS in general cheaper production of electrical energy.

**References**

1. Gorokhovski M.A., Karpenko E.I., Lockwood F.C., Messerle V.E., Trusov B.G., Ustimenko A.B. *Plasma Technologies for Solid Fuels: Experiment and Theory* // Journal of the Energy Institute. 2005. V. 78. № 4. P. 157.
2. Matveev I.B., Messerle V.E., Ustimenko A.B. *Plasma Gasification of Coal in Different Oxidants* // Plasma Science, IEEE Transactions on. Volume 36, Issue 6, Dec. 2008 P.2947 – 2954.
3. Messerle V.E., Ustimenko A.B. *Solid fuel plasma gasification* // Advanced Combustion and Aerothermal Technologies, N.Syred and A.Khalatov (eds.), Springer, 2007, pp.141-156.

***Vladimir E. Messerle*** *was born on June 10, 1947 in Alma-Ata, Kazakhstan. In 1970 he graduated from Physical department of Kazakh State University. He received a Candidate Degree on physical and mathematical sciences (equivalent to Ph.D.), Moscow, 1979, a Doctor Degree on technical sciences, Moscow, 1991. He has been a Professor, Moscow, 1997, an academician of the International Energy Academy, Moscow, 1997, and an academician of the International Informatization Academy, Moscow, 2003. He is Professor of the Chair "Thermal Power Plants" of East-Siberian State Technological University, Ulan-Ude, 1998, and Professor of the Chair of Thermal Physics of the Department of Physics of Kazakh National University after al-Farabi, 2002. He is a head of the laboratory of Plasma Chemistry of the Combustion Problems Institute, 2001. Vladimir Messerle is the main author of the technology of electrothermochemical preparation of the solid fuel for burning. Under the direction of Professor Messerle, 11 Ph.D. theses and 2 doctoral theses were prepared and defended.*

***Alexander B. Ustimenko*** *was born on August 24, 1962, in Alma-Ata, Kazakhstan. He graduated from Kazakh State University, Physical department in 1984 and received a Candidate Degree on physical and mathematical sciences (equivalent to Ph.D.) in 1991. The topic of the thesis is "High-Temperature Heating and Gasification of Coal Particles". From 1984 to 2001 he was a researcher of the Kazakh Scientific-Research Institute of Energetics. From 2001 to 2007 he was a leading staff scientist of Combustion Problems Institute at al-Farabi Kazakh National University. Since 1991 he has been with the Research Department of Plasmotechnics (Kazakhstan) as CEO, and since 2002 he has been a leading staff scientist of Research Institute of Experimental and Theoretical Physics at the Physical Department of al-Farabi Kazakh National University.*

***Petar M. Rakin*** *is a Senior Research Scientist, and also the general director of IHIS Science & Technology Park Zemun, Belgrade, Serbia (+381 11 2195 700; mob. +381 63 212 512; e-mail: ihis@eunet.yu).*

*He started (1963) research on kinetics of electrode processes (PhD) and applied electrochemistry and fuel cells at the Faculty of Technology and Metallurgy.*

*He earned his PhD at Belgrade University - Yugoslavia in technical sciences (electrochemistry). He is a founder (1971) of Chemical Power Sources Institute leading many development projects in the same field.*

*He is a founder (1991) of a Technology Park which in 2006 has been registered by the Ministry of Science of Serbia as a Science & Technology Park.*

*He is keen on Renewable energy, Electric Vehicles, Clean technologies and Environment. He is member of Rotary International.*

***Dejan P. Rakin*** *has a dipl.ing. in Mechanical Engineering. He earned his diploma at Belgrade University, Faculty of Mechanical Engineering. He is the owner and Director of IHIS Development & Production Center Ltd. (a member of the S&T Park) and at the same time the Manager of IHIS Science & Technology Park Zemun Corp. (Tel. +381-2195-700; Mob. +381-63-445-320; e-mail: dejarak@eunet.rs)*

*He started his research in technical chemistry, but already several years he paid attention to innovation technologies using plasma techniques. He is very familiar with techno-economic studies preparing business plans for different innovation projects.*

# Plasma Coal Gasification Pilot Plant

*Igor B. Matveev*
*Applied Plasma Technologies, McLean, USA*

Progress in the development of high power, high effective, and long lasting plasma sources enables many technologies, including coal gasification [1 - 3]. A pilot plant based on a recently engineered line of the hybrid torches and according to suggested APT flow diagram in Fig. 1 is currently under development by the international team, including research centers and scientists from the USA, Ukraine, Russia, Turkey, and Germany.

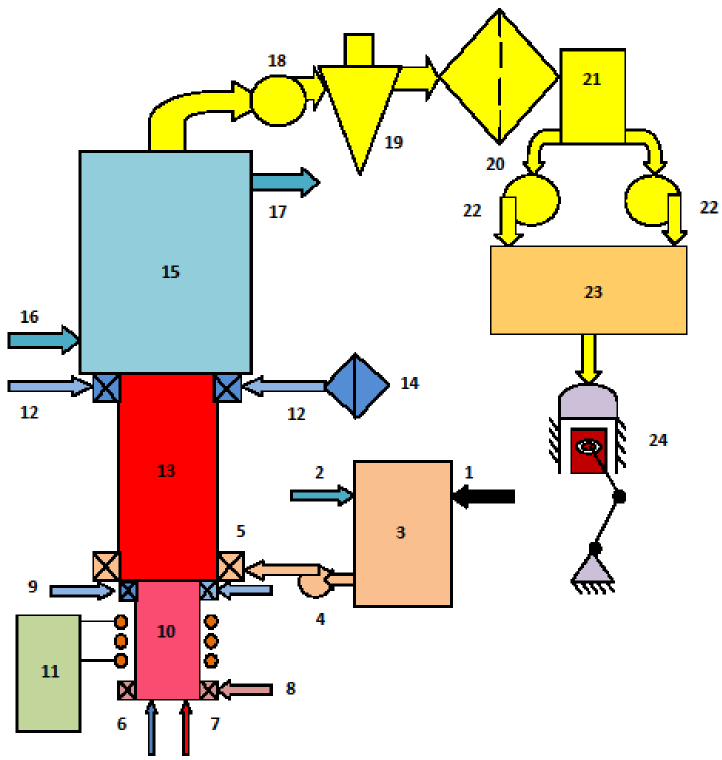



*Fig.1. Coal gasification pilot plant:*
*1 – coal dust; 2 - water; 3 – slurry tank; 4 – slurry pump; 5 – slurry feeder;*
*6 – plasma torch cooling water input; 7 – igniter; 8 – start up gas;*
*9 – plasma gas (air or oxygen); 10 – plasma torch; 11 – plasma torch power supply;*
*12 – oxidant (O2); 13 – triple vortex gasification chamber; 14 – oxygen separation unit;*
*15 - synthesis gas cooler – water/steam boiler; 16 – water input; 17 – hot water or steam output;*
*18 – fan; 19 – cyclone filter; 20 – fine particles filter; 21 – syngas control and distribution unit;*
*22 – synthesis gas compressors; 23 – syngas storage tank;*

The customer - Turkish coal enterprises (TKI) plans to establish the test facilities near one of the coal mines to work out technology based on a 150 kW torch with further scaling up and utilizing different feedstocks. The pilot plant will generate electricity and steam/hot water for district heating. As an option, it could be converted into a mobile version for remote sites powering and heating.

**References**


1. I. Matveev, S. Serbin, *Preliminary Design and CFD Modeling of a 1 MW Hybrid Plasma Torch for Waste Destruction and Coal Gasification*, 2-nd Int. Workshop and Exhibition on Plasma Assisted Combustion, Falls Church, Virginia, pp. 43–44, 2006.
2. I.B. Matveev, V.E. Messerle, A.B. Ustimenko. *Plasma Gasification of Coal in Different Oxidants.* IEEE Trans. Plasma Sci., 36 (6), pp. 2947-2954, Dec. 2008.
3. I.B. Matveev, V.E. Messerle, A.B. Ustimenko. *Investigation of Plasma-Aided Bituminous Coal Gasification*. IEEE Trans. Plasma Sci., 37 (4/2), pp. 580-585, Apr. 2009.


