# 6th International Workshop and Exhibition on Plasma Assisted Combustion (IWEPAC)

**13-15 September 2010**
**Heilbronn , Germany**

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# Contents

## PLASMA FLOW DYNAMICS

## WASTE INTO ENERGY

## NEW PLASMA EFFECTS AND PROSPECTIVE APPLICATIONS

# Synopsis

Among about 110 Plasma Conferences to be held in 2010, **IWEPAC** is the only one devoted to the field of Plasma Assisted Combustion (PAC). 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 21st century.

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

**IWEPAC-6** is expected to have one plenary lecture, 32 oral presentations (25-30 minutes in duration, including questions and answers), one poster session, half-day visit to the Institute of Space Propulsion of the German Aerospace Center (DLR), and medieval dinner at Götzenburg castle Jagsthausen.

**IWEPAC-6** will be held September 13 to 15, 2010 in Insel – Hotel, Willy-Mayer-Brucke, D-74072 Heilbronn, Germany. 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-6** proceedings will be available in two formats: color booklet with abstracts and after-meeting DVD. The cost is included in the registration fee.

# IWEPAC – 6
# Tentative Agenda

| 16.00 – 18.00 | Registration: Insel - Hotel Lobby<br>Willy-Mayer-Brucke, D-74072 Heilbronn, Germany<br>Phone: +49 071 31 6300, fax: +49 071 31 6260 |
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**Monday, 13 September**

| 8.00 – 8.30 | Registration: Insel – Hotel Conference Center, 5th floor |
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| 8.30 – 9.15 | **IWEPAC-6 OPENING**<br><br>Welcome remarks from:<br>• *Dr. Igor Matveev* (Applied Plasma Technologies, LLC)<br>• *Dr. Louis Rosocha* (Los Alamos National Laboratory, DOE and Applied Physics Consulting)<br>• *Dr. Oskar Haidn* (German Aerospace Center )<br><br>Announcements<br><br>*Plenary lecture:* **An Overview of Plasma-Assisted Combustion:**<br>**History, Applications and Classification of Technological Systems**<br><br>*Dr. L.Rosocha*, Applied Plasma Consulting, USA<br><br>*Dr. I. Matveev*, Applied Plasma Technologies, LLC |
| 9.15 – 9.30 | Break |
| 9.30 – 14.45 | **PLASMA GENERATION, DIAGNOSTICS, AND MODELING**<br>Chaired by *Prof. Homero S. Maciel*, Technological Institute of Aeronautics, Brazil |
| 9.30 – 10.00 | **Basic Characteristics of Gliding Arc Discharges in Air and Natural Gas**<br><br>*J. C. Sagás, A. Hadade Neto, A. C. Pereira Filho, H. S. Maciel, P. T. Lacava* (Technological Institute of Aeronautics, Brazil) |
| 10.00 – 10.30 | **Investigation of Low-Current "Gliding Arc" in Air Flow**<br><br>*Prof. Yu. D. Korolev, O.B. Frants, N.V. Landl, V.G. Geyman, A.A. Enenko* (Institute of High Current Electronics, Russia) |
| 10.30 – 11.00 | **Power Supply for Nonsteady State Discharges in a Gas Flow**<br><br>*Prof. Yu.D. Korolev, V.G. Geyman, O.B. Frants, V.A. Panarin, S.B. Alekseev* (Institute of High Current Electronics, Russia)<br><br>*Y. Kim, L.A. Rosocha* (Los Alamos National Laboratory, USA)<br><br>*C. Cassarino, T. Frambes* (Leonardo Technologies, Inc., USA) |

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| 11.00 – 11.30 | **Investigation of a Plasma Torch Generated by Nonsteady State Plasmatron** |
| | *Prof. Yu.D. Korolev, O.B. Frants, S.I. Galanov, O.I. Sidorova, V.S. Kasyanov* (Institute of High Current Electronics, Russia) |
| | *Y. Kim, L.A. Rosocha* (Los Alamos National Laboratory, USA) |
| | *Dr. I. Matveev* (Applied Plasma Technologies, LLC, USA) |
| 11.30 – 12.00 | **Laser-induced Ignition of Oxygen/Hydrogen and Oxygen/ Hydrocarbon Propellants for Rocket Propulsion Applications** |
| | *O.J. Haidn, C. Manfletti, J. Sender* (German Aerospace Center, Institute of Space Propulsion, Germany) |
| 12.00 – 13.00 | Lunch |
| 13.00 – 13.30 | **Test Results for a Power Supply for a Near-Zero Emissions Combustor System for Syngas and Biofuels** |
| | *Dr. L. A. Rosocha, Dr. Y. Kim* (Los Alamos National Laboratory, USA) |
| | *Prof. Yu.D. Korolev* (Institute of High Current Electronics, Russia) |
| | *C. Cassarino, T. Frambes* (Leonardo Technologies, Inc., USA) |
| 13.30 – 14.00 | **Properties of Hybrid Gas-Water Torch Used for Gasification of Biomass** |
| | *T. Kavka, A. Maslani, V. Kopecky, M. Hrabovsky* (Institute of Plasma Physics ASCR, Czech Republic) |
| 14.00 – 14.45 | Round Table on Plasma Generation, Diagnostics, and Modeling |
| 14.45 – 15.00 | Break |
| 15.00 – 18.15 | <div align="center">**FUEL REFORMATION AND ACTIVATION**</div> |
| | <div align="center">Chaired by *Dr. I. Matveev,* Applied Plasma Technologies, LLC, USA</div> |
| 15.00 – 15.30 | **Gas Turbine Combustor With Steam Injection and Plasma Activation** |
| | *Prof. S. Serbin, Dr. A. Mostipanenko* (National University of Shipbuilding, Ukraine) |
| | *Dr. I. Matveev* (Applied Plasma Technologies, LLC, USA) |
| 15.30 – 16.00 | **Non-Thermal Plasma Assisted Reforming of Liquid Fuels in Dynamic Combined Plasma – Liquid Systems** |
| | *Prof. V. Chernyak, S. Olszewski, O. Nedybalyuk, S. Sydoruk, V. Yukhymenko, I. Prysiazhnevych* (Taras Shevchenko Kyiv National University, Ukraine) |
| | *A. Shchedrin, D. Levko, V. Naumov, V. Demchina, V. Kudryavzev* (Institute of Physics, National Academy of Sciences of Ukraine) |

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| 16.00 – 16.30 | **New Approaches to Partial and Complete Plasma Coal Gasification** |
| | *Dr. I. Matveev*  (Applied Plasma Technologies, LLC, USA) |
| | *Prof. S. Serbin*  (National University of Shipbuilding, Ukraine) |
| 16.30 – 16.45 | Break |
| 16.45 – 17.15 | **Experimental Investigation of Plasma Assisted Combustion Using a Low-Swirl Burner** |
| | *B.F.W. Vermeltfoort, N.J. Dam, A.J.M. Pemen, L.P.H. de Goey* (Technical University of Eindhoven, The Netherlands) |
| 17.15 – 17.45 | **Flame Modifications Induced by Electronically Excited Oxygen Generated by a Cold Plasma** |
| | *K. Zähringer, A. Bourig, D. Thévenin (*Lehrstuhl für Strömungsmechanik und Strömungstechnik, Otto-von-Guericke-Universität, Magdeburg, Germany) |
| 17.45 – 18.15 | Round Table on Fuel Reformation and Activation |
| 15.00 – 18.00 | <div align="center">**POSTER SESSION**</div> |
| 15.00 – 18.00 | **Combustive Decomposition of Anesthetic Gas for Medical Operation Using Atmospheric Multi-Gas Inductively Coupled Plasma** |
| | *Dr. Hidekazu Miyahara, Toshiyuki Tamura, Yuki Kaburaki, Ryota Sasaki, and Akitoshi Okino*  (Department of Energy Sciences, Tokyo Institute of Technology, Japan) |
| 15.00 – 18.00 | **Heavy Oil Burner Utilizing Plasma Assisted Combustion** |
| | *A. C. Pereira Filho , A. Hadade Neto, M. Médici*  (Fundação Valeparaibana de Ensino, Brazil) |
| | *H. S. Maciel*  (Technological Institute of Aeronautics, Brazil) |

Tuesday, 14 September

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| 8.30 – 13.10 | <div align="center">**PLASMA IGNITION AND FLAME CONTROL**</div> |
| | <div align="center">Chaired by *Dr. Louis A. Rosocha*, Los Alamos National Laboratory, DOE and Applied Physics Consulting, USA</div> |
| 8.30 – 8.55 | **Low NO$_X$ Gas Turbine Combustor Assisted by Vortex Plasma Torch** |
| | *P. T. Lacava , J. C. Sagás, A. Hadade Neto, A. C. Pereira Filho, H. S. Maciel*  (Technological Institute of Aeronautics, Brazil) |
| 8.55 – 9.20 | **Non-Self-Maintained Discharge and Electron Beam Plasma in Propane-Air Mixture II. (Experimental Results)** |
| | *Prof. V. L. Bychkov, D. V. Bychkov, S. V. Denisiuk,          V. A. Gudovich*  (FSUE "Moscow Radiotechnical Institute of Russian Academy of Sciences", Russia) |

| 9.20 – 9.45 | **Non-Self-Maintained Discharge and Electron Beam Plasma in Propane-Air Mixture II. (Theoretical Results)** |
|---|---|
| | *N. V.Ardelyan, K. V. Kosmachevskii (M.V .Lomonosov Moscow* State University, Russia) |
| | *Prof. V. L. Bychkov (*FSUE "Moscow Radiotechnical Institute of Russian Academy of Sciences", Russia) |
| | *I. V. Kochetov* (Troitsk Institute for innovation and Thermonuclear Research (TRINITI), Russia) |
| 9.45 – 10.00 | Break |
| 10.00 – 10.25 | **Plasma Combustion Nature of a Fireball with a Metallic Core** |
| | *Prof. V.L. Bychkov* (FSUE "Moscow Radiotechnical Institute of Russian Academy of Sciences", Russia) |
| | *S. E. Emelin* (Saint-Petersburg State University, Russia) |
| 10.25 – 10.50 | **Deeply-Subcritical Microwave Discharges System in a Supersonic Flow** |
| | *D.V. Bychkov, I. I. Esakov, A.A. Ravaev, K.V. Khodataev* (Moscow Radiotechnical Institute Russian Academy of Sciences, Russia) |
| 10.50 – 11.15 | **Cylindrical Flame Kernel and Flame Propagation Induced in Air-Propane Mixtures by a Single Corona Discharge** |
| | *S.Bentaleb, P.Tardiveau, N. Moreau, F. Jorand, S.Pasquiers* (Université Paris-Sud Orsay, France) |
| 11.15 – 11.40 | **Numerical Investigation of Plasma Ignition Process in a Utility Boiler** |
| | *Haining Gao, Eddy Chui, Allan Runstedtler* (CanmetENERGY, Natural Resources, Canada) |
| | *Hong Tang* (YanTai LongYuan Electric Power Technology co., LTD, China) |
| 11.40 – 11.55 | Break |
| 11.55 – 12.20 | **Plasmic Initiation of Detonative Combustion of Preheated Supersonic Hydrogenous Flows** |
| | *V.A. Pavlov, O.P. Shatalov, Yu.V. Tunik* (Scientific Research Institute of Mechanics of Moscow State University Russia) |
| 12.20 – 12.45 | **Convergent (Cumulative) Shock Wave Generation and Its Application as Igniter of Flammable Gas Mixtures** |
| | *E.M.Barkhudarov, N.K.Berezhetskaya, I.A.Kossyi, V.A. Kop'ev, M.I.Takatakishvili, S.M.Temchin* (A.M.Prokhorov General Physics Institute of Russian Academy of Sciences, Russia) |
| | *V.A.Levin, V.V.Markov, I.S.Manuilovich* (Institute of Mechanics, Moscow State University, Russia) |
| | *N.A.Popov, D.V.Skobeltsyn* (Institute of Nuclear Physics, Moscow State University, Russia) |

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| 12.45 – 13.10 | **Subcritical Microwave Coupling to Laser Ionization for Ignition**<br><br>*J. B. Michael, A. Dogariu, M. N. Shneider and R. B. Miles* (Department of Mechanical and Aerospace Engineering, Princeton University, USA) |
| 13.10 – 14.00 | Lunch |
| 14.00 | **VISIT TO INSTITUTE OF SPACE PROPULSION OF THE GERMAN AEROSPACE CENTER** |
| 18.00 | Medieval dinner at Götzenburg castle Jagsthausen |

Wednesday, 15 September

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| 8.30 – 9.00 | Round Table on Plasma Ignition and Flame Control |
| 9.00 – 11.00 | **PLASMA FLOW DYNAMICS**<br>Chaired by *Prof. Serhiy Serbin*, National University of Shipbuilding, Ukraine |
| 9.00 – 9.25 | **Flow Pattern Around Targets of High-Porosity Cellular Material in the Supersonic Pyrolytic Reactor**<br><br>*Vasilii Fomin, Boris Postnikov, and Konstantin Lomanovich* (Khristianovich Institute of Theoretical and Applied Mechanics Russian Academy of Sciences, Siberian Branch, Russia) |
| 9.25 – 9.50 | **Computer Simulation of Gas-Discharge and Chemical Processes in a Non-Steady-State Plasmatron**<br><br>*A.I. Suslov* (Institute of High Current Electronics, Russia) |
| 9.50 – 10.15 | **Theoretical Investigations of the Working Processes in a Plasma Assisted Afterburner with Reverse Vortex Flow**<br><br>*Prof. S. Serbin, Dr. A. Mostipanenko* (National University of Shipbuilding, Ukraine)<br><br>*Dr. I. Matveev* (Applied Plasma Technologies, LLC, USA) |
| 10.15 – 10.40 | **Plasma Instabilities as Instrument for Supersonic Mixture Formation**<br>*S. Kamenshchikov, I. Kuznetsov* (Moscow State University, Russia) |
| 10.40 – 11.00 | Round Table on Plasma Flow Dynamics |
| 11.00 – 11.15 | Break |
| 11.15 – 12.45 | **WASTE INTO ENERGY**<br>Chaired by *Prof. Vladimir Bychkov*, Moscow State University, Russia |
| 11.15 – 11.45 | **Thermal Plasma Gasification of Organic Waste**<br><br>*M. Hrabovsky, M. Hlina, M. Konrad, V. Kopecky, T. Kavka, O. Chumak, A. Maslani* (Institute of Plasma Physics ASCR, Praha, Czech Republic) |
| 11.45 – 12.15 | **New Approaches to Plasma Waste Gasification**<br><br>*Dr. I. Matveev* (Applied Plasma Technologies, LLC, USA) |

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| 12.15 – 12.45 | **Plasma Gasification of Organic Waste Using a Closed Loop ICP-Driven Facility** |
| | *G. Herdrich, M. Auweter-Kurtz* (Steinbeis Transfer Centre Plasma and Space Technology, Germany) |
| | *S. Fasoulas* (Institut für Raumfahrtsysteme (IRS), University of Stuttgart, Germany) |
| 12.45 – 13.00 | Round Table on Waste into Energy |
| 13.00 – 14.00 | Lunch |
| 14.00 – 15.30 | ### NEW PLASMA EFFECTS AND PROSPECTIVE APPLICATIONS |
| | Chaired by *Dr. Oskar Haidn*, Institute of Space Propulsion, Germany |
| 14.00 – 14.30 | **Catalytic Conversion Usage** |
| | *Prof. A.L. Kuranov, Dr. A.V. Korabelnikov* (Hypersonic Systems Research Institute of Leninetz Holding Company, Russia) |
| 14.30 – 15.00 | **Plasma Jets Magneto-Inertial Fusion for Space Propulsion** |
| | *Dr. S.V. Ryzhkov* (Bauman Moscow State Technical University, Russia) |
| 15.00 – 15.30 | **Prospective Applications for a New Generation of High Power ICP Torches** |
| | *Dr. I. Matveev* (Applied Plasma Technologies, LLC, USA) |
| 15.30 – 16.00 | Round Table on New Plasma Effects and Perspective Applications |
| 16.00 – 17.00 | ### MEETINGS, DISCUSSIONS, NEGOTIATIONS, ENTERTAINMENT |
| | Conference Closing |

# An Overview of Plasma-Assisted Combustion: History, Applications and Classification of Technological Systems

*Dr. L.Rosocha,*
*Applied Plasma Consulting, Los Alamos, USA*

*Dr. Igor Matveev*
*Applied Plasma Technologies, LLC, McLean, 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, coal gasification, conversion of municipal waste into energy, and the reduction of pollution through ultra-lean burn combustion.