***Igor Matveev*** *was born in Russia on February 11, 1954. He earned his Master of Science degree in mechanical engineering from Nikolaev Shipbuilding Institute, Nikolaev, Ukraine, in 1977 and his Ph.D. degree in 1984. His Ph.D. thesis was entitled "Development and Implementation of The Plasma Ignition Systems for Naval Gas Turbines." From 1977 to 1990 he was a Researcher, Teacher and Associate Professor with the Nikolaev Shipbuilding Institute. In 1990 Dr. Matveev established a privately owned company Plasmatechnika (Ukraine) for development and mass production of plasma systems. Over 1,200 plasma systems developed under his supervision are in operation worldwide. In 1996 he was awarded the title "Citizen of the Year" in his native city. From 2000 to 2002 he served as an international consultant for the UN Economic Commission for Europe in energy and water conservation. During that time the UN project established the Energy and Water Conservation Zones in Ukraine, Kazakhstan, and Kyrgyzstan. Since 2003 he is with Applied Plasma Technologies, McLean, VA, as President and CEO. Since 2004 Dr. Matveev has been a guest editor for the IEEE Plasma Assisted Combustion special issue and the organization committee chair for the 2nd, 3rd, 4th, and 5th International Workshop and Exhibition on Plasma Assisted Combustion (IWEPAC).*

# CAT Gas Engines and Challenges for Syngas Application

*Dr. Myoungjin Kim*
*Caterpillar Inc., USA*

For more than 80 years, Caterpillar Inc. has been making progress possible and driving positive and sustainable change on every continent. With 2008 sales and revenues of $51.324 billion, Caterpillar is the world's leading manufacturer of construction and mining equipment, diesel and natural gas engines and industrial gas turbines. Total gas engine revenue in 2008 is around $1.2 billions and the gas engine sales didn't sag even at current economic downturn. The primary market for large CAT gas engine is electric power generation and gas compression, which has high profit margins. For electric power generation, CAT has a line up from 85kW ~ 6.5MW generator set fueled by the natural gas. As the concern about global warming and energy security issues grows up, the fuel sources for the gas engine is being diversified and alternative gaseous fuels are derived from a variety feedstock such as biomass, waste products, and coal via various conversion technology including gasification, pyrolysis, anerobic/aerobic digestion, etc. The gaseous fuels converted from biomass are getting spotlight in these days as a renewable resource with almost zero net $CO_2$ emission since carbon and energy are fixed during the biomass growth.

However, the gaseous fuels produced from diverse feedstocks have different gaseous composition and the heating values can be as low as $1/10^{th}$ of that of natural gas depending on the feedstock, conversion, and gas clean up process. Important gas properties of the producer gas that may impact the gas engine performance are laminar flame speed and methane number. Methane number is the determining parameter for the assessment of the knock resistance and the laminar flame speed is the main criteria of the producer gases as to whether or not they can be combusted in the gas engine. Another critical properties regarding the producer gas for the gas engine application are the impurities generated during the gasification of the biomass and the coal. Gasification is a proven technology and has been commercially applied for more than a century for the production of fuels and chemicals. However, the unwanted components in the producer gases including particles, alkali, tars, and ammonia should be removed before going to the gas engine combustion since they could damage turbocharger, compressor, and other gas engine components and shorten the engine life time. Thus, the gas cleanup and conditional process are indispensible and critical for the success of the gas engine application for utilizing the biogas and syngas produced via gasification process.

***Arnold Kim:*** *graduated from the University of Texas at Austin in 2005 with a Ph.D degree in mechanical engineering. He joined the University of Texas at El Paso as an assistant professor in the mechanical engineering department in fall 2005 and taught the student till spring 2008. He was also a director of Engine and Alternative Fuels Research Lab (EAFRL) in the university. In 2008, he resigned the faculty in the university and started new career in Caterpillar Inc. as an engineering project team leader in gas engine development for electric power generation and gas compression. He worked for Hyundai Motor Company for 7 years as a research engineer in the development of combustion system for automotive engines before going to USA for his Ph.D study in 2001.*

# Development and Experimental Investigations of High Power Hybrid Plasma Torches

*Dr. Igor B. Matveev, S. Matveyeva, E. Kirchuk*
*Applied Plasma Technologies, USA*

*Dr. Sergey Zverev, Saint-Petersburg State Polytechnic University,*
*Saint-Petersburg, Russia*

The authors report results of a three year initiative project on development of a product line of high power (over 50 kW), high efficient (total efficiency from grid to a plasma plum enthalpy over 65%), atmospheric pressure, low maintenance (lifetime over 1,000 running hours), multi-purpose plasma torches with remote ignition. These torches will be mainly applied for gasification of coal, petro-coke, waste, and hydrocarbons; pyrolysis of bio mass; synthesis of new materials; production of nano- powders and fullerenes; for etching, coating, and melting; for treatment of hazardous liquids, coal ash, and fly ash; recovery of contaminated soil; simulation of hypersonic flights; destruction of bio weaponry, ammunition, and drugs; possible combining with the plasma chemical reactors.

Comparison of developed hybrid plasma system efficiency with other plasma sources is provided in a table below. It shows that new plasma system is significantly more efficient than know ICP, existing DC ones, and provide similar scores as even expected from the future MW systems, which at the moment have power limitations and much more expensive. Such a progress in efficiency improvement allowed authors to name their products as the 2$^{nd}$ generation of the ICP systems. General view of the 50 kW and 150 kW torch samples could be seen in Fig. 1.

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

Established for the project development international research team is focused on the product line extension in the near future up to 1 MW per unit and testing of the new technologies, enabled by employment of the new generation of plasma sources.

*Fig. 1. Hybrid torch samples*

*Fig.2. Experimental setup for the hybrid torches investigations*

**References**


1. I. Matveev, S. Serbin, *Preliminary Design and CFD Modeling of a 1 MW Hybrid Plasma Torch for Waste Destruction and Coal Gasification*, 2-nd Int. Workshop and Exhibition on Plasma Assisted Combustion, Falls Church, Virginia, 2006, pp. 43–44.
2. S.G. Zverev, V.Ya. Frolov, D.V. Ivanov, B.A. Ushin, G.K. Petrov, I.B. Matveev, *Experimental Investigations of the Hybrid Plasma Torch with Reverse Vortex Stabilization* , 4-th Int. Workshop and Exhibition on Plasma Assisted Combustion, Falls Church, Virginia, 2008, pp. 39–44.


***Igor Matveev** was born in Russia on February 11, 1954. He earned his Master of Science degree in mechanical engineering from Nikolaev Shipbuilding Institute, Nikolaev, Ukraine, in 1977 and his Ph.D. degree in 1984. His Ph.D. thesis was entitled "Development and Implementation of The Plasma Ignition Systems for Naval Gas Turbines." From 1977 to 1990 he was a Researcher, Teacher and Associate Professor with the Nikolaev Shipbuilding Institute. In 1990 Dr. Matveev established a privately owned company Plasmatechnika (Ukraine) for development and mass production of plasma systems. Over 1,200 plasma systems developed under his supervision are in operation worldwide. In 1996 he was awarded the title "Citizen of the Year" in his native city. From 2000 to 2002 he served as an international consultant for the UN Economic Commission for Europe in energy and water conservation. During that time the UN project established the Energy and Water Conservation Zones in Ukraine, Kazakhstan, and Kyrgyzstan. Since 2003 he is with Applied Plasma Technologies, McLean, VA, as President and CEO. Since 2004 Dr. Matveev has been a guest editor for the IEEE Plasma Assisted Combustion special issue and the organization committee chair for the 2nd, 3rd, 4th, and 5th International Workshop and Exhibition on Plasma Assisted Combustion (IWEPAC).*

***Svetlana Matveyeva** – MS in mechanical engineering, graduated from the Moscow Technical University named after Bauman. Specialized in robotics design including electric, hydraulic, pneumatic, and mechanical systems. Also studied manufacturing of specialized aircraft and space systems. Has over 25 years of intensive expertise in development of the plasma assisted combustion systems, including plasma torches, plasma pilots and nozzles, and reverse vortex combustors.*

***Evgeniy Kirchuk*** *was born in Ukraine on July 2, 1977. He earned his Master of Science degree in electrical engineering from Nikolaev Shipbuilding Institute, Nikolaev, Ukraine, in 2000.*
*Since 2003 he has been a manager of Plasma Technika Consult – the APT strategic partner in Ukraine. He served as a technical secretary for the 2nd, 3rd, 4th, and 5th International Workshop and Exhibition on Plasma Assisted Combustion (IWEPAC).*

***Sergey Zverev*, Ph.D.,** *Associate Professor of St-Petersburg State Polytechnic University (SPbSPU), Russia. Dr. Zverev teaches special courses, serves as a project manager for the Russian-France Plasma Technology Laboratory. He earned the M.S. and Ph.D. degrees in physics from St-Petersburg State Polytechnic University in 1999 and 2003, respectively.*
*PhD Thesis title: Investigation of RF plasma torch for treatment of fine-dispersed powders.*
*Dr. Zverev has 30 referred publications.*
*Research interests: plasma generation, plasma technologies and their industrial applications, power supplies, modeling of the plasma processes.*

# Arc Plasma Torches for RF Plasma Ignition and Other Technological Processes

*Prof. Vladimir Frolov, Dr. Boris Ushin, Dr. Georgy Petrov,*
*Dr. Sergey Zverev, Dr. Dmitry Ivanov*
*Saint-Petersburg State Polytechnic University,*
*Saint-Petersburg, Russia*

Investigations in the field of low temperature plasmas, DC arc plasma torches design, and their application have been carried out in the Science, Education, and Technology Centre "Electrotechnology" based on the State Polytechnic University, Saint Petersburg, Russia within a long time period.

As a result of numerous investigations a plasma torch concept with special inter-electrode sections has been chosen as a basis for initial discharge initiation in the high power RF torches. Employment of the inter-electrode sections allows significantly extend the arc length and accordingly the plasma jet power to make it sufficient for spraying and coatings of a wide variety of materials as metals, alloys, cermets, oxides, etc. Meanwhile, operating current does not exceed 250 A that favorably affects a resistance of arc channel elements. Operating voltage dependents on a plasma gas composition and flow rate. For argon it varies in the range from 60 to 120 V, for air and nitrogen in the range from 140 to 250 V.

Use of other type of plasma gases is also possible. The main application area of these plasma torches is spraying of coatings. However they can be used for ignition of RF plasma, to perform a number of plasma chemical reactions (see Fig. 1), or as a source of high enthalpy gas.

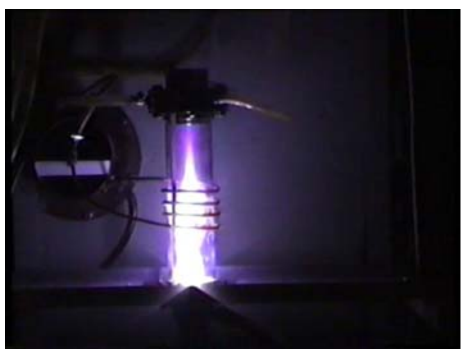


*Fig. 1. The prototype of a hybrid plasma torch*
*(application of arc plasma torch for initiation of RF plasma)*

Fig. 2 shows design of the model PN-V1 plasma torch, which was successfully applied in the Science, Education, and Technology Centre "Electrotechnology" and at a number of Russian companies. This plasma torch consists of the anode and cathode units divided by six inter-electrode sections. The range of operation power is 8–40 kW. Plasma gas is compressed air. Nitrogen is also an option. The cathode is a thermochemical one with hafnium insertion. It can be used for ignition of RF plasma in various environments as air, $N_2$, $CO_2$, mixtures of combustible gases, and also for spraying and coatings of metals, except easy oxidizing ones, plated powders of ceramics WC + Co, oxides $Al_2O_3$, $TiO_2$, $ZrO_2$, etc..

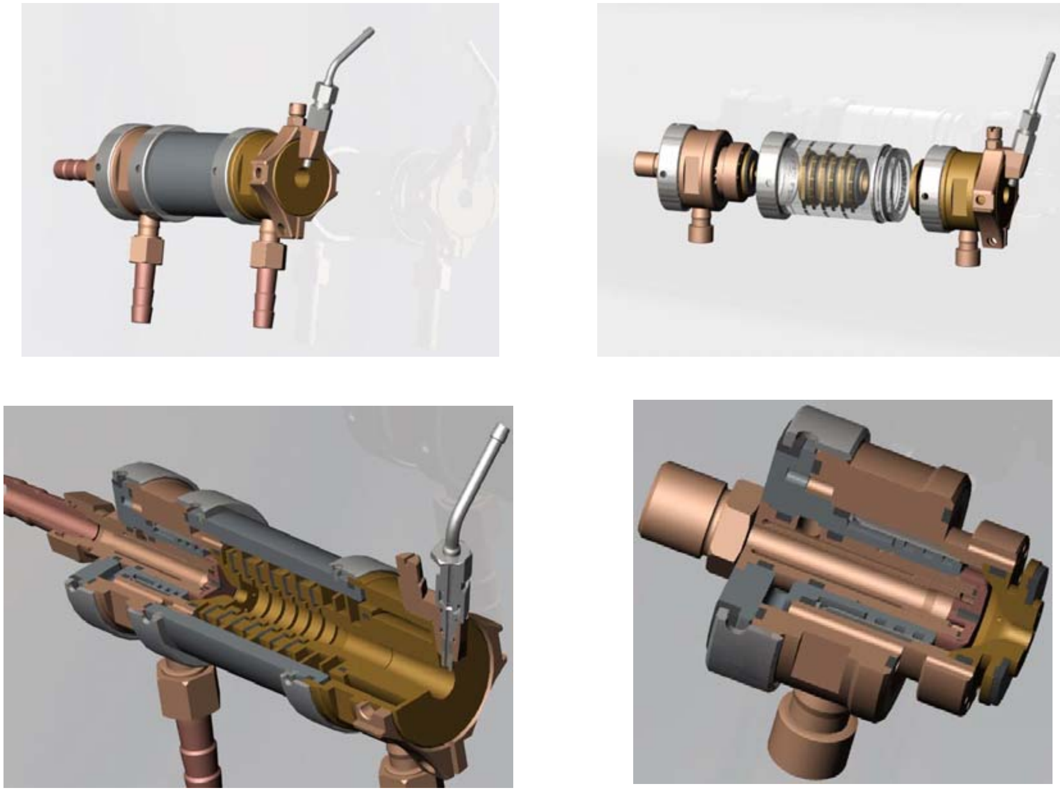


*Fig. 2. Air-arc plasma torch PN-V1 with 6 interelectrode sections: general view, disassembled view, sectional view and cathode unit*

The design of a plasma torch for operation on both inert and inactive plasma gases have been also developed. A product line of units is unified with the plasma torch PN-V1. This model is used to minimize oxidation of performed coatings if necessary.

The latest improvements of the arc working process in a cathode zone allowed increase the plasma torch lifetime up to 800 switching cycles.

## References


1. S.G. Zverev, V.Ya. Frolov, D.V. Ivanov, B.A. Ushin, G.K. Petrov, I.B. Matveev, *Experimental Investigations of the Hybrid Plasma Torch with Reverse Vortex Stabilization* , 4-th Int. Workshop and Exhibition on Plasma Assisted Combustion, Falls Church, Virginia, 2008, pp. 39–44.
2. V.Ya. Frolov, V.S. Klubnikin, G.K. Petrov, B.A. Ushin. *Engineering and Technology of Coating Deposition*. Saint Petersburg Polytechnic University publishing house, 2008, p. 387.