This talk will present a brief historical background on electric field and plasma effects on combustion and will then focus the discussion on plasma-assisted combustion applications, as mainly applied to ignition, combustion stability, efficiency, and pollution reduction. 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 current industrial systems. One key aim of the presentation is to provide a framework for classifying various PAC systems, so that the field can develop a standard nomenclature for various PAC systems and technology.
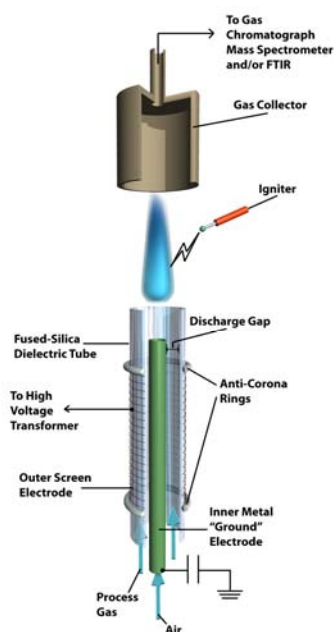


*Fig. 1. Dielectric-barrier-based plasma, gaseous fuel 'activator' (Los Alamos National Laboratory)*



*Fig. 2. Plasma-based igniter in operation (Applied Plasma Technologies, LLC)*

# Basic Characteristics of Gliding Arc Discharges in Air and Natural Gas

*J. C. Sagás, A. Hadade Neto, A. C. Pereira Filho, H. S. Maciel, P. T. Lacava*
*Technological Institute of Aeronautics, Brazil*

Gliding arc discharges have been utilized in plasma assisted combustion processes due their properties of high electron density and chemical selectivity in a transitional regime. These discharges operate at atmospheric pressure and are obtained between electrodes of divergent geometry (the electrode gap increases in the direction of gas flow) and create plasmas that can operate in different regimes: thermal, non-thermal and transitional. In the transitional regime the discharge starts like a thermal arc, but the gas flow pushes and elongates the arc, causing an increase of discharge voltage and discharge power. When the power reaches its maximum, the discharge makes a transition to a non-thermal regime and proceeds its evolution until the voltage reaches the breakdown voltage; so that a new arc is created in the smallest gap between the electrodes, extinguishing the previous arc and restarting the cycle. Although the large number of publications about the applications of gliding arc discharges, the number of works about the fundamental relations between the parameters of operation (discharge power, mass flow rate, residence time) is small.

The experiments were carried out in an AC powered gliding arc reactor having a reverse vortex flow configuration. Electrical measurements, optical emission spectroscopy and mass spectrometry were the used techniques for these investigations in air, natural gas and mixture of both. The results presented here describe the behavior of breakdown voltage, frequency of discharges and conversion rates of methane and molecular oxygen with respect to the variation of the mass flow rate (directly related to the residence time) and discharge current.

It is observed an increase in breakdown voltage with the mass flow rate, result of the greater diffusion of charged particles as they are dragged away from the arc region more quickly, thus requiring a higher voltage to stabilize the plasma channel. The value of breakdown voltage is different for each half cycle of discharge. This is result of the breakdown mechanism that, in this case, is a streamer breakdown, due to the high pressure and non-uniformity of the electric field. Discharges operating in pure natural gas present higher repetition frequencies than discharges in air due to, among other factors, the low electronegativity of natural gas. The higher frequencies imply that the discharge extinguishes more quickly, probably decreasing the power dissipated. In the mixture of air and natural gas, it is observed that the reduction of the mass flow rate reduce the "fluctuations" in the voltage waveform (for the same equivalence ratio), indicating that it is a consequence of the gas composition and mass flow rate. A smoother waveform implies in a more stable discharge, which is very important for plasma assisted combustion processes. The reduction of mass flow rate also causes the increase of residence time leading to a greater reduction of the $CH_4$ signal in the mass spectrum due to the increase in the probability of occurrence of chemical reactions. It is noticeable that signal reduction about 90% for methane can be achieved in this system.
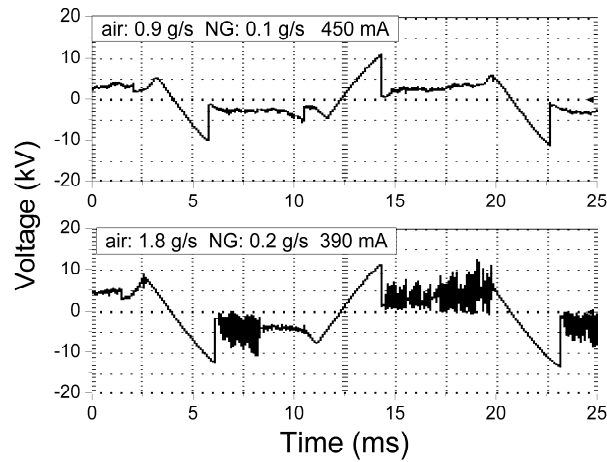
*Fig. 1.Discharge voltage waveform for total mass flow rate of 1.0 g/s (top)
and 2.0 g/s (bottom). Equivalence ratio equal to 1.9*
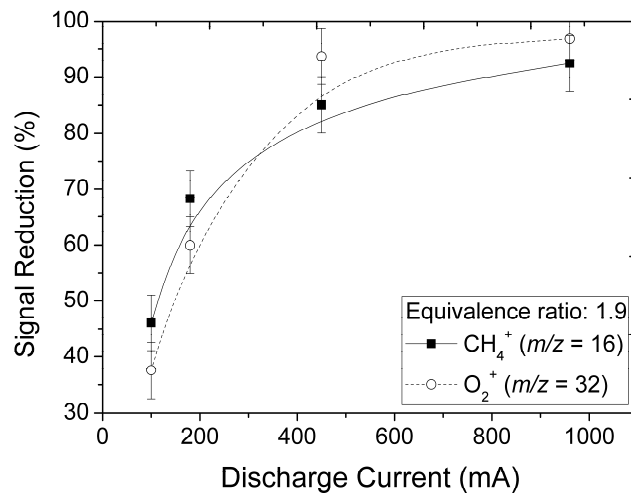


*Fig. 2. Signal reduction as function of effective discharge current to a total
mass flow rate of 1.0 g/s.*

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*His main research interests are concentrated in the fundamental and applied physics of plasmas, especially gliding arc discharges.*

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*He is currently Titular Professor of the Technological Institute of Aeronautics. He has experience in Plasmas Physics with emphasis on: cold thermal plasmas and non-thermal plasma technology, process of etching and deposition, treatment of surfaces and plasma assisted combustion.*

**Pedro T. Lacava** *received the M.S. degree in Space Sciences from National Space Research Institute, São José dos Campos, Brazil in 1995 and the Ph.D degree in Aeronautical and Mechanical Engineering from the Technological Institute of Aeronautics, São José dos Campos, Brazil in 2000.*
*He is currently professor of the Propulsion Department at the Technological Institute of Aeronautics, São José dos Campos, Brazil . He has experience in fundamental and applied combustion.*

# Investigation of Low-Current "Gliding Arc" in Air Flow

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

One of the methods to provide a complete or partial oxidation of gaseous hydrocarbons in a wide range of equivalence ratios is plasma assisted combustion technology [1]. In general, a plasma assisted combustion system includes a combustion chamber and a plasma device where a gas discharge burns in a gas flow. Different types of gas discharges have currently been investigated in the plasma devices [2], including the so-called gliding arc. This paper deals with the investigation of the influence of a gas flow and an external electric circuit on the properties of a gliding arc discharge.

The principle of discharge operation is demonstrated in Fig. 1. In most publications [3-5], the discharge properties are interpreted in a framework of steady state models. Such models imply that at an initial instant of time, the very first breakdown occurs over the shortest distance between the electrodes under the effect of voltage $V_D$. After that due to the gas flow, the plasma column moves along the electrode surface. The column length increases with time and the discharge burning voltage increases as well. When the column length reaches a critical value [4], the discharge is extinguished, the current is interrupted and new breakdown occurs over the shortest path in the interelectrode gap. Then the above-described cycle is repeated. In the temporal stages between the successive repeated breakdowns, the discharge column is considered as sustaining in steady state conditions with a permanent specific conductivity [4].
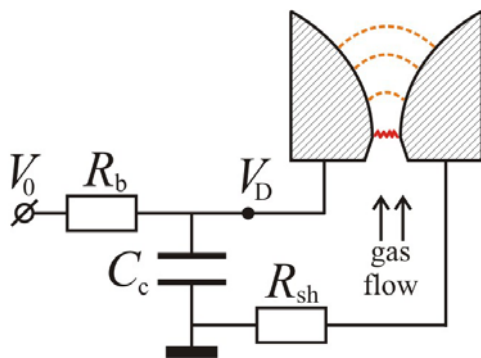


*Fig. 1. Principle of gliding arc operation and time-integrated photograph of discharge luminosity ($R_b$ = 10 kΩ, $C_c$ = 300 pF, $V_0$ = 3 kV, $R_{sh}$= 1 Ω).*

In this paper, we demonstrate that, with a rather high gas flow velocity, the discharge properties are essentially non-steady state. The discharge behavior resembles that for the so-called low-current nonsteady state plasmatron [6]. The principal features of the discharge are reduced to the following.

Due to the very first breakdown, a kind of spark discharge appears in the gap. The energy to the spark is delivered from the capacitance of the connecting cable $C_c$. However, with a low current level from power supply (less that 0.5 A), the discharge is not able to be sustained as a steady state arc. After a time interval of about 1 ms, the discharge burning regime transforms into

a glow mode. Therefore, at the stage of displacement of the discharge column over the electrode surface, we deal with a glow type discharge.

In some regimes, metal vapor cathode spots arise abruptly and chaotically at the location of glow discharge current attachment at the cathode surface. At these instants of time, the discharge burning voltage sharply decreases as the cathode voltage drop region of the glow discharge is bridged by a metal vapor plasma. The origin of the arc cathode spot could initiate the glow to arc transition process [6]. Nevertheless, the lifetime of arc cathode spot is limited. As a result, this spot is extinguished and the discharge starts burning again in a glow mode. In such regimes, we can speak of non-completed glow to spark transitions.

The new spark discharge over a short interelectrode distance appears but not due to repeated breakdown after the current interruption in the primary discharge column. In most cases, the spark discharge occurs long before the primary glow discharge current could be interrupted. The main features of this phenomenon resembles a glow to spark transition process, rather than a repeated breakdown of the gap. The transitions are accompanied by current pulses with duration of about 100 ns. The pulses appear due to discharging the capacitance $C_c$ across the gap.

The above data have been obtained in the experiments by recording the current and voltage waveforms jointly with photographing the discharge image by a CCD camera. An example of such data is presented in Fig. 2. For this particular case, in the time interval from $t_1$ to $t_9$, the discharge burns in a glow mode and the area of the current attachment at the cathode surface corresponds to the current density in a normal glow discharge.
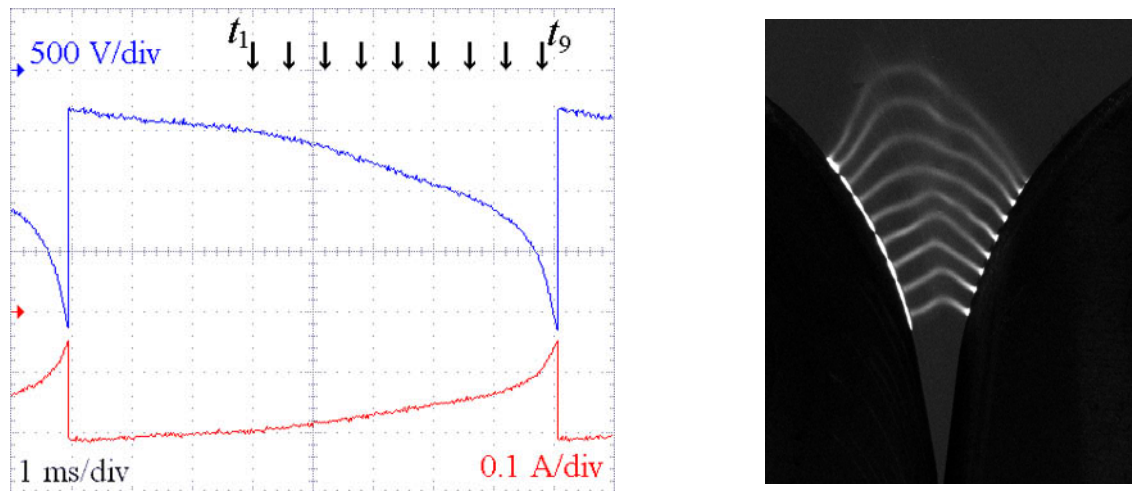


*Fig. 2. Voltage and current waveforms and CCD frames of the gap at different instants of time (exposition time - 50 µs, $V_0$=3 kV, gas flow 0.1 g/s, cathode is at the left side of the photograph)*

### Acknowledgment

### References

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# Laser-induced Ignition of Oxygen/Hydrogen and Oxygen/ Hydrocarbon Propellants for Rocket Propulsion Applications

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Propellant injection and ignition and the transient engine start-up are clearly among the most challenging phases of rocket engine operation and even more so for cryogenic propellant and therefore the dominating effects of these processes have been in core of the propulsion research of the Institute of Space Propulsion for years [1-6]. In order to focus the research on physical processes dominating in the combustion chamber, high power UV laser light has been used as one of the most reliable means to initiate the chemical reaction in their model combustors used to study the process of flame propagation, flame anchoring and interaction of the initial reactive medium with the injected propellants. These processes are of particular importance since they define together with the propellant injection conditions a reliable and safe start-up of the combustor.

The presentation reports focuses on experimental results achieved at the M3 Micro Combustor facility and summarizes ignition experiments performed with gaseous (oxygen / hydrogen), gas liquid (oxygen / hydrocarbon) and cryogenic (LOX / hydrogen) propellants at ambient and low pressure conditions. The measurements techniques applied were high speed imaging of Schlieren, shadow-graphs and spontaneous OH emission of the flame.



Fig.1. M3 Micro combustor

While Fig. 1 shows the experimental setup with the combustion chamber and the laser arrangement, Fig. 2 presents a Schlieren image of conditions in the combustion chamber of the M3 micro combustor just after the laser pulses. The gaseous propellants hydrogen and oxygen enter the chamber from the left side and are injected at supersonic conditions as the Mach discs clearly indicate. Addition-ally, the shock wave which was generated by the laser pulse can be seen as well as the flame kernel.