***Dr. Sc., Professor Vladimir Frolov.*** *Graduated from the St-Petersburg State Polytechnic University. From 2005 head of department of electotechnics and electric technologies. Head of the Science, Education, and Technology Center Electrotechnologia. The main research results are in the field of investigation and modeling of the plasma processes, development of contact plasma processing of materials, thermal gas spraying and coating. Prof. Frolov published over 150 scholar articles. He is the author of 22 patents, was honored by a title Inventor of the USSR.*

***Sergey Zverev, Ph.D.,*** *Associate Professor of St-Petersburg State Polytechnic University (SPbSPU), Russia. Dr. Zverev teaches special courses, serves as a project manager for the Russian-France Plasma Technology Laboratory. He earned the M.S. and Ph.D. degrees in physics from St-Petersburg State Polytechnic University in 1999 and 2003, respectively.*

*PhD Thesis title: Investigation of RF plasma torch for treatment of fine-dispersed powders.*

*Dr. Zverev has 30 referred publications.*

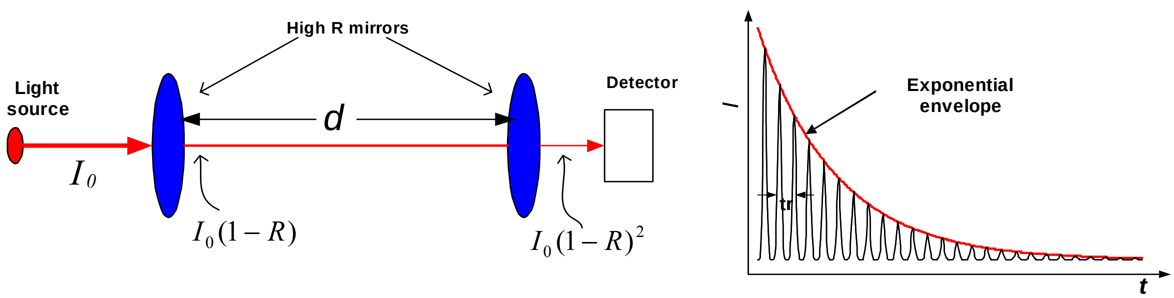
*Research interests: plasma generation, plasma technologies and their industrial applications, power supplies, modeling of the plasma processes.*

# Cavity Ringdown Spectroscopy - a New Tool to Study Mechanisms of Plasma-Assisted Combustion through Measuring Absolute Number Densities

*Dr. Chuji Wang, Department of Physics, and the Institute for Clean Energy Technology, Mississippi State University, Starkville, USA*

The combination of cavity ringdown spectroscopy (CRDS) with optical emission spectroscopy and visualization imaging can provide a full characterization spectrum of plasma/ combustion in terms of temperatures, electron densities, plasma plume/combustion flame images, and absolute number densities of plasma/combustion intermediates.

CRDS is a relatively new laser absorption technique used in the spectroscopy community and the basic concept is illustrated in Figure 1. The unique features of high sensitivity, near real-time response, and the capability of measuring absolute number density make CRDS attractive in many applications. CRDS has been used for pressure- and temperature-dependent kinetics studies in a chemical reaction chamber, taking advantage of its high sensitivity and capability of tracking variations in the concentrations of reactants/products in real-time, *in situ*. CH, OH, CN, HCO, $CH_2$, etc. radicals in combustion flames and atmospheric ovens have been quantified by CRDS. During the last eight years, CRDS has been demonstrated for plasma diagnostics, plasma processing, and quantification of plasma species,




**The effective absorption path-length is readily increased more than 10,000-fold**

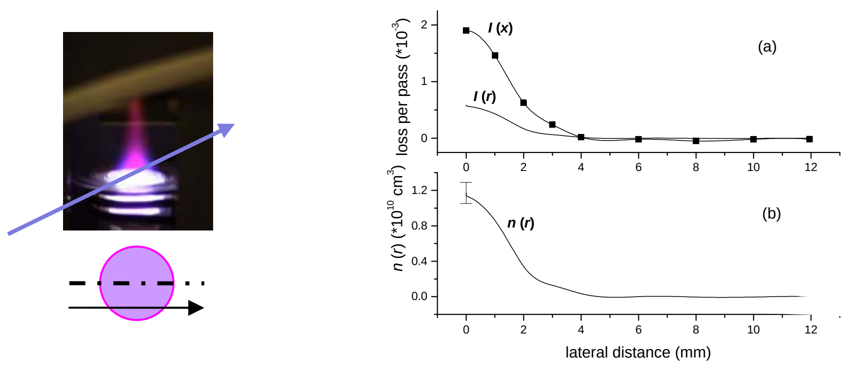
*Fig. 1. Illustration of CRDF concept*

including OH radicals in an inductively coupled plasma, microwave plasma torch (MPT), DBD, AC discharge, and MW plasma jet. Figures 2 - 5 show a few examples of the determination of absolute densities of OH radicals in different plasmas using the CRDS technique. To date, no publication has reported the application of CRDS to measurements of absolute number densities and to the study of reaction kinetics in plasma-assisted combustion (PAC).

Given typical mirror reflectivities of 99.995% and an experimentally achievable ringdown baseline noise of ~ $10^{-3}$, the minimum detectable absorbance is ~ 5 ´ $10^{-8}$, corresponding to, e.g., minimum detectable OH radicals of $10^{-10}$ - $10^{-11}$ molecule/$cm^3$ (parts per billion (ppb) levels), given the absorption cross-section of OH radicals to be $10^{-18} cm^2$/molecule at 308 nm. By using a broadly tunable laser source with ringdown mirrors coated at different wavelengths, a large number of species can be quantified with detection limits of ppb or even lower.

Given typical mirror reflectivities of 99.995% and an experimentally achievable ringdown baseline noise of ~ $10^{-3}$, the minimum detectable absorbance is ~ 5 ´ $10^{-8}$, corresponding to, e.g., minimum detectable OH radicals of $10^{-10}$ - $10^{-11}$ molecule/$cm^3$ (parts per billion (ppb) levels),

given the absorption cross-section of OH radicals to be $10^{-18} cm^2$/molecule at 308 nm. By using a broadly tunable laser source with ringdown mirrors coated at different wavelengths, a large number of species can be quantified with detection limits of ppb or even lower.




Abel inversion: $$i(r) = -\frac{1}{\pi}\int_{r}^{R_0} \frac{I'(x)}{\sqrt{x^2 - r^2}}\,dx$$

*Fig. 2. Density distribution of trace lead (Pb) atoms in an inductively coupled plasma measured by CRDS*

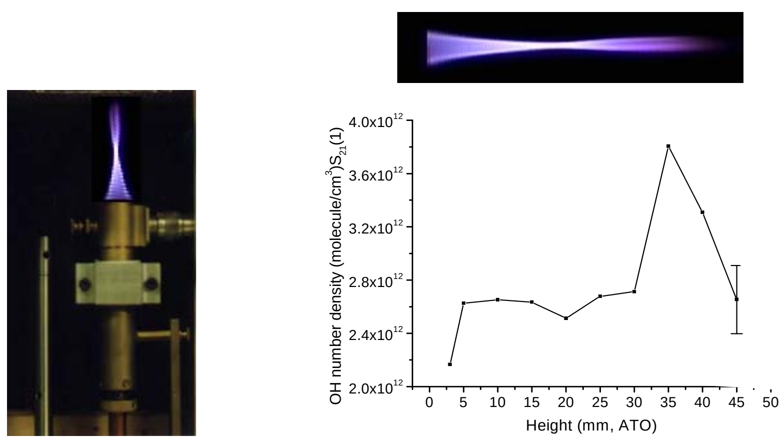
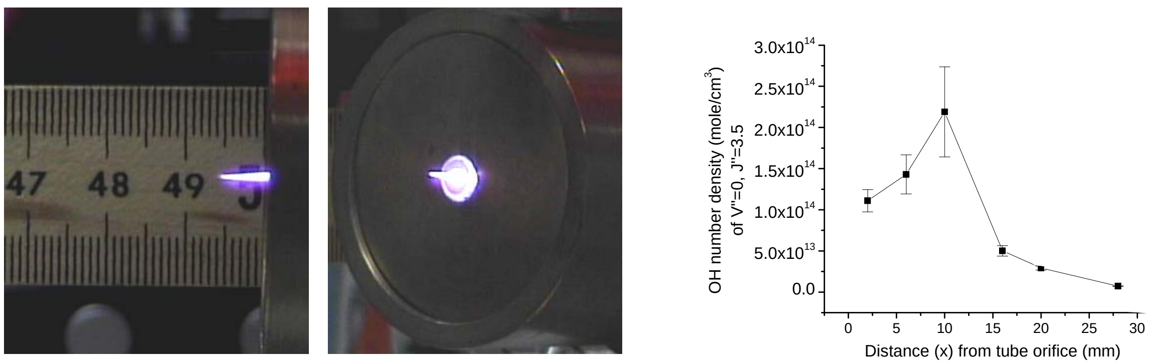



*Fig. 3. Absolute OH densities in an MW plasma torch measured by CRDS*

*Operating Conditions:*
*Power: 15 -120 W; Middle FR: 0.45 lpm; Central FR: 0.65 lpm;*
*Gas: argon; MIP source: 2.45 GHz*

CRDS differentiates itself from LIF in that CRDS has no adverse impact from the quenching effect of the excited states and CRDS offers measurements of absolute number density sans calibration. CRDS also differs from resonance-enhanced multiphoton ionization and is universally applicable to measurements at high and low pressures. CRDS cannot be simply replaced by the much simpler tunable diode laser absorption spectroscopy (TDLAS) technique because when radicals or species concentrations are low, e.g., ~ ppb levels, single-pass TDLAS is not sensitive enough. When CRDS is combined with OES, as we demonstrated very recently, information about temperature(s), electron density, and species concentration can be simultaneously determined.