Fig. 3 shows a series of 12 consecutive high speed shadowgraphs and OH images taken during the first 5 ms after laser energy deposition for the case of low pressure ignition (initial pressure in the combustion chamber < 250 mbar) of a liquid oxygen / gaseous hydrogen propellant. While the top picture for each time step shows the



Fig. 2. Schlieren image of M3 combustion chamber after laser pulse

OH image, the bottom one presents the shows the shadowgraphs. From these pictures the disruptive nature of the chemical reaction which yields a disintegration of the liquid oxygen jet can be seen.
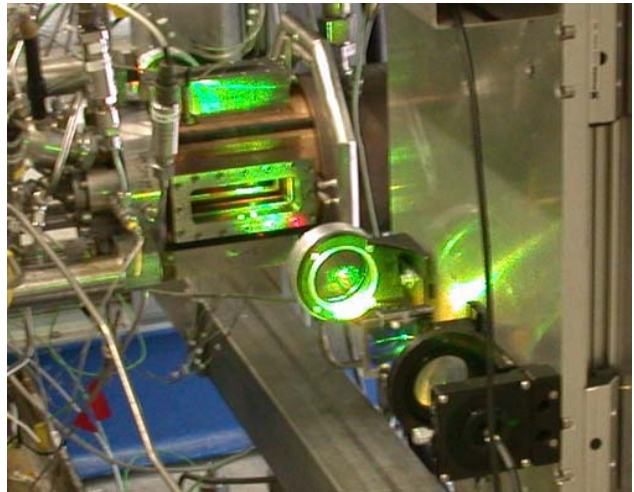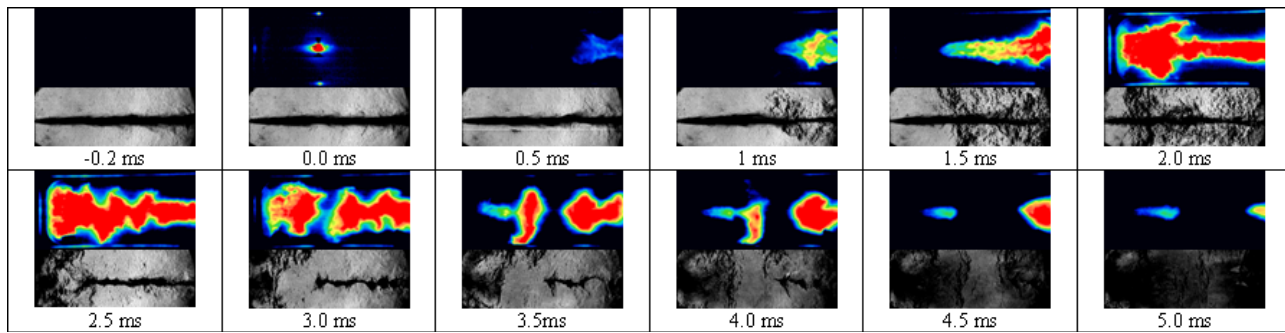
*Fig. 3. High speed shadowgraphs and OH images of LOX/H2 low pressure ignition*

In the future the institute will work towards identifying the key requirements for a laser-based ignition system for in-space propulsions system of space-craft or satellites. Among the various challenges which have to be overcome and open questions which have to be answered are: is more feasible to go for in-chamber ignition with original propellants or apply a separate ignition chamber with dedicated propellants, what are the compatibility limits of a laser-optical arrangement with the boundary conditions of a rocket such as vibration loads during lift-off or the thermal loads of the propellants shocks, what are the maximum number of cycles for re-ignition, are there lifetime limits for optical components under these special boundary conditions. Furthermore, details such as propellant depended optimum laser wave length, laser beam focus geometry and non-equilibrium chemical kinetics will be important, too [7-9]. Obviously, minimum laser energy for reliability ignition for a given propellant combination, size and weight constraints of the equipment and durability of the components are of key importance as well.

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# Power Supply for Nonsteady State Discharges in a Gas Flow

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Research and development associated with plasma assisted combustion and catalytic plasma conversion are a progressing field of activity [1]. In the recent papers [2, 3], investigations of specific gas-discharge regimes in a plasmatron for sustainment of a combustion process have been presented. These regimes can be referred to as a kind of glow discharge at an average current of about 0.2 A, with the random transitions from glow to sparks. Such a type of discharge manifests itself as an essentially nonsteady state load for a dc power supply. This paper describes a power supply that has been intentionally developed for similar types of gas-discharge loads.

An example of a nonsteady state load is the so called "gliding arc" discharge [4, 5]. The electric circuit for testing the power supply $PS$ with the gliding arc is shown in Fig. 1.
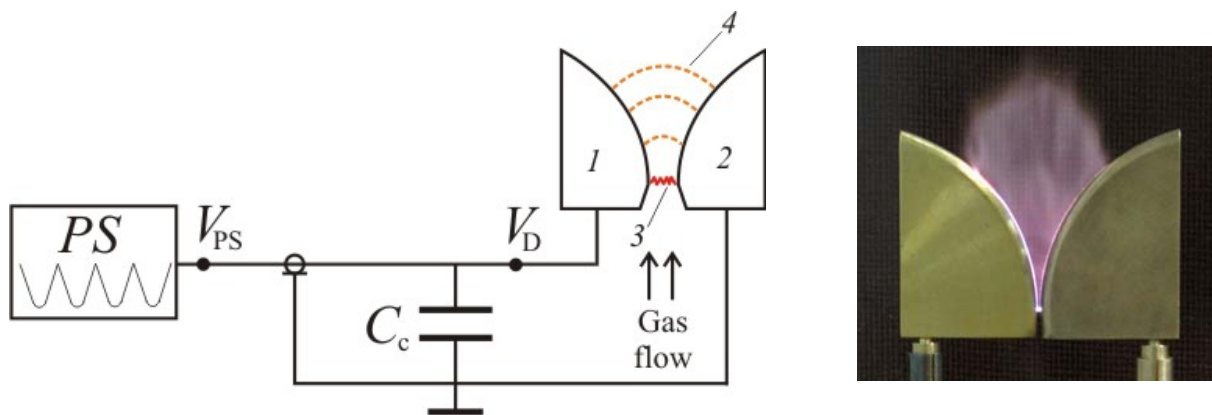


Fig. 1. Electric circuit for powering the model gas-discharge load (gliding arc), and a photo-
graph of the discharge gap with the presence of air flow
1 – cathode of the discharge gap; 2 – grounded anode of the discharge gap; 3 – point of discharge
initiation; 4 – discharge column positions at later temporal stages.

The electric circuit for the powering the discharge should satisfy some specific requirements that can be understood proceeding from analysis of the nonsteady discharge behavior. An ideal power supply would be an electric unit intended for generating a predetermined current value (for example 0.2 A) independent of the gap resistance. Then just after the instant when the power supply is switched on, the capacitance of the connecting cable $C_c$ starts charging. Voltage $V_D$ increases with time, reaches the static breakdown value and the very first breakdown occurs in the narrow part of interelectrode gap (position 3 in Fig. 1). Because of the breakdown, a spark channel appears in the gap. After that, the spark discharge transforms into a kind of glow discharge. The glow discharge column moves over the electrode surface under the effect of gas flow. The length of the column increases with time (positions 4 in Fig. 1), so that the discharge burning voltage

increases as well. When the voltage becomes rather high, a new breakdown in the narrowest part of the gap (position *3*) occurs, and the cycle is repeated.

It should be also noted that, for a high gas flow velocity, a phenomenon of current interruption can manifest itself. In this case, the role of the power supply is to ensure the repeated breakdown of the gap.

A diagram to illustrate a principle of power supply operation is shown in Fig. 2.



*Fig. 2. Operating diagram for power supply.*

*SA – power control switch, R1/R2 – resistive divider for indication of high voltage.*

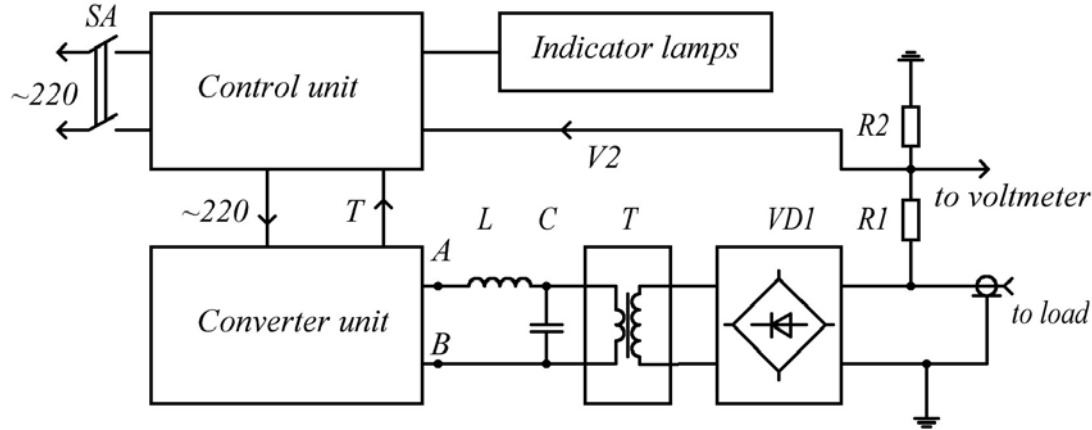The main part of the power supply that determines the principle of its operation is the Converter unit. The alternating industrial voltage is rectified to a value of 310 V and is converted to a bipolar pulsed voltage ± 155 V with a frequency of 50 kHz (output voltage between the points *A* and *B*). The bipolar voltage is applied to the *LC* circuit and to the primary coil of the pulse transformer *T*, with multiplication factor $k = 20$. The voltage at the secondary coil of the transformer is rectified by the diodes *VD1* so that a pulsating current with a frequency of 100 kHz is delivered to the load.

The power supply is intended to deliver a current value of about 0.1 – 0.2 A in a wide range of variations of load resistance $R_{load}$. Then the voltage at the load $V_{load}$ is determined by its resistance. The parameters of the *LC* circuit are selected from the condition of providing an approximately constant current to the load when the load resistance is varied from zero to 50 kW. The *LC* circuit operates by the following way.

When $R_{load}$ is close to zero (for example, a short circuit with arc discharge) then the influence of the capacitance *C* on the current in the load is negligibly small. The current is limited by the inductance *L* at a level of 0.1 – 0.2 A.

Increasing $R_{load}$ results in a situation whereby the capacitance *C* starts affecting the load current in conjunction with the inductance *L*. In an equivalent circuit representation, the serially connected *L* and *C* represent a kind of resonant oscillatory circuit with respect to the Converter unit. The resistive losses in the circuit are determined by the load resistance and by the multiplication factor of the pulsed transformer *T*. If the load resistance is extremely high (larger than 100 kΩ), the *LC* circuit can be considered as a resonant circuit in the absence of resistive losses. Formally speaking, in these conditions, the voltage at the capacitance *C* tends to approach an infinite value. The power supply provides the conditions for limiting the voltage at the secondary coil of transformer *T* and at the load to less than 10 kV.

An example of voltage waveforms for the gliding arc is presented in Fig. 3. At the instant $t_2$, the Converter unit starts operating in the rated regime. The capacitance $C_c$ is charged by a current of about 0.1 A and, at the instant $t_3$, the very first breakdown occurs at a voltage $V_D \approx 7$ kV. After

that, the discharge column is displaced in the electrode system under the effect of gas flow (see Fig. 1). The length of the column increases with time so that the discharge burning voltage increases as well. At the instant $t_4$, a new breakdown occurs in the narrowest part of the electrodes (position *1* in Fig. 5) and the cycle is repeated. Comparison of the data in Figs. *3a* and *3b* shows that the duration of the time interval from $t_3$ to $t_4$ depends on the gas flow velocity.



(a) (b)
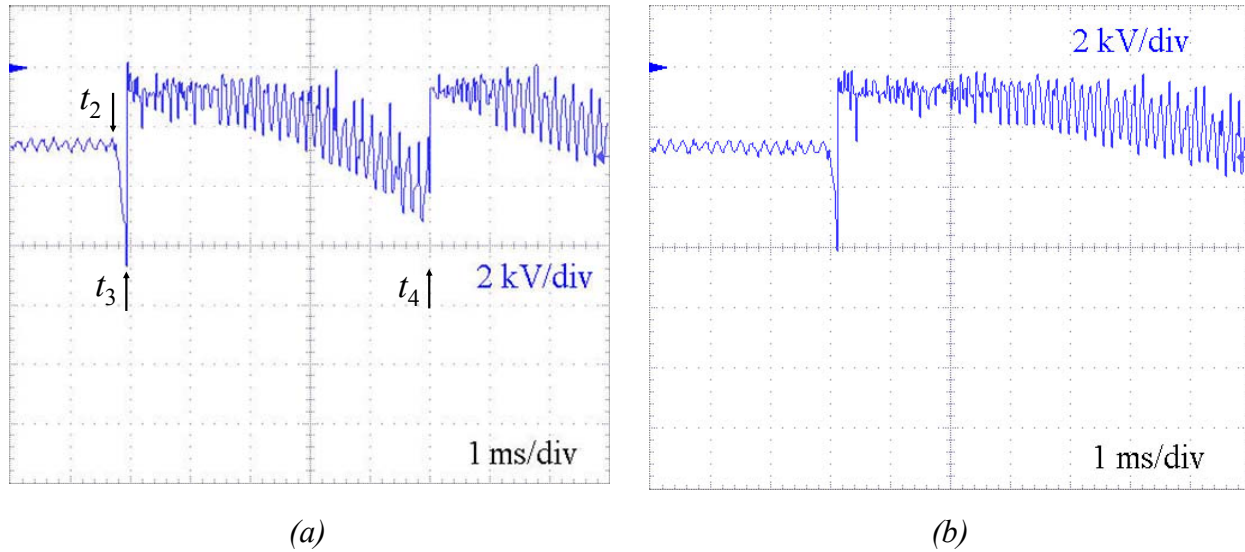
*Fig. 3. Voltage at the gliding arc for the very first breakdown and for successive temporal stages.*
*a) Gas flow velocity v ≈ 10 m/s; b) v ≈ 5 m/s.*

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# Investigation of a Plasma Torch Generated by Non-Steady State Plasmatron

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Investigations of the nonsteady-state discharge properties in coaxial low-current plasmatron are described in [1]. Compared with a thermal plasmatron mode, the average discharge current in this device is decreased to about 0.2 A. Then the discharge regime can be interpreted as a kind of glow discharge with random transitions from glow to sparks. In [2], such a nonsteady state plasmatron has been used in a plasma-assisted combustion system for gaseous hydrocarbon decomposition. The present paper deals with the investigations of the propane conversion in the plasma torch of the plasmatron.

A schematic diagram of our experimental arrangement is presented in Fig. 1. An average discharge power in the plasmatron is about 200 W. Samples of flue gas from the plasma torch are extracted by the probe via the ports 4‑6.
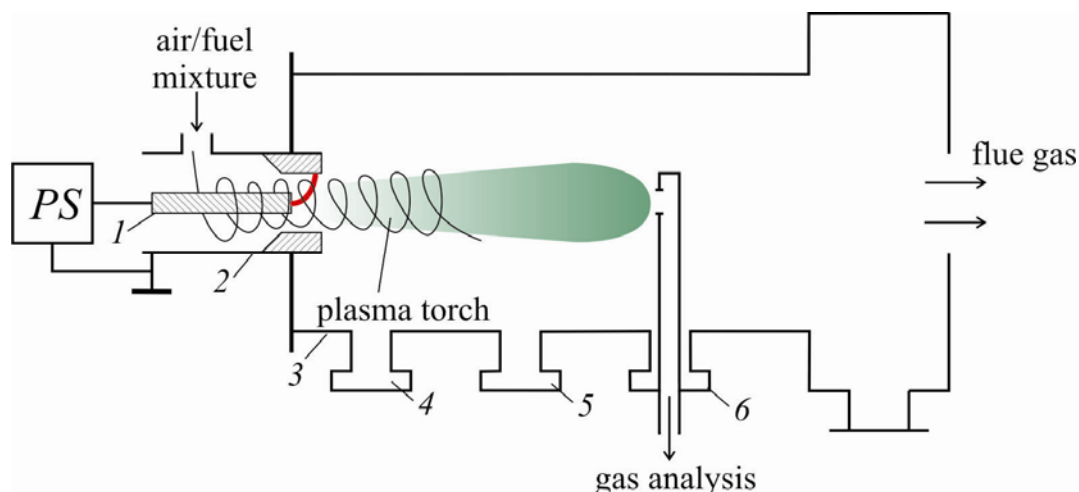


*Fig. 1. Schematic diagram of experiments on measurements of chemical gas composition generated due to the plasma torch operation, in atmospheric pressure chamber (4, 5, 6 – the windows to insert a probe for extractions of the flue gas samples).*

The relative concentrations of different species reduced to "dry" gas c are measured by a gas chromatographic method. Examples of measurements for different gas flows $G$(air) are shown in Fig. 2. It is seen that the percentage of the gas species depend on the gas flow velocity. For the flows $G$(air) = 0.1 g/s and 0.2 g/s, oxygen and propane are completely converted and the relative concentration of $CO_2$ $\chi$ remains approximately the same. However, a difference is demonstrated for the products of non-complete propane oxidation (CO and $H_2$). Further increase in the gas flow $G$ to 0.5 g/s results in recording of $O_2$ and $C_3H_8$ in the flue gas samples and an increase in the percentage of CO and $H_2$.

With a fixed gas flow velocity, a distance $x$ at which the samples are located, actually determines a characteristic time of chemical reactions for the experimental conditions. For $G$(air) = 0.1 g/s (gas flow velocity in $x$ direction $v$ = 4 m/s), we have a negligibly low amount of CO and $H_2$. Then we can speak of a complete propane oxidation for a characteristic time $\tau$ = 60 ms in accordance with the reaction shown below [3]:

$$C_3H_8 + 5O_2 = 3CO_2 + 4H_2O, \qquad \Delta H = -490.2 \text{ kcal/mol} \qquad (1)$$
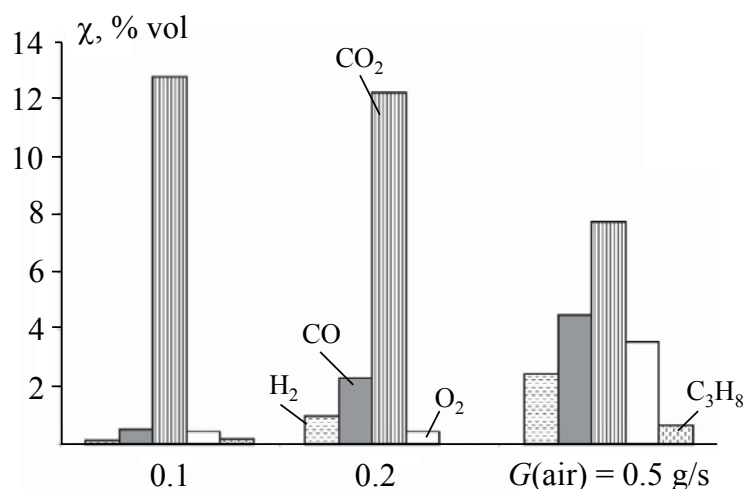


*Fig. 2. Percentage (volume) $\chi$ of the main products resulting from propane oxidation reduced to "dry" gas and the normal conditions*

*$\alpha$ = 0.065 ′ G(air)/G(propane) = 1. The probe for extraction of the gas samples is located at a distance $x$ = 25 cm from plasmatron exit.*

With a characteristic time $\tau$ = 30 ms, the reactions of the complete oxidation of the intermediate products (CO and $H_2$), have not yet completed. However, propane is not detected in the samples. The experimental data with a distance $x$ = 12.5 cm ($\tau$ = 15 ms) show that a characteristic time for conversion of propane into intermediate species can be estimated as about 15 ms.

Beside the above species in the gas samples, we also define the products of propane destruction whose concentration increases with an increase in the gas flow velocity. Such products have been also detected in [4]. The data are presented in Table 1.

*Table 1. Percentage of the hydrocarbon products $\chi$ resulting from propane destruction reduced to "dry" gas and normal conditions. $\alpha$ = 1. The probe for extraction of the gas samples is located at a distance $x$ = 25 cm from plasmatron exit.*

| $G$(air) g/s | $C_2H_2$ acetylene | $CH_4$ methane | $C_2H_4$ ethylene | $C_3H_6$ propylene |
|---|---|---|---|---|
| 0.1 | 0 | 0 | 0 | 0 |
| 0.2 | 0.007 | 0.025 | 0.013 | 0 |
| 0.5 | 0.110 | 0.256 | 0.278 | 0.059 |

Similar trends related to the influence of the gas flow velocity on the gas chemical composition are also characteristic of gas mixtures with a decreased oxygen contents $\alpha$ = (0.4 − 0.5). These mixtures turned out to be optimal for syngas production. With the characteristic reaction time $\tau$ = 60 ms, we have maximum concentrations of CO and $H_2$ and maximum oxygen expenditure for

formation of these products. It seems that the reactions follow both in accordance with the channel (1) and with the following mechanism:

$$C_3H_8 + 1.5O_2 = 3CO + 4H_2, \qquad \Delta H = -50.5 \text{ kcal/mol} \qquad (2)$$

With an increase in the gas flow velocity, the oxygen and propane have not enough time to enter into oxidation reactions, and their content in the flue gas increases as well. It is evident that the relative concentrations of CO, $H_2$ and $CO_2$ decrease in this case. The content of acetylene remains approximately constant.

**Acknowledgment**

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# Test Results for a Power Supply for a Near-Zero Emissions Combustor System for Syngas and Biofuels

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Recently, a multi-institutional plasma combustion team was awarded a research project from the DOE/NNSA GIPP (Global Initiative for Proliferation Prevention) office. The Institute of High Current Electronics (Tomsk, Russia); Leonardo Technologies, Inc. (an American-based industrial partner), in conjunction with the Los Alamos National Laboratory are participating 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 power supplies and plasma-assisted combustion system technologies for use on contemporary gas-turbine engines operating on syngas/biofuels (two types of alternative fuels).

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.

In this presentation, an overview of the project, along with descriptions of the plasma-based combustors, associated power supplies and, particularly, related tests of the power supplies at LANL will be presented.
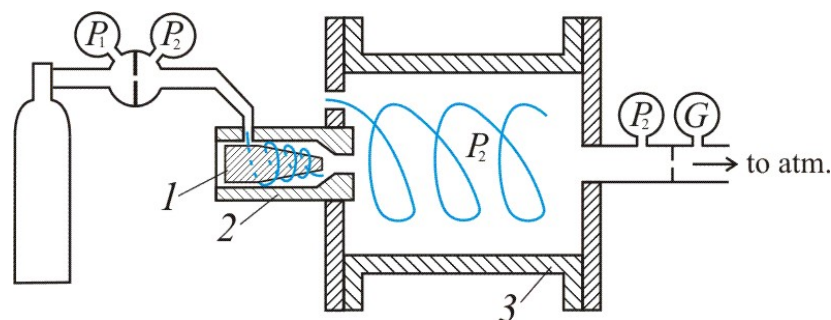


*Fig. 1. Schematic and photograph of the system for plasma assisted combustion at a high pressure*

*1 - inner electrode of a non-steady-state plasmatron; 2 - grounded outer electrode of plasmatron; 3 - combustion chamber*
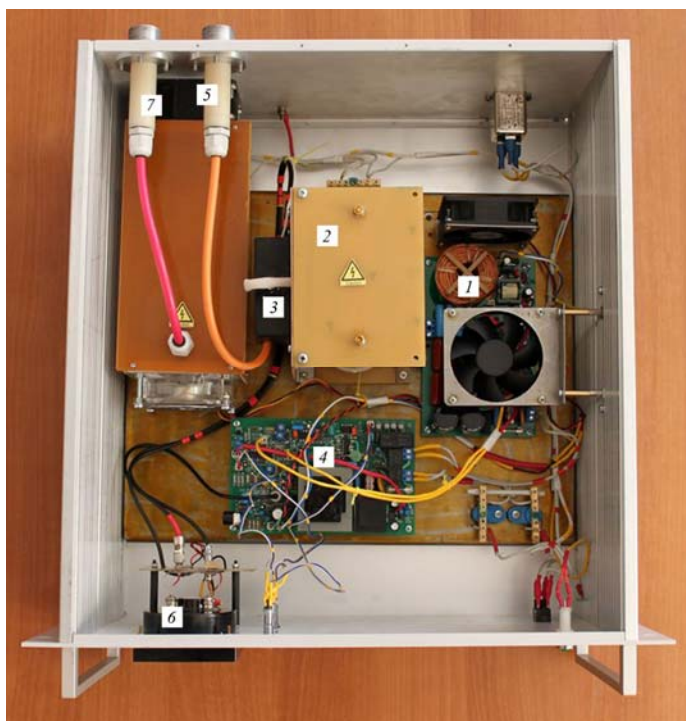
*Fig. 2. Inner arrangement of power supply (IHCE/Tomsk, Russia)*

*1 – plate of inverter circuit; 2 - high-voltage pulse transformer; 3 – high-voltage rectifier diodes; 4 – plate for control unit; 5 – output insulator for high voltage; 6 – voltmeter for measuring of an averaged high-voltage; 7 - input insulator for resistive load.*

# Properties of Hybrid Gas-Water Torch Used for Gasification of Biomass

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Among a number of processes being used for gasification of biomass plasma aided gasification is rather new and has not been intensively studied yet. There has been an increased interest in this technology in recent years due to its potential beneficial effects on properties of the produced syngas. Indeed, plasma is a medium with high energy content contained in a rather small amount of plasma gas and can be efficiently utilized for production of clean syngas.

Different types of plasma torches are used as plasma generators, which mostly works on air or different mixtures of gases. The present paper describes properties of the DC arc plasma torch with hybrid gas-water stabilization used for gasification of biomass [1]. A distinctive feature of the torch is extremely high enthalpy and temperature of the generated plasma with rather low plasma gas flow rate due to a specific design. The arc chamber of the torch consists of two main parts: a cathode part with gas stabilization and a water stabilized part. The gas part is similar to the gas torch configuration, while in the water part a principle of Gerdien arc is utilized, where the arc is burning inside a channel formed by water vortex. Plasma gas is a mixture of steam with a gas, which is usually argon. A specific principle of the torch allows varying its parameters in a rather wide range. The torch can operate with the arc current from 200 to 600 A, which results in arc power from 50 to 180 kW. Modification of the plasma gas flow rate, arc current and geometry of the arc chamber strongly affects properties of the generated plasma. The present work is aimed to describe effect of the plasma torch parameters and arc chamber geometry on properties of the generated plasma. Knowledge of these properties will facilitate control of the gasification process resulting in its higher reliability and efficiency.

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# Gas Turbine Combustor With Steam Injection and Plasma Activation

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The main requirements for modern gas turbine engines are effectiveness, reliability, long life time, low emission of harmful substances, and high operational stability of fuel burning devices. One of the most prospective methods for decreasing thermal $NO_x$ emission is water-steam injection into the primary flame zone, which reduces the flame temperature. At the same time, decreasing the temperature causes destabilization of the burning process, especially for partial load operation modes. That is why plasma activation is desired for sustaining the working processes in combustors with steam injection.

A 16 MW gas turbine engine combustor was chosen as the subject of investigation. In this chamber, the injection of an ecologically-relevant and energy-efficient steam is practically realized [1-2].

The analysis of a flow structure in the combustor was obtained from numerical modeling for full-load operational conditions, which allowed the identification of the following imperfections in the burning process:

- high non-uniformity of the ecologically-relevant steam feeding into the primary combustor flame zone, which leads to the appearance of zones with intensive nitric oxides formation. As a result of non-optimized steam injection (Fig. 1, *a*) there are local zones without any steam in the flame tube (Fig. 1, *b)*;

- high non-uniformity across the holes for primary air-feeding and the resultant partial aspiration towards the swirler. Note, that air from the upper three holes flows towards the swirler, and the air from the other primary holes flows towards the outlet section of the flame tube. This causes significant temperature-field variation in the combustor secondary burning zone and, as a result, increase of $NO_x$ emissions, and outlet-temperature field non-uniformity.

The authors offer the following improvements for the flame tube design to avoid the burning process imperfections, which were found during the CFD analysis:

- place an additional deflector-ring before the blade swirler to prevent the steam from flowing into the annular space;

- move upper three rows of the primary air holes towards the outlet section and decrease their diameters by 25% to get reasonable outlet temperature characteristics;

- apply a plasma stabilization device in the primary combustion zone area.

All of these improvements allow the reduction of CO, as calculated from 12 to 4 ppm and $NO_x$ emission from 33 to 10 ppm for the updated version of the flame tube (Fig. 2, *a, b*). Thus, the 3-D numerical experiment shows that the emission of nitric oxides significantly decreases – by up to 65 %. The reason for such $NO_x$ emission reduction is not only the lower maximum temperature level inside the flame tube, but also the shortening of the zones having near-stoichiometric combustion values (1.1-1.2) of the air excess coefficients.

The temperature field in the flame tube becomes more uniform (Fig. 3, *a, b*), and the outlet radial temperature variation decreases from 8 % up to 4.1 %, while the tangential temperature

variation stays at the same level.

Moreover, stability of the combustion process and reduction of the harmful emissions for the partial-load operational modes are provided by the system of plasma assisted combustion [3-5].



a)                                                                          b)
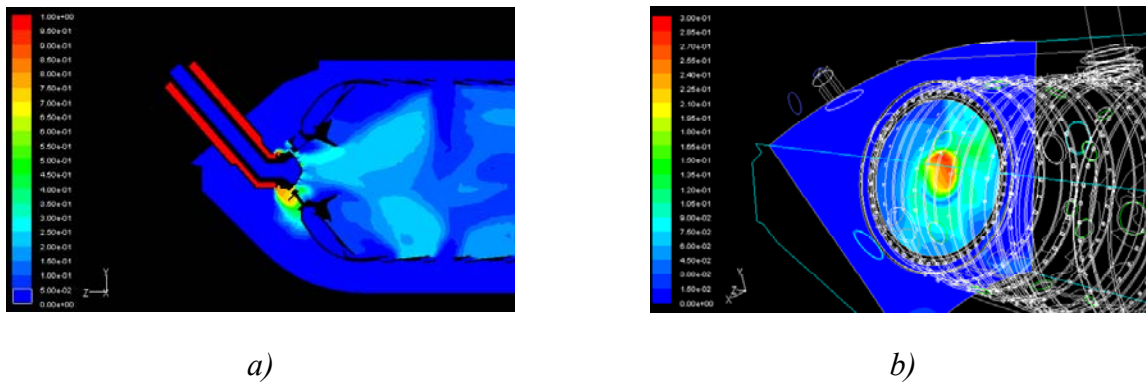
*Fig. 1. Non-uniformity of the ecological steam injection into the flame tube:*

*a – steam concentration field in the longitudinal section of the combustor;*
*b – steam concentration field in the cross-section after the swirler*



a)                                                                          b)

*Fig. 2. NO$_x$ concentration field in the longitudinal section of the combustor:*
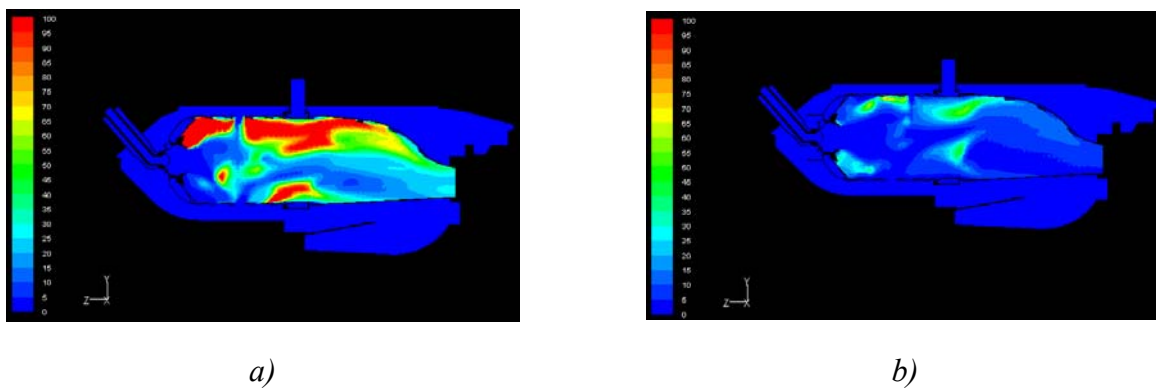*a – basic design of the flame tube; b – update design of the flame tube*



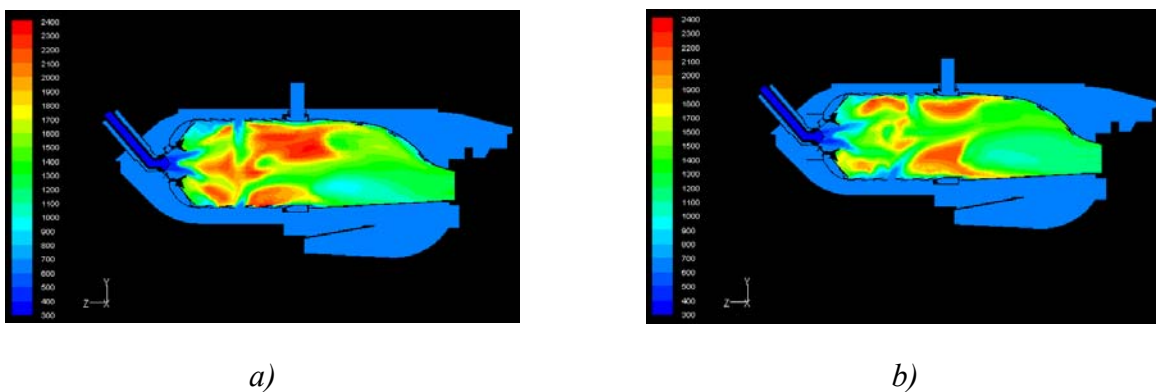a)                                                                          b)

*Fig. 3. Temperature field in the longitudinal section of the combustor:*
*a – basic design of the flame tube; b – update design of the flame tube*

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# Non-Thermal Plasma Assisted Reforming of Liquid Fuels in Dynamic Combined Plasma – Liquid Systems

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## I. INTRODUCTION

Today, hydrogen ($H_2$) is considered as one of the most perspective energy sources for the future that can be renewable, ecologically clean and environmentally safe. Among possible technologies for $H_2$ production, including steam reforming and partial oxidation of hydrocarbons, a low-temperature plasma reforming of biomass-derived ethanol (ethyl alcohol $C_2H_5OH$) is believed to be a good alternative approach .