Combination of CRDS with mass spectrometry (MS), as proposed in this work, will provide a whole spectrum of combustion species (chemical components and their number densities). The typical measuring time of a single ringdown event is on the order of microseconds. This is especially important for the study of PAC, in which the three distinct combustion processes (pre-, during-, and post-ignition) can be probed in near real-time.




*Side view* *Front view*

*Fig, 4. Measurements of OH in an MW plasma jet by CRDS*

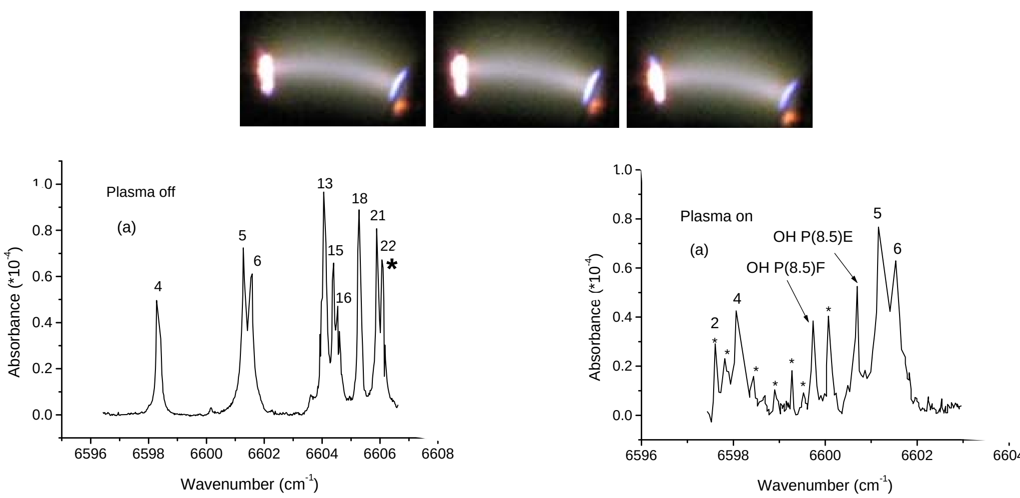



*Fig. 5. Measurement of OH in an AC discharge by NIR-CRDS*

We report latest results, including determination of OH radical density profiles in the aforementioned plasmas, and propose a new measuring and diagnostic means to study plasma-assisted combustion.

***Dr. Chuji Wang*** *is an Assistant Professor in the Department of Physics and Astronomy at Mississippi State University. He received his PhD degree in Chemical Physics at the University of Science and Technology of China in 1998. His research interests include diagnostics and applications of low-temperature atmospheric plasmas and development of novel sensors using cavity ringdown spectroscopy techniques. He has authored more than 50 peer-reviewed journal publications and holds four US patents. http://www2.msstate.edu/~cw175/.*

# Application of Thermal Plasma to Waste Treatment and Energy Recovery

*Pierre Carabin*
*PyroGenesis Canada Inc., Montreal, Quebec, Canada*

PyroGenesis Canada, Inc. has developed two unique waste treatment systems: the Plasma Arc Waste Destruction System (PAWDS) and the Plasma Resource Recovery System (PRRS).

In the PAWDS process, solid waste is pre-treated to render it into a lint-like material which is rapidly gasified in a patented plasma fired eductor. The process is highly automated requiring only minimal skills to operate and can be started up and shut down with the push of a single button. The programmable logic controller advises the operator when and where problems arise.

PAWDS has been developed under support of the US Navy to quickly gasify solid waste generated on board aircraft carriers. The PAWDS prototype in PyroGenesis' facility in Montreal has successfully undergone a sixty (60) day endurance test, being operated and maintained by US Navy sailors under the supervision of US Navy and PyroGenesis Canada personnel. The goal of these tests was to assess the overall maintainability and availability of the PAWDS and more importantly identify specific components which, if improved, would increase the PAWDS performance and reduce downtime. Atmospheric emissions from the system were measured by a certified independent laboratory. These tests confirmed that the design of the PAWDS off-gas cleaning system prevents the formation of dioxins and furans and as such these compounds were well below the most stringent worldwide emission criteria.

The patented Plasma Resource Recovery System (PRRS) converts waste into electrical energy, metal, and vitreous slag in two stages. Unsorted waste is fed into a graphite arc furnace. The organic portion is gasified to synthesis gas (syngas) while the inorganic portion melts and is tapped separately as metal ingots and vitrified slag usable as construction material. The syngas is polished using an air plasma torch removing long chain hydrocarbons, and tars, and then cleaned of particulates, heavy metals and acid gases. The clean syngas (typical composition of 24% CO, 6% $CO_2$, 15% $H_2$, 0.5% $O_2$ and balance $N_2$) can be fed into an internal combustion engine to produce energy.

PyroGenesis Canada, Inc. (PGC) operates a PRRS prototype facility in Montreal, Canada. PGC is currently scaling-up the system to treat 10.5 TPD of Municipal Solid Waste (MSW), Hazardous Waste and Biomedical Waste for a commercial application in the United States. Towards this scale-up, a computer process simulation model was developed to establish a basis for the mass and energy balance. Simulation results were validated on the prototype.

# High Power Microwave Devices and Their Applications for Solving Technological Problems

*J. Gulaev, V. Cherepenin, Institute of Radiotechnic and Electronics, Moscow, Russia*

*O. Maslennikov, I. Guzilov, P. Kruglenya, Federal State Unitary Enterprise "Research and Production Corporation TORIY", Moscow, Russia*

The results of experimental investigation of physical methods of suppressing biological activity of grain product pests: harmful insects at each stage of development including eggs and for destruction of hard gold containing ores are presented. The technologies under development are based on irradiation of grain and gold ores by high-frequency (HF) pulsed electromagnetic fields. The purpose of this preliminary study was to find conditions of pulsed microwave radiation in high frequency cavity, which leads to the death of insects and eggs and of increasing gold extraction from the hard rock ores.

**Grain processing**

Grain producers are actively seeking alternatives to chemical pesticides because of general concerns about effects on human health and the environment and because insect resistance to chemical pesticides is increasing. One of alternative treatments for infested stored products is usage of microwave radiation at frequencies >1 GHz. The power dissipated within a complex dielectric material:

$$P_d = \oiiint_v \omega \varepsilon_{eff} |E|^2 dv \quad (1)$$ ,

where $P_d$ is the power dissipated, ω is the angular frequency, $\varepsilon_{eff}$ is the effective dielectric loss factor (which is medium-specific and a nonlinear function of frequency) and the square of the magnitude of the electric field intensity $|E|^2$. At any frequency the factors $\varepsilon_{eff}$ and $|E|^2$ will determine the power dissipated in the dielectric body and consequent Joule heating of the body. Water is common to both insects and grain in bound form. However, unlike the relatively dry stored grain, a significant amount of free water occurs in insects. So, the moisture of insects and eggs (50-70%) is several times higher than the moisture of the grain (12-14%). Therefore, the effective dielectric loss factor of the insect will gradually increase at high frequencies whereas that of the product, which is below the critical moisture content, will not. This could lead to a more efficient selective heating of the insect and consequent higher mortality at a lower product temperature.

**Gold industry**

Gold typically occurs at very low concentrations in ores - less than 10 g/t or 0.001% (mass basis). At these concentrations the use of aqueous chemical (hydrometallurgical) extraction processes is the only economically viable method of extracting the gold from the ore. The first step in ore preparation is crushing and grinding, which reduces the particle size of the ore and liberates the gold for recovery. In hard rock ores small parts of gold are enclosed in sulfide shell, which prevents gold from the solution by cyanide. Sulfide shell might be destroyed by short high frequency power pulses. The ore processing is based on nonthermal action of pulsed electromagnetic fields on solid materials invented by Gulyev J., Cherepenin V.[1]. As a result, the percent of extracting gold by the following cyanidation increases.

**Experiment**

The goal of the tests was to determine the requirements for pulsed power signal to produce high levels of energy sufficient for the positive effect (mortality for the grain pests and increasing of gold extraction for hard ores). The test samples were exposed to 1,85 GHz pulse microwave power 7 MW, average power 1 kW in rectangular microwave cavity (Fig. 1). Magnetron was used to generate pulse microwave power with an efficiency of 50% and 5 μsec duration. Output power from the magnetron was transmitted in 13 cm by 6,5 cm copper rectangular waveguides to the cavity with a sample.

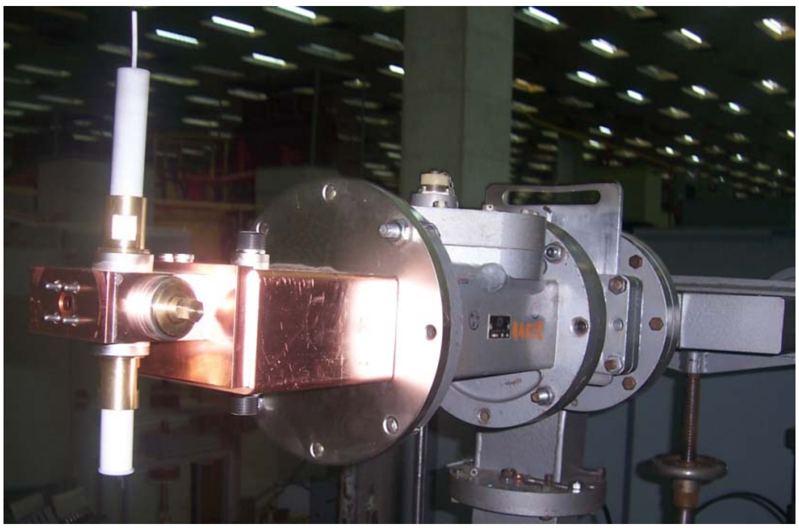


*Fig. 1. The sample (white color) in the cavity*

The sample consisted of the cylindrical envelope 110 mm length, and 18 mm diameter filled with infected grain or parts of hard rock ore, which can move through the high frequency field of the cavity. The time of exposure for one passage was 0,1 sec. During all exposures, HF power was measured with an accuracy of 4.0%.

**Results**

**Mortality of grain pests**

For the high-power test, 4 groups of four 26-g samples of wheat containing weevils, *Sitophilusgranarius L.*, at each of seven age stages. Three of these groups were designated as A, B, or C, and the 4th group (X) was used as a control. During the test effects of exposure on most of the adults appeared to be instantaneous. Immediate cessation of movement of all individuals was observed. Those adults that were killed during the exposure remained in a moribund state. A reconfirmation of adult mortality was obtained upon return of the samples 1 and 2 days after the exposure. The remaining samples with beetles and eggs were then observed for emergence over an additional period of 9 days for beetles and 26 days for eggs. Mortality of beetles and eggs is summarizing in table 1 and 2.

*Table 1*

| TIME OF EXPOSURE, sec | NUMBER OF BEETLES | MORTALITY, % | | | |
|---|---|---|---|---|---|
| | | 0 DAY | 1 DAY | 2 DAYS | 9 DAYS |
| 0 (control) | 50 | 0 | 0 | 0 | 0 |
| 0.1 | 100 | 4 | 36 | 39 | 53 |
| 0.3 | 109 | 14 | 54 | 64 | 100 |
| 0.6 | 56 | 43 | 82 | 88 | 100 |

*Table 2*

| TIME OF EXPOSURE, sec | NUMBER OF EGGS | MORTALITY, % | | | |
|---|---|---|---|---|---|
| | | 0 DAY | 1 DAY | 2 DAYS | 26 DAYS |
| 0 (control) | 70 | 0 | 0 | 0 | 0 |
| 0.1 | 120 | 6 | 25 | 30 | 46 |
| 0.3 | 131 | 10 | 46 | 52 | 95 |
| 0.6 | 72 | 35 | 75 | 82 | 100 |

It was shown, that the implementation of high-frequency technology in the cavity leads to destruction of harmful pests. It results in increase of efficiency of destruction grain pests, with complete environmental safety.

**Gold extraction from hard rock ores**

The average size of sulfide ores in experiment was 0,3 and 0,074 mm. The weight of samples was 52 g. After 0,1 sec of preliminary high power microwave treatment percent of extracting gold increased from 79% to 91% for 0,3 mm samples and from 83% to 94% for 0,074 mm samples.

**References**

1. Patent RF N2139142, B03B7/00.

**J. Gulaev,** *Academician of RAS, Director of Kotel'nikov Institute of Radio-Engineering and Electronics*

**V. Cherepenin,** *Professor, Vice Director of Kotel'nikov Institute of Radio-Engineering and Electronics*

**O. Maslennikov,** *Professor, Vice Director of FSUE "Toriy"*

**I. Guzilov,** *Ph.D. in physics and mathematics, Project Leader of FSUE "Toriy"*

**P. Kruglenya,** *Director of Scientific Research Center "VMZ"*

# System for Hydrocarbon Decomposition and Generation of Carbon Nanotubes Based on a Nonself-Sustained Microwave Discharge

*Yu. D. Korolev, O. B. Frants, N. V. Landl, V. G. Geyman*
*Institute of High Current Electronics, Tomsk, Russia*

*A. G. Zerlitsyn, V. P. Shiyan, Yu. V. Medvedev*
*Institute of Nuclear Physics, Tomsk, Russia*

Our previous experiments had demonstrated that a microwave discharge plasma torch with a power level of several kW and frequency of 2.45 GHz in nitrogen/natural gas mixtures served as efficient medium for production of carbon nanotubes [1]. The above experiments had been carried out with a usage on self-sustained microwave discharge. A schematic of previous experimental installation is shown in Fig. 1. Microwave power from 2 to 3 kW is supplied from a microwave generator via rectangular waveguide *1* and coaxial waveguide that forms by outer conductor *2* and inner conductor *3*. If the supplied microwave power is sufficient for the gas breakdown then a microwave plasma torch appears at the end of inner conductor. The gas composition is delivered in the discharge area through the aperture of 12 mm in diameter. Typical gas expenditure for the installation is about 1 $m^3$/hour.

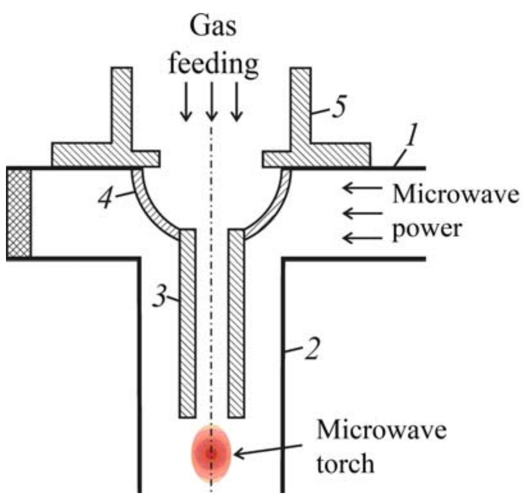



*Fig. 1. Experimental arrangement with a self-sustained microwave discharge.*
*1 - upper wall of the rectangular waveguide; 2 - outer conductor of the coaxial waveguide; 3 - inner conductor of the coaxial waveguide; 4 - interface; 5 - envelope of the system for preparing a nitrogen/natural gas composition*