There are various electric-discharge techniques of plasma conversion of ethanol into $H_2$ using thermal (equilibrium) and non-thermal (non-equilibrium) plasmas: arc, corona, spark, MW, RF, DBD, etc. Among them, one of the most efficient is the plasma processing in the dynamic plasma-liquid systems (PLS) using the DC and pulsed electric discharges in a gas channel with liquid wall (DGCLW) [1] and the DC discharge in a reverse vortex gas flow of tornado type with a "liquid" electrode (TORNADO-LE) [2]. Advantages of this technology are high chemical activity of plasma and selectivity of plasma-chemical transformations, providing high-enough productivity and efficiency of conversion at relatively low electric power consumption on the high-voltage discharging in a flow at atmospheric pressure [3]. The nonequilibrium plasma assists as an energetic catalyst containing charged particles and electronically excited atoms and radicals, which initiate fast chain-branching conversion of hydrocarbons that does not occur in usual conditions [4]. The highly developed plasma-liquid interface with the large surface-to-volume ratio and the deep injection of active plasma particles into the liquid also favor to the intensification of conversion in the plasma-liquid system [5, 6]. At that, there is no problem with excess heat removal since such plasma system is thermally 'cold' [7, 8].
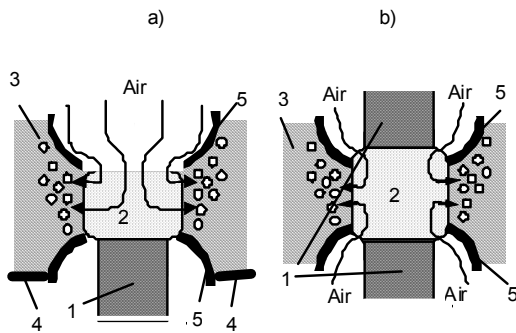


*Fig. 1. Schematic of electric discharges in a gas channel with liquid wall*

In this paper we report new results of our experimental and theoretical studies of the process of plasma-assisted reforming of ethanol in the PLS with the DC and pulsed DGCLW and TORNADO-LE using available methods of diagnostics and numerical modeling.

## II. EXPERIMENTAL SETUP

Experiments were done with the PLS reactors using the DGCLW with one (Fig. 1a) or two (Fig. 1b) gas streams injected in the liquid. It consists of the cooper rod electrodes *1*, plasma column *2*, work liquid *3*, electrode in liquid *4*, and quarts tubes *5*. The voltage was supplied from the high power source with a ballast resistor. The discharge channel in the liquid was formed in two modes: with a constant gas flow ($G \neq 0$) and without it ($G = 0$). The compressed air was served as working gas; ethanol, water and their mixture were used as working liquids. Three different modes of discharge were studied: 1st mode, where the voltage was applied to the electrodes on the top and bottom flanges (mode of two solid Fig. 1. Schematic of electric

*Fig. 2. Schematic of the PLS reactor with the DC discharge in a reverse vortex gas flow of tornado type with a "liquid" electrode*

discharges in a gas channel with liquid wall electrodes); 2nd mode, where "+" was applied to the electrode on the bottom flange whereas "–" was applied to the liquid ("liquid" cathode, LC); and 3rd mode, where "–" was applied to the electrode on the bottom flange whereas "+" was applied to the liquid ("liquid" anode, LA). Another PLS reactor used with the discharge TORNADO-LE is shown in Fig. 2. It consists of a cylindrical quartz vessel *1* with diameter of 9 cm and height of 5 cm, sealed by the flanges at the top *2* and at the bottom *3*. The vessel was fueled by the work liquid *4* via the inlet pipe *5*; the level of liquid was controlled by the spray pump. The basic water-cooled *T*-shaped 2.5 cm-diameter cylindrical electrode *6* on the bottom flange *3* made from stainless steel was fully immersed in the liquid. The second electrode on the top flange *2* made from duralumin had the copper hub *11* with the axial nozzle *7* of 2 mm inner diameter and 6 mm length. The gas was fed into the reactor chamber through the orifice *8* in the top flange *2* tangentially to the wall *1*
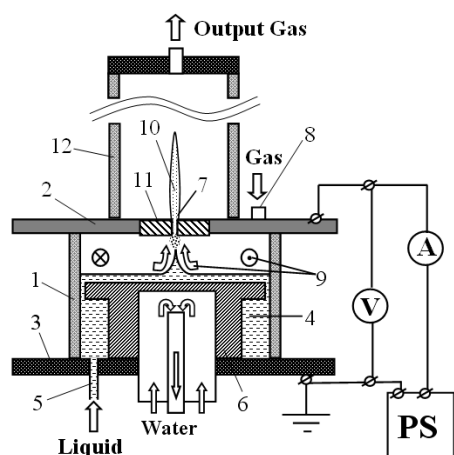
and formed a vortex flow of tornado type. The swirling gas went down to the liquid surface and moved to the center of the system, where it flowed out through the nozzle *7* in the form of jet *10* into the upper quartz camera *12*. Since the area of minimal static pressure above the liquid surface during the vortex gas flow was located near the central axis, it created the column of liquid at the gas-liquid interface in the form of the cone of ~1 cm height above the liquid surface as is shown in Fig. 2.

The plasma torch *10* of ~5 cm long was formed during the discharge in the chamber. The voltage was applied between the top flange *2* and the electrode *6* in the liquid *4* from the DC source powered up to 10 kV. In experiments, two basic modes of discharge were studied: 1) with "liquid" cathode (LC), and 2) with "solid" cathode (SC), using "+" on the flange *2* in the LC mode, and "–" on the
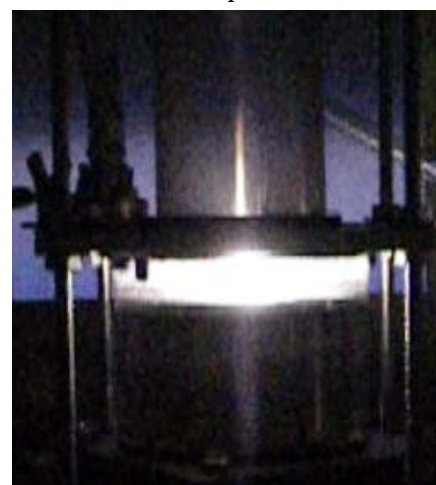


*Fig. 3. Photo of TORNADO-LE working in ethanol-water solution.*

flange *2* in the SC mode. The conditions of breakdown were regulated by three parameters: by the level of working liquid; by the gas flow rate *G*; and by the applied voltage *U*. The discharge ignition began with the appearance of axial streamer. Time for establishing a self-sustained discharge burning was ~1-2 s after the first streamer. The discharge current varied within the range 100-400 mA. The pressure in the discharge chamber during the discharge was ~1.2 atm, the static pressure outside the reactor was ~1 atm. Fig. 3 shows the TORNADO-LE working in ethanol-water solution.



*Fig. 4. Current-voltage characteristics of the TONADO-LE with solid cathode working in water at different airflow rates*

## III. RESULTS AND DISCUSSION

The typical current-voltage characteristics of the TORNADO-LE in the mode with "solid" cathode working in water at different airflow rates are shown in Fig. 4. The data are given for the case of mixture $C_2H_5OH : H_2O = 5:1$ and airflow rate $G = 55$ cm$^3$/s In the discharge conditions, the kinetics of $H_2$ formation is determined mainly by reaction $C_2H_5OH + H \rightarrow CH_3CH_2O + H_2$. As the $[C_2H_5OH]$

concentration in solution changes slowly, the [$H_2$] production is determined entirely by concentration of H. In the case under consideration, the main process responsible for the H generation is an electron impact dissociation of $H_2O$. The rate of this process is proportional to specific power deposited to the discharge (i.e., discharge current). Therefore, the [$H_2$] production is also a linear function of the discharge current in accordance with experimental data. Outside the discharge, the only process that influences the $H_2$ concentration is the water-gas shift reaction (WGS) $CO+H_2O \rightarrow H_2+CO_2$. Via this process, the system reaches the complete conversion of CO into $CO_2$ and $H_2$.



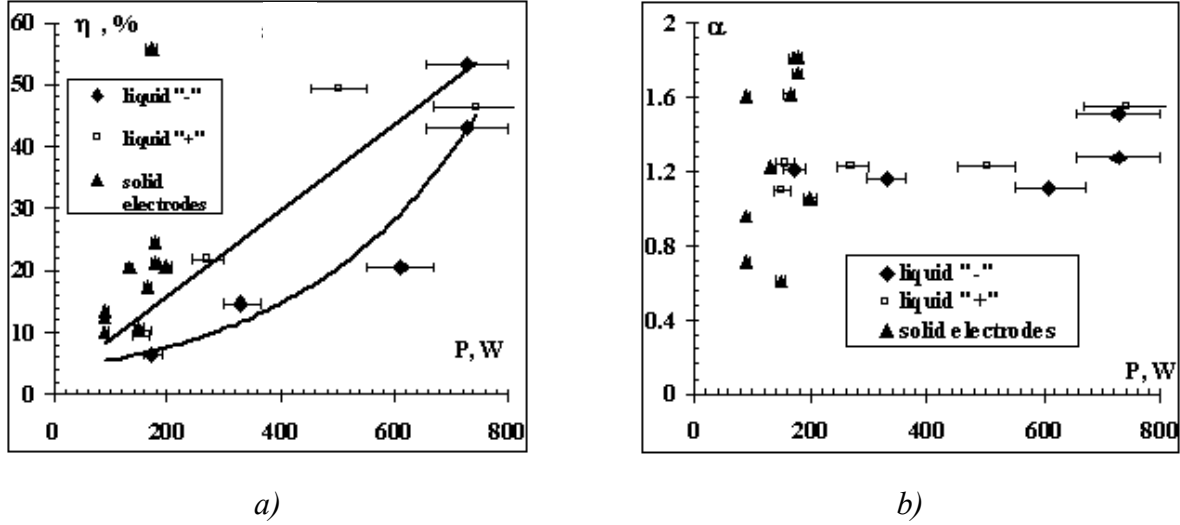*a)*                                                            *b)*

*Fig. 5. Efficiency of ethanol conversion (a) and coefficients of energy transformation (b) for ethanol reforming in the DGCLW in different modes as a function of discharge power (discharge currents are from 50 to 400 mA)*

Estimations of efficiency of reforming of ethanol into the hydrogen-rich syngas in the studied PLS was performed on the basis of thermochemical analysis using criteria: (a) energy cost of 1 m$^3$ syngas products; (b) productivity of conversion; (c) specific heat of 1 m$^3$ syngas combustion, and (d) energy efficiency.

Calculations were made with taking into account standard thermochemical constants of hydrocarbons using the formula for the coefficient of energy transformation [6] and also for the conversion efficiency by Fulcheri et al [5].

The results of estimations in the form of *a* and *h* dependencies for the ethanol reforming in the PLS with the DGCLW as a function of the discharge power for different modes are presented in Fig. 5 (a, b). The data are given for the case of the mixture $C_2H_5OH : H_2O = 5:1$.

We obtained the net $H_2$ yield in the discharge at $I = 300$ mA is ~15% whereas the energy efficiency of the ethanol conversion into the syngas is up to 50%. The power consumption lies between 2.4 and 3 kWh/m$^3$.

IV. CONCLUSIONS

In summary, our investigations have shown the following.

- The dynamic plasma-liquid systems with the DC and pulsed electric discharges in a gas channel with liquid wall and the DC discharge in a reverse vortex gas flow of tornado type with a "liquid" electrode are quite efficient in low-temperature plasma reforming of ethanol into syngas comparable to other known electric-discharge systems of atmospheric pressure such as diaphragm and arc types.

- According to optical spectrometry, the investigated discharges are characterized by high degree of nonequilibrium and nonisothermality. Reactive plasma contains a lot of excited atoms and radicals (H, O, OH, etc.) associated with dissociation of molecules in ethanol-

water vapors, thus providing desirable selectivity and productivity of plasma-chemical conversion.

- According to mass-spectrometry and gas-phase chromato-graphy, the main components of syngas produced from ethanol in the plasma-liquid reactor are molecular hydrogen $H_2$ and carbon oxides $CO$ and $CO_2$, which relative fraction reaches 90%, i.e. many times higher than other hydrocarbons $CH_4$, $C_2H_2$, $C_2H_4$, and $C_2H_6$.

- The composition content of output gas products and the electric power inputs on the ethanol conversion depends on the gas that forms the plasma in the discharge and on the ethanol-water ratio in the solution. At that, the output concentration of $H_2$ grows with the discharge power up to the saturation.

- The maximal absolute yield of $H_2$ (~15%) was obtained when ethanol and water in the mixture taken in equal amounts. In that case the efficiency of conversion reaches ~50%.

- The minimal value of the electric power consumption on the ethanol conversion in the studied regimes is about 2.4 kWh/m$^3$ at the heat capacity of the output syngas ~4.4 kWh/m$^3$.

- The kinetic plasma-chemical modeling gives a fairly good agreement with experimental data, at least, for the main syngas components, $H_2$, $CO$, and $CO_2$, thus explaining nonequilibrium character of the non-thermal plasma-chemical mechanism of the ethanol conversion in the studied plasma-liquid systems.

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# New Approaches to Partial and Complete Plasma Coal Gasification

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Since the 1950s, plasma-related processing has been a promising tool to enable and speed up numerous processes and technologies, but with the major disadvantage of high-power device requirements, such as limited lifetime because of electrode erosion or melting. This problem was successfully solved by our partner APT, which recently introduced to the market its 50-150-300 kW hybrid plasma torches, with the main focus on coal and waste gasification, electronic grade silicon production, materials modification, nano-powder production, and related applications.

Precise analyses of coal gasification technologies and preliminary modeling of plasma-based coal gasifiers [1-3] have lead to ideas for pilot plant development, a schematic of which is shown in Fig.1. This concept was discussed during a Coal Gasification Meeting and Open Discussion within the 5th International Workshop and Exhibition on Plasma Assisted Combustion, which was held 15-18 September, 2009 in Alexandria, VA, and initially at the APT-Turkish Coal Enterprises meeting on 18-19 June, 2009 in Ankara. Going forward on this program plan was supported by over 30 world-leading scientists in the field of plasma assisted combustion and was suggested for funding, implementation, and experimental operation to potential customers, initially in the USA, India, and Turkey.

A suggested pilot plant is shown in Fig. 1. It will be based on a 50-100 kW hybrid plasma torch (10) with optional plasma gases - such as air, oxygen, and water-steam - and a downstream gasification chamber (13). Feeding of coal will be provided in the form of a variable- composition coal slurry and coal dust (air/coal mixture). Conditioned syngas is produced after cooling in a heat exchanger (15), and also by means of a double-stage ash separation process in a cyclone filter (19), which at the project feasibility stage, the ash will be burned in a reverse vortex combustor [4].

As the first stage on the way of such a plant development, we envision a time scale of 12 months for the development of key element s according to the scheme in Fig. 2.



*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 ($O_2$); 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; 24 - power generation unit , optionally IC engine, turbine or boiler*
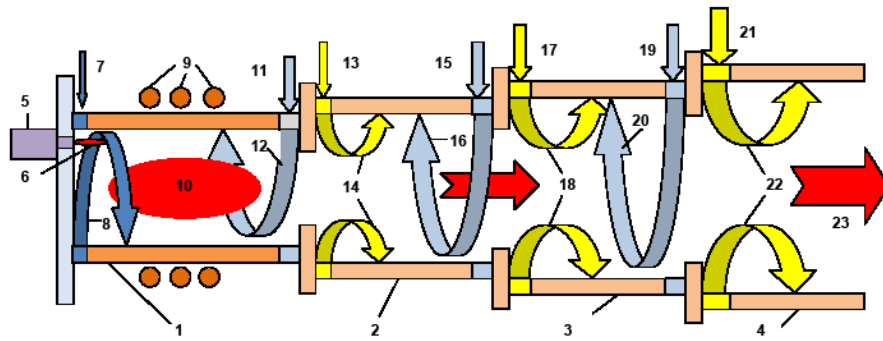
*Fig. 2. Plasma assisted coal burner/gasifier scheme (US Patent 7,452,513 B2):*

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

Preliminary plasma coal gasification modeling using 3D CFD calculations of flow dynamics have already been conducted. For the modeling of physical and chemical processes inside the plasma gasifier, a generalized method has been used, based on numerical solution of the combined conservation and transport equations for a turbulent-flow, 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 gasification system has two sections: a plasma pre-gasification or combustion module and a gasification module. Each module can be accordingly divided into 2 to 3 stages. Plasma air is injected through the cylindrical duct. Two air-coal streams are injected in series into the plasma for initial heating, devolatilization, and combustion (partial oxidation). Next, a portion of the air-coal mixture (or pure air) is supplied into the gasification module through a special swirler to guarantee stable combustion (partial oxidation) of the previously-processed plasma-air-coal mixture. Steam and coal are injected in a radial direction for the production of gasification products, including carbon monoxide and molecular hydrogen (i.e., syngas).

Contour plots of CO mass fraction and particles, colored by particle char fraction, for two and three coal injections are shown in Fig. 3. Case *a)* corresponds to partial oxidation of coal in the plasma pre-gasification module, and case *b)* corresponds to coal steam gasification in the gasification module.
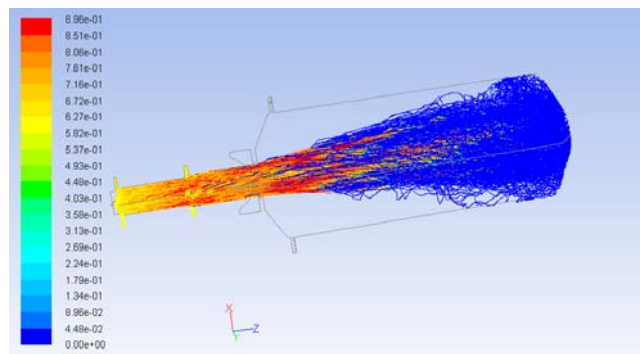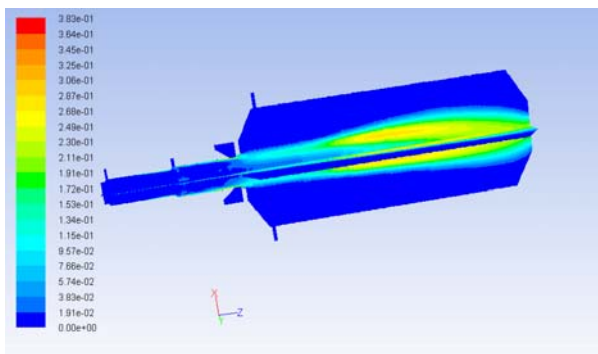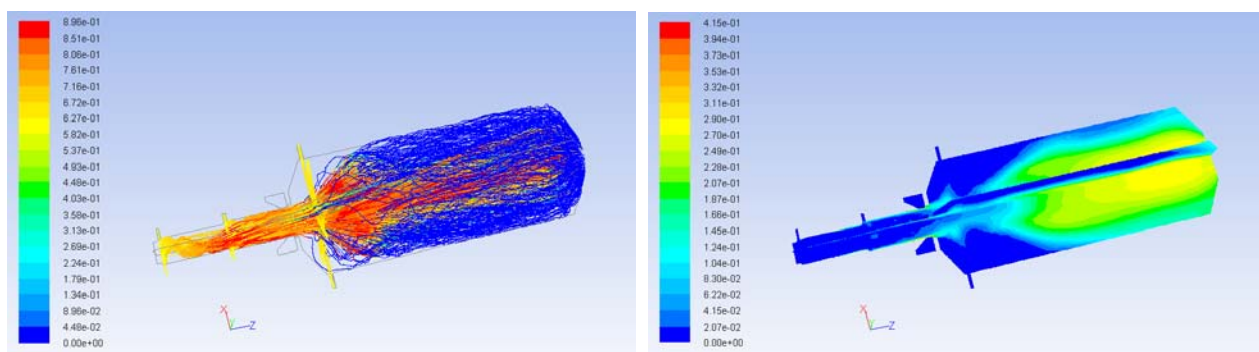


*a)*

Fig. 3. Contour plots of CO mass fraction and particle traces, colored by particle char fraction:

a – two coal injection; b – three coal injection

These calculations have demonstrated the principal possibility of using CFD codes/models for prediction and parameter optimization of plasma coal gasifiers. 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 verify the proposed chemical and physical mechanisms, which requires conducting coordinated experimental and theoretical investigations.
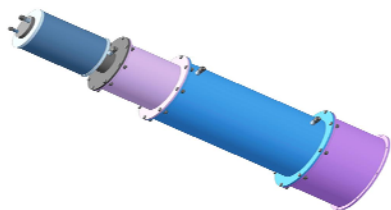


Fig. 4. Expected appearance of the three-stage gasification chamber with a plasma torch

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# Experimental Investigation of Plasma Assisted Combustion Using a Low-Swirl Burner

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In the modern society energy is an all-important commodity. The combination of achieving the best possible efficiency, lowest possible emissions and least thermal stresses when producing energy is a challenge. A promising improvement is combining lean combustion with a non-equilibrium plasma. A theoretical approach shows that artificial chain initiation of combustion should be more efficient than thermal initiation. [1]

The scope of the work focuses on lean, plasma-assisted combustion. Combustion of lean mixtures lowers the flame temperature, and has a potential to decrease harmful emissions such as $NO_x$. To investigate lean flames combined with plasma a Low-Swirl Burner (LSB) is used. This burner has the advantage over commonly used high swirl burners that, even without plasma assistance, it can burn lean with near-zero emissions of $NO_x$ and CO. [2]

The burner was modified so that a Dielectric Barrier Discharge (DBD) could be generated inside the burner exit (Fig. 1). The modification consists of an extension of the burner by a quartz tube with a metal mesh, the high voltage electrode, wrapped around it. In the center of the quartz tube a grounded steel pin is mounted. This design was inspired by Rosocha et al.[3] A Teflon insert holds the quartz tube to insulate the high voltage electrode from the original burner exit that holds both the swirler and the grounding pin.

Fig. 2 shows the various plasma modes that where found during the research. The glow mode can only be found at specific mixture settings and high plasma powers (>300 W). It can only be sustained for short periods of time, as the grounding pin slowly melts down. Therefore, no repetitive measurements could be done using this regime.

Measurements focused on the lean blow-off limit of premixed methane/air and propane/air flames, as a function of gas flow speed at atmospheric pressure and ambient temperature. Data processing is still in progress, and we present preliminary results here. The unassisted combustion was taken as the reference configuration, to which two plasma-assisted modes were compared. These modes differed in the plasma generator used. One plasma generator is an AC source capable of 40 kHz, 20 kV and a maximum power of 2 kW. The other source is a nanosecond pulsed plasma source (FID FPG-20), with maximum power of 50 W, maximum voltage of 20 kV, maximum repetition rate of 10 kHz and a pulse width of 10 ns.



*Fig. 1. DBD low-swirl burner*

The power that could be delivered to the flow is limited by the occurrence of arcing. Arcs, a form of thermal plasma, are relatively inefficient in creating reactive species, and thus are undesired for our goal. The maximum power depends on flow speed, which can be seen in Fig. 3. This figure
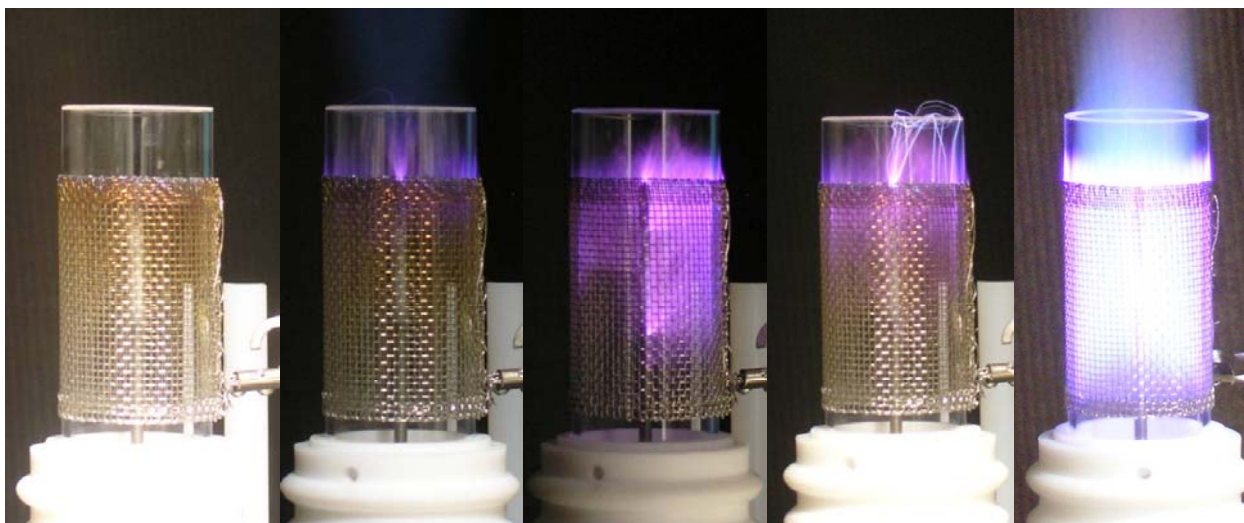
*Fig. 2. The diverse plasma modes.*
*From left to right with increasing plasma power: no plasma, corona, corona in air, arcing, glow*

also indicates the leanest stable methane/air flames that the burner could sustain with and without plasma. For an equivalence ratio between 0.5 and 0.6 the plasma-assisted flames were so faint that they were hard to detect by eye, suggesting combustion was not complete. This was tested using an exhaust gas analyzer (Arex Type 40). The device was designed for higher order hydrocarbon

measurements so there are no quantitative results. However, comparing results with and without plasma gave interesting insights. With a flow speed of 3 m/s and an equivalence ratio of 0.75 this gave a decrease of 16% of unburned hydrocarbons when the plasma generator was activated. Decreasing the equivalence ratio increases the number of unburned hydrocarbons significantly. Going from $\varphi= 0.7$ to $\varphi=0.6$ increases the emission of unburned hydrocarbons with 37%. This illustrates the need for finding an optimum between power introduced into the plasma, equivalence ratio and completeness of combustion.
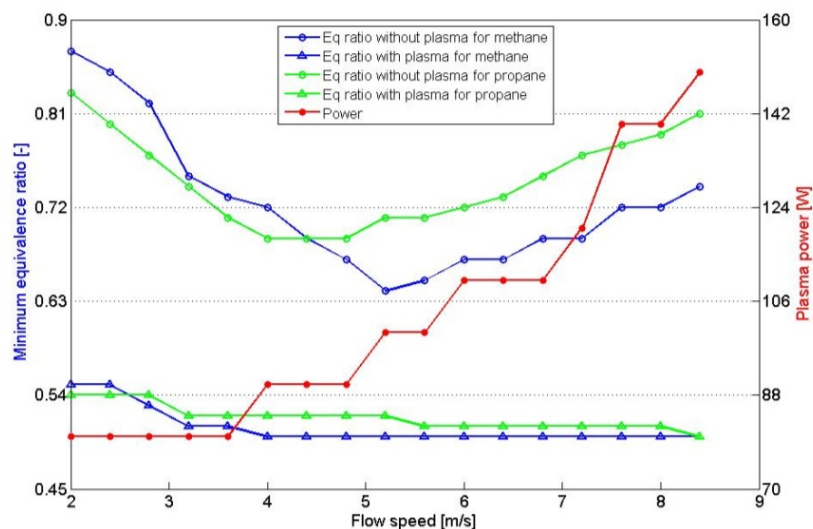


*Fig. 3. The minimum equivalence ratio and maximum plasma power as function of flow speed with and without plasma for methane/air and propane/air mixtures*

The same measurements are done for a propane/air mixture, the results are included in figure 3. The maximum plasma power that could be delivered to the flow is the same as for the methane/air mixture. At low flow speeds the influence of plasma on methane is higher than for propane, but at higher flow speeds, the influence is larger for propane.

When set at its maximum power of 50 W the results with the nanosecond pulsed plasma source are comparable to those with the AC source at 70 W. It can be seen in figure 4 that when increasing the flow speed, the minimum equivalence ratio before blow-off increases when the
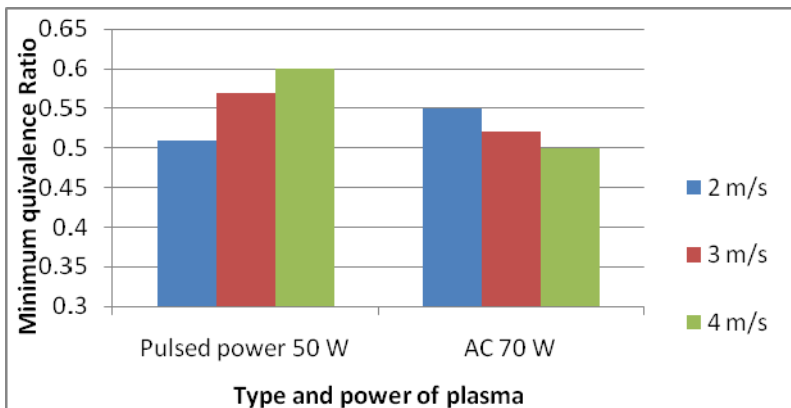
*Fig. 4. Comparison between pulsed power and AC plasma*

pulsed source is used, while with the AC source it shows a decrease. A more powerful pulsed source is needed to make a fair comparison at flow speeds above 4 m/s.

To get more insight in the reasons why a plasma improves the blow-off limit spectrographic measurements are done. Emission spectra were recorded by means of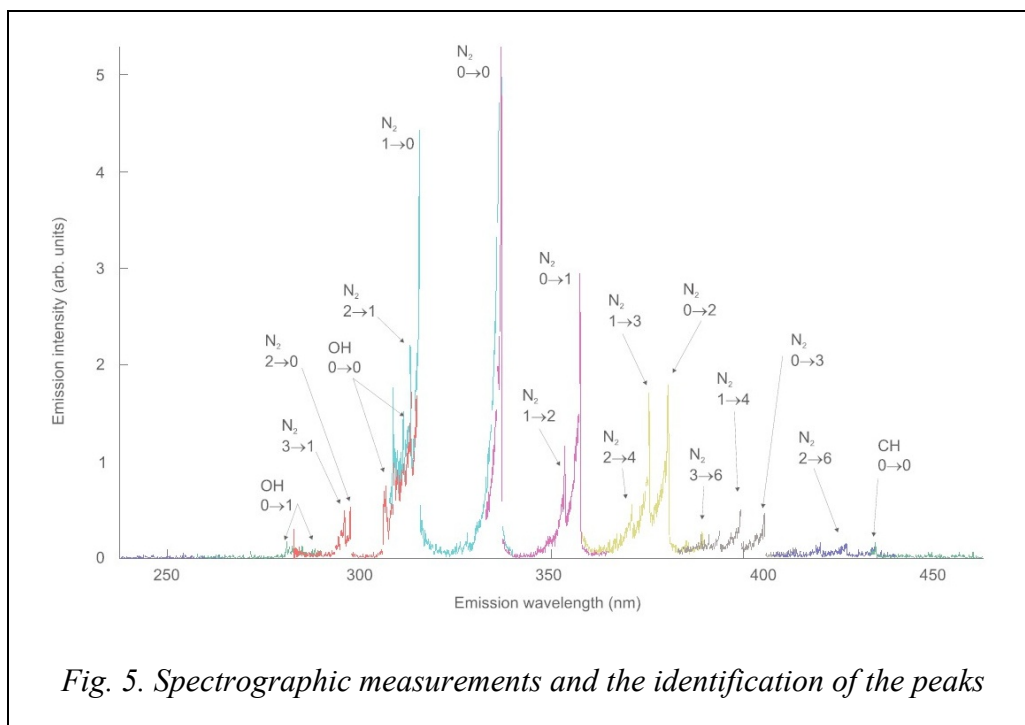 an intensified CCD camera (Princeton Instruments) mounted behind an imaging spectrograph (Chromex 250i) equipped with a 300 grooves/mm UV-blazed grating.