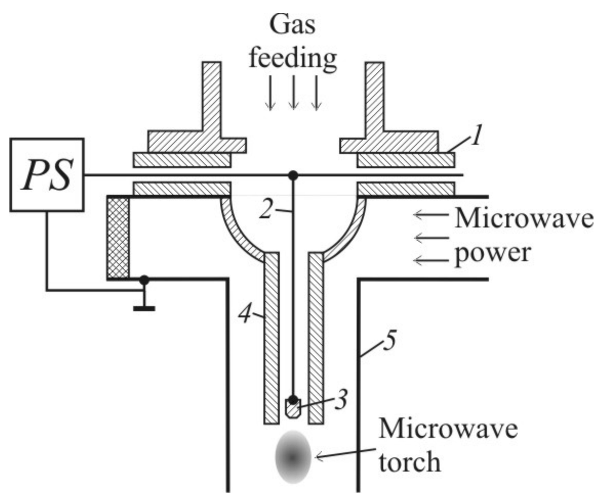



*Fig. 2. Experimental arrangement with a use of nonself-sustained microwave discharge.*
*1 - auxiliary flange; 2 - holder of plasmatron cathode; 3 - plasmatron cathode; 4 - plasmatron anode (inner conductor of coaxial waveguide); 5 - outer conductor of coaxial waveguide*

The natural gas decomposition and generation of nanotubes is provided due to the microwave power dissipated in the plasma torch. However, with a low power level a problem of discharge ignition appears since the electric field at the end of tube *3* becomes insufficient for gas breakdown. This is one of the drawbacks as applied to the regimes of self-sustained discharge. On the other hand, when the supplied power is extremely high (larger than 3 kW) the plasma torch has tendency to burn in a constricted mode, i.e. with a local current attachment at electrode *3*. In some regimes, such a mode can result in melting of the electrode surface.

This paper deals with the investigation of a method for external sustainment of the high-pressure microwave discharge in the installation for natural gas decomposition. The idea of the method is to generate an additional gas-discharge plasma in the area of microwave torch due to auxiliary discharge. Experimental arrangement is shown schematically in Fig. 2. It can readily be seen that as compared to Fig. 1, the installation is equipped with auxiliary flange *1* and with the electrode system for generation of auxiliary discharge plasma. The flange *1* has two side boreholes through which a high voltage from power supply *PS* is fed to electrode *3* of the auxiliary discharge. The discharge itself burns between electrode *3* and inner surface of tube *4*.

In most cases, we used dc current power supply *PS*, which is connected to the discharge gap via the ballast resistor $R_b$. Then, the auxiliary discharge unit resembles a coaxial nonsteady-state plasmatron were the discharge is sustained in a gas flow [2, 3]. Maximum voltage of power supply amounts to 4 kV, and an average discharge current is limited at a level of about 0.1 A. The obtained data demonstrate that the nonself-sustained microwave discharge operates a wide range of delivered microwave power.

The system as a whole combines the catalytic activation of natural gas and its further decomposition in the microwave plasma torch. The type of catalyzer and the discharge regimes influence both on the rate of natural gas conversion and on the structure of nanotubes. With a typical gas flow of 1 $m^3$/hour the natural gas conversion achieves 40-80 per sent. Three types of nanotubes are contained in the final product: multi-layer tubes, single-layer tubes and onion-type tubes.

## References


1. Yu. V. Medvedev, A. G. Zerlitsyn, V. E. Gunter et al, *Russian Patent No. RU 2317943 C2*, Published in: Electronic Bulletins-Inventions and Utility Models, no. 6, 2008.
2. Yu. D. Korolev, O. B. Frants, N. V. Landl, V. G. Geyman, and I. B. Matveev, *Glow-to-Spark Transitions in a Plasma System for Ignition and Combustion Control*, IEEE Trans. Plasma Sci., vol. 35, no. 6, pp. 1651-1657, Dec. 2007.
3. Yu. D. Korolev, O. B. Frants, N. V. Landl, V. G. Geyman, and I. B. Matveev, *Non-steady-State Gas-Discharge Processes in Plasmatron for Combustion Sustaining and Hydrocarbon Decomposition,* IEEE Trans. Plasma Sci., vol. 37, no. 4, pp. 586-592, April

# Flame Electrodes for Various Technological Applications

*V. Yu. Plaksin, O. V. Penkov, S.B. Joa, and H. J. Lee*
*Department of Nuclear & Energy Engineering, Jeju National University, South Korea*

Flame electrodes were designed for various technological applications as soot filters regeneration, fuel reformation processes, $CF_4$ decomposition.

For the development of the heating technology we took particulate filters from the Notox company, which they use at the exhaust cleaning process in the automobile industry. The filters made of SiC have an electrical conductivity; the resistivity is strongly altering with the temperature – the change can reach 5-6 orders of magnitude.

The resistivity to electrical current can be used to heat the block to eliminate (oxidize and volatilize) the soot collected by the filter. Also the fuel reformers which have the SiC blocks in the active area can use the electrical heat to initiate the reaction or partial oxidation or the $CF_4$ decomposition.

So, an application of voltage to the SiC structure can bring energy, or additional power to the process without any intermediary.

A connection of the ceramic block to the electrical circuit is not simple because of mechanical properties of carbide block and necessity to work at elevated temperatures. So, the direct electrode connection to the ceramic is not very reliable.

For the supplying of current we used the electrical conductivity of flame. We put a burner in front of the SiC block to make the flame contact the ceramic.

The filter is separated from the housing's side wall by an electrical and thermal insulation mat. One end of the filter is opened to the gas flow and has no direct connection to housing. By this side we applied the flame contact. Another end of the filter contacts to supporting armature, and at the place of contact has the same potential as the side walls. The voltage to support the above mentioned processes vas applied to the burner and side wall. Instead of applying voltage to the burner we can insert high temperature electrode to the flame itself.

# Report from the INTAS Project: Hydrogen Production and Safety Promotion by Innovative Processes

*Iskender Gökalp*
*ICARE-CNRS, France*

This project lasted 30 months from May 1, 2006 to October 31, 2008 and involved 3 Russian and 4 European teams. One main axis of the project was investigating novel methods for hydrogen generation, including plasma aided processes. The second research axis was related to the safety aspects of hydrogen utilization.

Concerning the hydrogen generation aspect of the project, several methods were developed and tested. The work carried out by GREMI (CNRS-University of Orleans, France) mainly concerned the development and evaluation of a sliding discharge for the steam reforming and oxygen assisted steam reforming of methane, propane, and ethanol. New reactor designs were proposed in order to optimize $H_2$ production efficiency using non thermal plasma processes from steam reforming.

Two institutes of the CNR in Milano (IFP-CNR and IENI-CNR) were concerned by the development and evaluation of a DBD plasma discharge with different geometrical characteristics and by the study of methane cracking process with nanosecond pulses at atmospheric pressure for hydrogen production.

NEQLab of the Moscow Institute of Physics and Technology was concerned by the optimization of a plasma chemical reactor for $H_2$ production by the conversion of the mixtures of methane and other hydrocarbons with $O_2$ and water vapor in the plasma of non-equilibrium pulsed nanosecond discharges as well as the determination of optimal conditions of the conversion process.

IENI-CNR also conducted work on the optimization of photo-assisted electrolysis of water. In this task, titania nanoparticles have been synthesized in a flame reactor and characterized by TEM, SEM and X-ray analysis. Electrodes coated with titania nanoparticles have been realized. A novel methodology consisting in titania coating trough direct thermal oxidation of Ti foils in a natural gas flame has been developed. A photoelectrochemical cell (PEC) has been realized and used for characterizing the electrodes. Some preliminary results concerning the photo-assisted electrolysis process have been obtained. In addition ICARE-CNRS (Orleans, France) conducted experimental work on the generation of hydrogen using low reactivity of aluminum particles with liquid water; both nano-sized non-activated and micron- sized activated aluminum particles were investigated.

For the hydrogen safety aspects of the project, two Russian institutes (ISMAN- Institute for Structural Makrokinetics and Materials Science, Chernogolovka and VNIIPO – Institute All-Russian Research Institute for Fire Protection, Balashiha) were concerned by the optimization of safety conditions for hydrogen mixtures by preventing their detonation propensity. It has been shown that addition of small amounts of chemically active additives (inhibitors) to initial mixture allows not only prevents the occurrence of detonation of hydrogen-air mixtures even when initiated by explosions, but also destructs stationary detonation waves.

The determination of hydrogen addition effects on the methane-air flame propagation velocities were investigated by ICARE-CNRS. The effects of hydrogen addition on the flame propagation velocities of laminar and turbulent methane-air mixtures have been experimentally determined and numerically modeled and simulated.