*Fig. 5. Spectrographic measurements and the identification of the peaks*

The results can be seen in figure 5; it covers the 250-400 nm range in several overlapping portions of about 30 nm each. Above the peaks the species and the transitions are noted. The emission intensity only varies with plasma power, but not with equivalence ratio or fuel. Almost all lines can be traced back to the transition of $N_2$ from $C^3\Pi_u$ to $B^3\Pi_g$ in the second positive system.[4] In the region from 280 to 320 nm transitions in OH have been found, and CH was observed weakly (relative to the nitrogen peaks) around 430 nm. OH and CH were also observed in the unassisted flames, at about the same intensities. Normally, $N_2$ does not have an influence on combustion. Although electronically excited $N_2$ can be expected to be considerably more reactive than ground state molecules (even in the lowest triplet state $N_2$ has about 5 eV of internal energy), we assumed that it acts as an intermediate species to transfer energy to other molecules such as $O_2$ and $CH_4$ or $C_3H_8$. A suggestion is that these molecules break up, and thereby a chain initiation is produced.

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# Flame Modifications Induced by Electronically Excited Oxygen Generated by a Cold Plasma

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The promoting action of discharges on combustion processes results in a reduction of ignition delay, improvement of flame stability as well as extension of flammability limits. These features are key technical issues for combustion improvement. One particularly promising approach for this purpose consists of plasma-enhanced activation of the oxidizing substance, such as when transforming molecular oxygen into its electronically excited singlet delta $O_2(a^1D_g)$ and singlet sigma $O_2(b^1S^+_g)$ states. In contrast with non-excited reactants, singlet oxygen molecules display a higher chemical activity and can affect reaction kinetics due to a decrease of the energy barrier associated with endo-energetic reactions.

The aim of the present study is to understand experimentally and numerically why and how combustion processes are modified in the presence of electronically-excited oxygen molecules, using numerical simulations involving detailed reaction schemes containing excited species as well as spontaneous emission of typical flame front marker molecules.

A specific partially-premixed burner has been developed for the experiments. The non-thermal plasma discharge is directly incorporated into the burner. The injection consists of two channels: one for the primary mixture ($CH_4/O_2/He$), the second for the secondary excited oxidizer injection ($O_2/He$), which integrates the discharge section. A two-dimensional flame finally stabilizes just above the slits. The plasma generator consists of a cross-discharge with two dielectric barrier discharge (DBD) electrodes and two continuous discharge (DC) electrodes. The pulsed dielectric barrier discharge electrodes are powered by a high voltage (20 kV), short pulse (20 ns), high repetition rate (25 kHz) generator. The DC electrodes are powered by a DC power supply (max. 3 kV, 3 A) operated in the voltage-stabilized mode.

Spontaneous emission of OH*, CH* and $O_2$* has been recorded with an intensified CCD camera (NanoStar from LaVision) equipped with corresponding bandpass-filters centered at 307 nm, 431 nm and 762 nm.

The experiments presented here have been conducted at an absolute pressure of 120 Torr and with a global equivalence ratio $\Phi = 1$. Some typical results obtained from spontaneous emission measurements are shown next. The production of excited oxygen can clearly be seen when the cross-discharge is turned on. The $O_2(b^1\Sigma^+_g)$ transition is visualized at 762 nm over the right burner slit. The excited oxygen changes the aspect of the flame. Particularly strong changes could be observed on the OH radical, but also CH is noticeably modified. The flame elongates towards the right burner slit, where the excited secondary oxygen is added to the flame, and becomes wrinkled. The quantity of excited oxygen generated by the crossed discharge reactor is considerably increased when the DC sustained voltage is increased from $U_{DC} = 1.2$ kV to 1.4 kV, until arcing is obtained. Plasma activation leads to an average increase of CH* intensity of 12% and of OH* intensity of 37%.

Further work will concern the production of excited oxygen at atmospheric pressure using a new, micro-wave plasma generator, with a view toward practical applications.
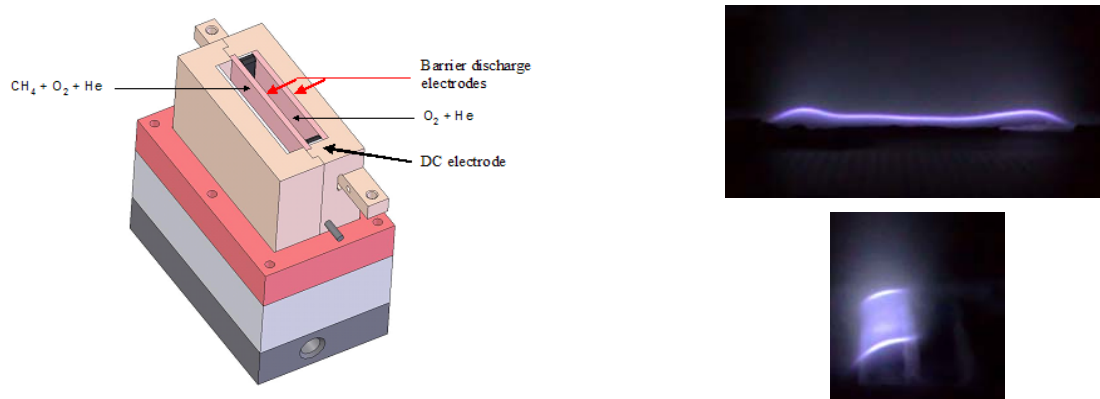
*Fig. 1. Left: Sketch of the burner configuration; Right: direct view of the flame: front view (top) and lateral view (bottom) with the secondary air flow on the right side*
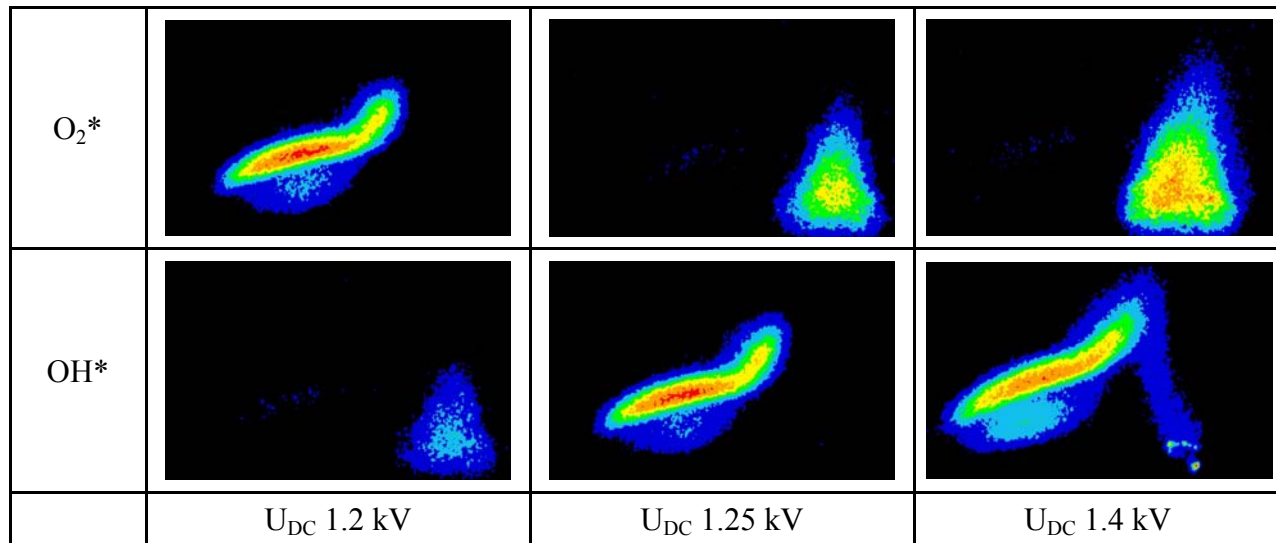


| | $U_{DC}$ 1.2 kV | $U_{DC}$ 1.25 kV | $U_{DC}$ 1.4 kV |
|---|---|---|---|
| $O_2$* | | | |
| OH* | | | |

*Fig. 2. Effect of DC sustainer voltage on $O_2$* production and flame structure modification (lateral view)*

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# Combustive Decomposition of Anesthetic Gas for Medical Operation Using Atmospheric Multi-Gas Inductively Coupled Plasma

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In recent years, increasing concentrations of greenhouse gases is concerned as the cause of global warming. Nitrous oxide ($N_2O$) has 298 times higher global warming potential compared with carbon dioxide ($CO_2$) and 112 years lifetime in atmosphere. Therefore, the emission of $N_2O$ has a considerable impact on global warming. Additionally, recent research indicates that $N_2O$ has become a substance which has the largest impact on ozone destruction instead of chlorofluorocarbon. In Japan, about 1,000 tons/year of $N_2O$ is used for medical operation and it is being emitted to the atmosphere without any treatment. To prevent global warming and ozone layer depletion, anesthetic gas including $N_2O$ has to be decomposed before atmospheric release. Some decomposition systems using combustion method or catalytic method have already been marketed. However, these systems are not spread at all due to the large sized equipment and the high-running cost. To popularize anesthetic gas decomposition devise, it is required to be "compact", "maintenance free" and "high efficiency". In this study, atmospheric multi-gas inductively coupled plasma (ICP) source as shown in Fig. 1 was applied for the anesthetic gas decomposition. The plasma source can stably generate atmospheric thermal plasma by not only Ar but also He, $N_2$, $O_2$, $CO_2$, Air, and their mixture gas.
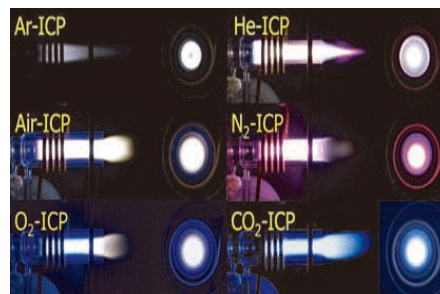


*Fig. 1. Atmospheric Multi-gas ICP*

The use of multi-gas ICP enables direct decomposition of anesthetic gas with high decomposition efficiency because it can generate the plasma by anesthetic gas itself. When anesthetic gas is released to atmosphere, it is exhausted with negative air pressure. Thus, 4 L/min of $N_2O$, 2 L/min of $O_2$ and 4 L/min of air are mixed to imitate the actual gas composition for medical operation.

As a result, when 10 L/min of flow rate and over 750 W of the RF input power was applied, 99.9% of $N_2O$ decomposition rate and 628 g/kWh of $N_2O$ decomposition efficiency were achieved. Our decomposition system can treat up to 20 L/min of flow rate, which corresponds to the flow rate for two surgery room. The highest decomposition efficiency was 819 g/kWh for 20 L/min at 1,150 W of RF input power. This energy efficiency was more than five times higher than that of other commercially available systems. However, 48 g/h of nitrogen dioxide ($NO_2$) was generated as a by-product. It was considered that this was caused by high gas temperature.
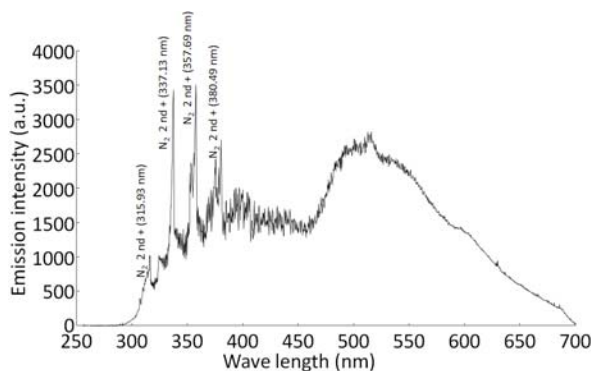


*Fig. 2. Emission spectrum of $N_2O$ plasma*

In this study, the plasma gas temperature was measured by using spectroscopic method. Fig. 2 shows an example of emission spectrum of the anesthetic gas plasma. The lines between 300 and 450 nm due to the nitrogen 2nd positive electronic transition $N_2(C^3\Pi_u$-$B^3\Pi_g)$ were observed. And strong continuous spectrum was observed. The measured spectroscopic properties of the plasma will be presented.

**Acknowledgement**
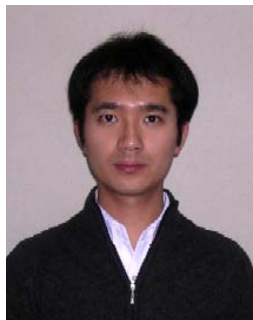
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# Heavy Oil Burner Utilizing Plasma Assisted Combustion

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Burning of heavy oil represents nowadays a great challenge due to the very rigorous rules concerning emissions control. Several processes are currently being tested in search for new ways to overcome this problem. A solution presented in this work consists in heavy oil plasma assisted combustion with the use of a rich combustion environment in a first reactor stage followed by a lean combustion environment in a second stage such that desired temperature can be achieved at the reactor's exit without any stoichiometric zone in the burner avoiding extreme temperatures and $NO_x$ production. Non-Thermal plasma technology has been applied in the construction of a combustor in order to securely burn several types of heavy oil.

In conventional burning processes, hydrocarbon combustion is initiated with ignition where, for instance, a thermal source or sparkling plug is responsible for mixture decomposition in free radicals and active species. Energy liberated by combustion continues to promote reactive species propagation thus generating combustion self sustainment. Reactive species self generation may not be sufficient to sustain conventional combustion under certain conditions such as very lean or very rich mixture environments. However, in plasma assisted combustion process, the amount of active species at flame front region is increased providing sustainability and thermal gain. Activation through non thermal plasma discharges can be continuously used in order to reinforce conversion of liquid atomized fuel into reactive species.

A Rotex[®] Plasma reactor has been built and experimentation was carried out revealing that Rotex[®] Plasma is able to effectively convert Heavy Oil into Syn Gas as well as to sustain gasification reaction for ultra rich mixtures, what can't be achieved without plasma assistance. The main advantage of Rotex[®] Plasma relies on the fact that despite the use of low electrical input power, a high enough density of energized electrons is reached and selective partial dissociation of Heavy Oil molecules can be achieved.