Main results from these investigations will be summarized in the presentation.

# Cities Without Garbage – Industry Without Waste

*Dr. Igor B. Matveev*
*Applied Plasma Technologies, USA*

*P.M. Rakin, IHIS Naučno Tehnološki Park ZEMUN, Belgrade, Serbia*

*D.P. Rakin, IHIS Development & Production Center, Belgrade, Serbia*

This presentation discusses one of the areas from the list of critical national needs - waste-into-energy. This affects every resident, involves over one million of employees only in the US, occupies millions of acres of land, relates to many environmental problems, and is becoming one of the 21st century's major challenges. It is a problem waiting for our solution.

Our solution means introduction of the new generation of waste processing technology with possibility to create 10 to 500 tons per day feedstock capacity plasma technology power plants, exporting yearly over 251,000,000 MWh of renewable electric energy.

The authors provide an overview of the problem, suggest feasible and technically sound solutions, and disclose possible strategies for national and international involvement and cooperation.

**References**

1. Nickolas J. Themelis, *An overview of the global waste-to-energy industry*, Waste Management World (www.iswa.org), 2003-2004 Review Issue, July-August 2003, p. 40-47.
2. Basel Convention www.basel.int/text/documents.html
3. Kyoto Protocol www.kyotoprotocol.com
4. Waste Business Journal www.wastebusinessjournal.com/overview.htm
5. Plasco Energy Group www.plascoenergygroup.com
6. Advanced Plasma Power www.advancedplasmapower.com
7. PyroGenesis www.pyrogenesis.com
8. Carabin, P., Gagnon, J-R., *Plasma Gasification and Vitrification of Ash-Conversion of Ash into Glass-like Products and Syngas*, 2007 World of Coal Ash (WOCA), Covington, Kentucky, pp. 1-11, 2007.
9. E. Leal-Quiros, *Hydrogen Production Using Plasma Torches and Plasmatrons for Plasma Gasification and Plasma Magmavication of Organic and Inorganic Materials*, 3-rd Int. Workshop and Exhibition on Plasma Assisted Combustion, Falls Church, Virginia, pp. 14-15, 2007.
10. P. Carabin, *Energy from Waste Using the Plasma Resource Recovery System (PRRS),* 3-rd Int. Workshop and Exhibition on Plasma Assisted Combustion, Falls Church, Virginia, pp. 22-23, 2007.
11. I. Matveev, Applied Plasma Technologies, *U.S. Patent 7,452,513 B2 "Triple Helical Flow Vortex Reactor",* Nov.18, 2008.
12. I. Matveev, Applied Plasma Technologies, *U.S. Patent Application for a "Power Plant and Method Using a Triple Helical Vortex Reactor",* 11/309644, filed 05 April, 2007.

13. I. Matveev, S. Serbin, *Preliminary Design and CFD Modeling of a 1 MW Hybrid Plasma Torch for Waste Destruction and Coal Gasification*, 2-nd Int. Workshop and Exhibition on Plasma Assisted Combustion, Falls Church, Virginia, pp. 43–44, 2006.
14. Matveev, I.B., Serbin, S.I., Lux, S.M., *Efficiency of a Hybrid-Type Plasma-Assisted Fuel Reformation System*, IEEE Trans. Plasma Sci. 36 (6), pp. 2940-2946, 2008.
15. S. Zverev, D. Ivanov, V. Frolov, I. Matveev, *Experimental Investigations of the Hybrid Plasma Torch with Reverse Vortex Stabilization*, 4-th Int. Workshop and Exhibition on Plasma Assisted Combustion, Falls Church, Virginia, pp. 39-44, 2008.
16. I.B. Matveev, S.I. Serbin, *Modeling of the Coal Gasification Processes in a Hybrid Plasma Torch*. IEEE Trans. Plasma Sci., 35 (6), pp.1639–1647, Dec. 2007.
17. I.B. Matveev, V.E. Messerle, A.B. Ustimenko. *Plasma Gasification of Coal in Different Oxidants.* IEEE Trans. Plasma Sci., 36 (6), pp. 2947-2954, Dec. 2008.
18. I. Matveev, *Alternative Solutions for MSW-To-Energy Processing*, 4-th Int. Workshop and Exhibition on Plasma Assisted Combustion, Falls Church, Virginia, pp. 84, 2008.

**JOURNAL PUBLICATION**

Dear IWEPAC Attendee!

You have an opportunity to submit and publish your paper at the IEEE Special Issue "Plasma Assisted Combustion - 2010". For submission use please the IEEE's Manuscript Central system. It is accessible through the World Wide Web at the following address: http://tps-ieee.manuscriptcentral.com

For authors, the web site offers the possibility to submit their manuscripts for review and to enter much information about the manuscripts. Once the author has registered on Manuscript Central, and obtained his or her User Name and Password, the manuscript submission process may proceed. Once signed onto the web site, the steps include submission of: manuscript title, author list, author affiliations, corresponding author contact information, manuscript abstract, index terms/keyword list, lists of reviewers preferred and those not preferred. The author can then upload his or her manuscript in a variety of electronic formats. These formats include: PDF, EPS, PS, MS Word, Tex, LaTex, etc. The manuscript's figures are also uploadable in a variety of formats including PDF, TIFF, JPG, EPS, PS, etc. Supplementary information about the manuscript can also be uploaded. This material can include cover letters, previous reviews and replies (in the case of a revised manuscript), previous publications, etc. Helpful instructions for authors and IEEE copyright forms are also available through the web site.

An author kit is available for help with formatting the final manuscript at http://www.ieee.org/portal/cms_docs/pubs/transactions/auinfo03.pdf

IEEE Copyright Forms are available at http://www.ieee.org/copyright/cfrmlink.htm

Need to translate some text? Use this link http://babel.altavista.com

Manuscript submission deadline **01-March-2010.**

# Announcing a Special Issue of the IEEE Transactions on Plasma Science Plasma-Assisted Combustion (Scheduled for December 2010)

The Technical Committee on Plasma Science and Applications of the IEEE Nuclear and Plasma Science Society along with the Guest Editors invite contributions to the Special Issue of the IEEE Transactions on Plasma Science on Plasma-Assisted Combustion to appear in December 2010.

The application of plasmas to enhance combustion processes is an emerging field of plasma science and technology. It is lately receiving considerable interest, driven by the need for more energy-efficient and less-polluting combustion techniques. A special forum for scientists and researchers to disseminate and review the current research and applications in this field is needed. Work in the field of plasma-assisted combustion has been reported in diverse journals and related media, and a past special issue (December 2009) has provided the needed special forum. The IEEE Transactions on Plasma Science provides an archival domain for the publication of new scientific, technological, and application results in plasma science and technology.

The intention of this Special Issue is to provide an integrated forum for high-quality publications in the field and to promote further interest and exchange of technical information in this exciting and technologically important area of plasma science. Contributions are solicited in, but not restricted to, the following topics:

- Ultra-low sulfur content
- Physics/chemistry of effects of plasmas on flames and deflagration-to-detonation transition.
- Use of plasmas to promote and/or improve efficiency in engines (automotive, aircraft, etc.) or flames and/or burners.
- Plasma sources (e.g., jets) for improved ignition.
- Applications to aircraft pulsed detonation engines.
- Applications to pollution reduction (i.e., combustion efficiency improvement - not exhaust cleaning).
- Applications to fuel reforming/conversion (e.g., fossil fuel to hydrogen).

Both full-paper and shorter technical-note manuscripts will receive consideration for publication in this Special Issue.

All contributions should reach the Guest Editors **no later than March 1, 2010** at the IEEE Transactions on Plasma Science IEEE Manuscript Central website at http://tps-ieee.manuscriptcentral.com. Questions regarding the Special Issue on Plasma-Assisted Combustion can be addressed to the Guest Editors:

*Dr. Louis Rosocha*
Applied Physics Consulting
536 Central Ave.
Los Alamos, NM 87544
Phone: 505-662-7123, Fax: 505-662-7123
E-mail: plasmamon@msn.com

*Dr. Igor Matveev*
Applied Plasma Technologies
1729 Court Petit
McLean, VA 22101
Phone: 703-560-9569, Fax: 703-849-8417
E-mail: i.matveev@att.net
www.plasmacombustion.com