In a first stage, an investigation of plasma electrical discharge influence over combustion process has been done. Several experimentations were carried out in a conventional burner where a plasma assisted pre-mix chamber for rich combustion (PAPC – Plasma Assisted Pre-Combustion) has been adapted. The combustion reaction occurred in two stages in order to avoid temperature peaks in primary zone – main cause of $NO_x$ formation. Emissions have been measured for both regular combustion and plasma assisted combustion. According to experiments results, combustion in rich mixture environment can be sustained by plasma discharges with lower temperatures thus providing low $NO_x$ generation and formation of $H_2$ and CO to be consumed by oxygen in lean mixture region afterwards.
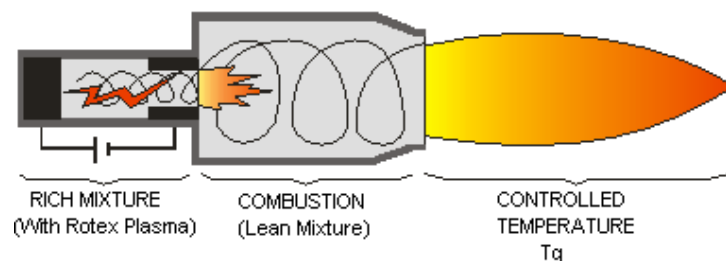


RICH MIXTURE (With Rotex Plasma)  COMBUSTION (Lean Mixture)  CONTROLLED TEMPERATURE Tg

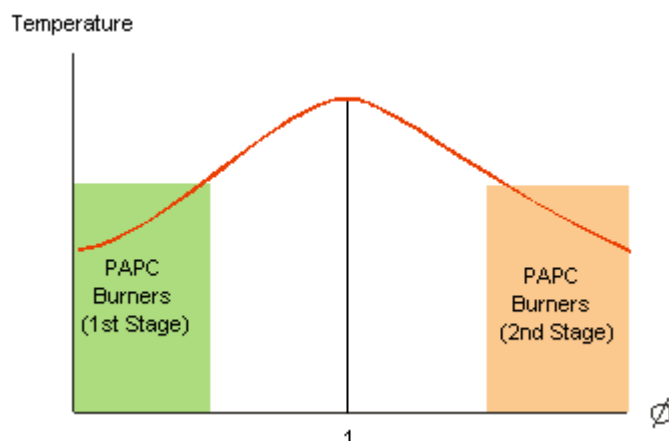*Fig. 1. Two-Staged Rotex[®] Plasma Assisted Heavy Oil Burner diagram*

## Acknowledgment

*Fig. 2. Two-Staged Rotex® Plasma Assisted Heavy Oil Burner Operational Regime*
*(Obs.: PAPC – Plasma Assisted Pre-Combustion)*

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# Low NO$_X$ Gas Turbine Combustor Assisted by Vortex Plasma Torch

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## Introduction

As result of the rapid increase of the air traffic and the large use of gas turbines to produce electric power, the reduction of pollutants has become the main objective in the design of gas turbine engines. To reduce $CO_2$ the tendency of the advance combustion chamber is to increase not only the inlet pressure and temperature but also the efficiency of the engine and to reduce the fossil fuel consumption. For aircraft gas turbines this is the only way to reduce $CO_2$ emission. However, it increases the maximum temperature in the combustor and more NO$_x$ is produced.

The present paper is concerned about a low NOx combustor assisted by plasma vortex torch. In this system, part of the fuel (natural gas - NG) is injected in combustor center line (50%) and a pilot flame is established. On the opposite side, air and fuel are injected non-premixed and tangentially to the combustor wall. Then, the flows are forced to a rotational movement in the direction of the pilot flame, where a quite lean mixture is formed and ignite by the energy released by the pilot flame. The Fig. 1 shows the schematic geometry of the combustor. This configuration promotes low NOx emissions; however CO emissions can increase drastically as compared with conventional gas turbine combustor. Probably the high CO emissions are consequence of the low temperature in the lean combustion zone, reducing the reactions velocities of the hydrocarbon oxidation mechanism.

An alternative to accelerate the hydrocarbon oxidation in the lean region is injection of the pilot fuel through a vortex plasma torch (gliding arc discharge), which operates in transitional regime, achieving high electron density and high degree of non-equilibrium. This type of discharge allows the excitation of rotational and vibrational levels of energy, without a great heating of the gas, favoring the occurrence of specific chemical reactions. The Figure 2 shows the plasma reactor used in the present work.
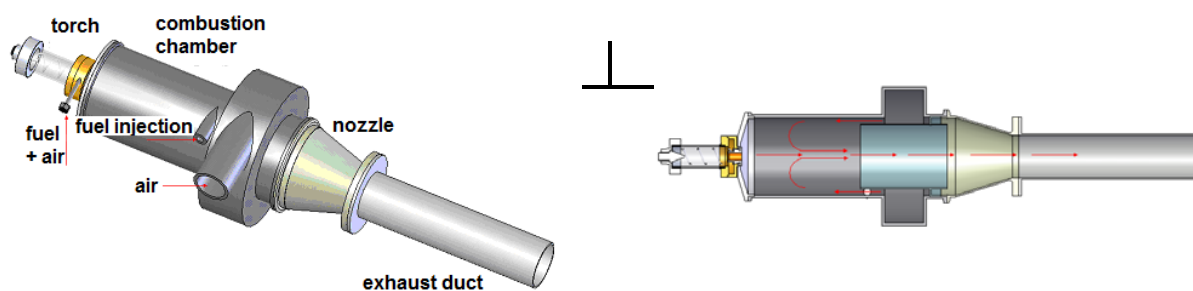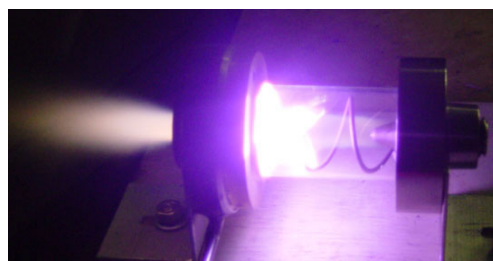


*Fig. 1. Combustor diagram*



*Fig. 2. Torch operation with the mixture natural gas/air*

**Results and Comments**

The experiments were conducted in a baseline operation condition: pre-mixed flow of 1g/s of NG and 2g/s of air trough the torch reactor (with or without plasma), 1g/s of NG and 137g/s of air injected directly into the combustor. The global equivalence ratio is 0.25 and the plasma operates with 4kV and 400mA.

The results show that the NOx emissions are quite low, less than 10 ppmv. However, the emission of CO is relatively high. When the plasma is on the level of $NO_x$ did not change, but the CO emission is reduced almost 50%.

*Table 1. Combustion Gases Emissions*

| Operation condition | Emissions[*] | | | |
|---|---|---|---|---|
| | $O_2$ | $CO_2$ | CO | $NO_x$[**] |
| **Without plasma** | 17,3% | 2,7% | 499 ppmv | <10 ppmv |
| **With plasma** | 17,3% | 2,8% | 255 ppmv | <10 ppmv |

\* Emissions in dry base.

\*\* $NO_x$ emissions were less than 10 ppmv, which is the $NO_x$ gas analyzer sensibility.

The mass spectroscopy for the gas from the torch, presented in Figure 3, shows that in addition of the expected presence of $N_2$, $O_2$ and $CH_4$, there are strong presence of $H_2$. The direct injection of $H_2$ in the lean combustion can accelerate the reactions by the $H_2$ mechanism of oxidation that will produce hydrogenated species. Since the conversion of CO to $CO_2$ is much faster through the reactions with these hydrogenated species (ex.: OH), the consequence is to reduce the CO emissions.
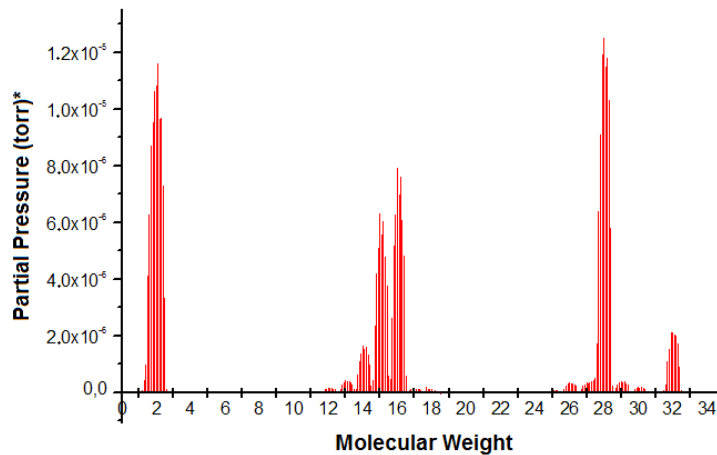


*Fig. Mass spectroscopy result for the gases produced by the torch*

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# Non-Self-Maintained Discharge and Electron Beam Plasma in Propane-Air Mixture II. (Experimental Results)

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This work is a continuation of experimental investigations of complex impact of electron beam and external electric field on combustion processes of propane-air mixture [1]. Here we represent description of experiments and experimental results obtained in course of experimental investigations with a help of industrial accelerator EOL-400 M.

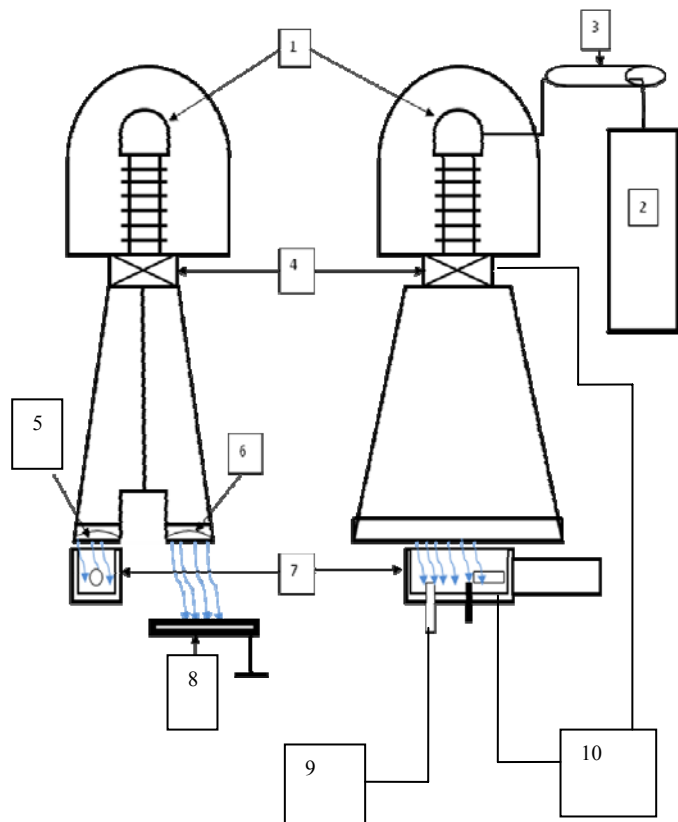**Experimental complex for undertaking of experiments**



*Fig. 1. Functioning scheme of the experimental complex.*

*Two projections of the experimental stand. To the left-a view from the front. To the right a view of the experimental section*

Experimental works were carried out with a help of a complex created specially for undertaking them. Functioning scheme of the experimental scheme is represented in Fig.1. Following devices are included into a composition of the complex. Industrial electron accelerator of direct action EOL-400 M (voltage E=300-350 kV and current I = up to 20 mA ) consists of: the accelerating tube with an injector of electrons (1); a high voltage rectifier; a high voltage cable (3); a scanning system of the accelerated beam (4); vacuum window for outletting of the beam into the atmosphere at undertaking of experimental investigations (5); a vacuum window for outletting of the beam into the atmosphere at accelerator's work (6). Experimental chamber (7). A receiver of the working current of the accelerator (8). Diagnostic devices (9). A system of synchronizing and ensuring experiments (10). A photos of the experimental chamber and is represented in Fig. 2

The industrial accelerator EOL-400 M was partially modernized. Since in our case one does not require large current value of the electron beam lead into the atmosphere then, after the modernizing of the scanning system, the continuous beam from the accelerator was constantly directed to one working window (6), and only for a short time it was moved to the investigation window (5).

The modernized scan allowed on the experimental window to ensure the maximal possible density of the electron beam in the area of experiments undertaking in necessary time moment.
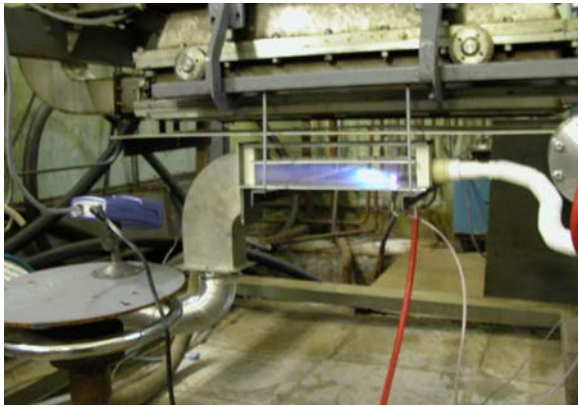
Fig. 2. *A photo of the experimental chamber*

In Fig. 3-5 are represented forms of flame without external impact of electric field and electron beam (Fig. 3); with electric field impact (Fig. 4) and combined electron-beam and external electric field impact (Fig. 5).

In the result of undertaken works it was revealed that the external electric field increases a combustion temperature of the propane-air mixture by 8-10 % in comparison with a combustion temperature in the experiments without the field (combustion was realized by the igniter). In the experiments the electric current inside the chamber rose by 18-20 % at increase by 1.5 times of the electric field strength in the experimental chamber.

Measurements of a flame temperature have shown, that the electronic beam only influence on the burning process practically does not lead to increase in temperature of the flame.

At complex impact of the external electric field and the electron beam.the tempetature in the flame rose by a factor of two (from 750° C to 1350° C) at the electric field 1.25 kV/cm and electron beam current density about 0.25 mA/cm$^2$.



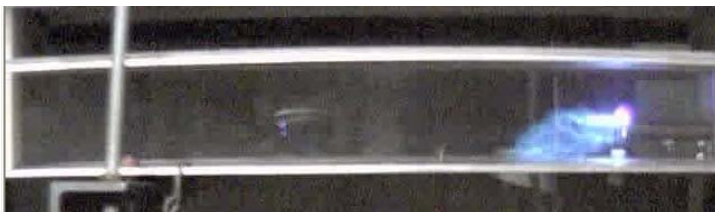*Fig. 3 Initial moment of the gas-air mixture ignition without an external impact*



*Fig. 4. Initial moment of the gas-air mixture ignition under the impact of the electron beam*



*Fig. 5. Initial moment of the gas-air mixture ignition under the combined impact of the external electric field and the electron beam*

### Results

Experiments with specially modernized electron beam device based on the electron accelerator EOL-400M have been made. Plasma of non-selfmaintained discharge with complex influence of the external electric field and the electron beam has been realized in conditions without ignition of propane-air flow and with it. Experiments on inflammation of the flammable mixture in the chamber and injection of the beam into air and flammable mixture have been fulfilled. Experiments have shown sharp increase in the temperature at application of the non-selfmaintained discharge. Gas temperature and ion currents to electrodes in the mixture have been measured at action of the non-selfmaintained discharge under combustion conditions and without them.

## Acknowledgment

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# Non-Self-Maintained Discharge and Electron Beam Plasma in Propane-Air Mixture I (Theoretical Results)

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The present work is devoted to a continuation of investigations [1, 2] on the application of a non-self-maintained discharge with electron accelerator-irradiation of a propane-air mixture. In [1] we designed, constructed, and set up an experimental chamber, controlling devices and diagnostic instrumentation. Adding a simplified chemical model for the ignition of a propane-air mixture to our model of air plasmas with the addition of detailed water-vapor kinetics, we created a joint model and computer code for the determination of plasma parameters under combined action of an electron beam and an external electric field. In [2] we extended our modeling approach to a propane-air mixture, including accounting for the water vapor concentration that can be increased in the process of combustion. In this paper we consider the properties of combustion under the conditions of a non-stoichiometric propane-air mixture.

## Model

For a the first problem, we have undertaken a calculation, using the Boltzmann equation, with the application of electron molecule collision cross sections for propane, oxygen and air taken from the literature [3]. As a second problem, we have connected the kinetic scheme of a propane-air mixture with the kinetic scheme for air excited by an electron beam in an external electric field. As in the literature [1,2], as a basis, we have chosen a simplified system of chemical reactions [4] with added reverse reactions (at first stage we considered a stoichiometric mixture) including 74 reactions: (Hydrogen-Oxygen chains , Hydroperoxyl and Hydrogen Peroxide reactions, Propane reactions, I-Propyl, N-Propyl and Propene reactions, Ethylene, Ethyl, Vinyl, Vinoxy and Ketene reactions, Methyl, Methoxy, Formaldehyde, Formyl reactions), a standard energy equation with enthalpies computed on the basis of [5]. Air chemistry and rate constants for air plasmas were taken from our detailed code for air plasmas [6, 7]. This model includes 20 components (neutrals, positive and negative ions) and 120 plasma chemical reactions, includingreactions involving $CO_2$. For a mixture excited by an electron beam, the electron distribution function of plasma electrons was considered to be close to a Maxwellian [9], and the energy costs of inelastic processes connected with excitation by the electron beam were taken from [8].

For modeling, it was necessary [10-13] to use reactions involving the f following reagents: positive ions $O^+$, $O_2^+$, $O_4^+$, $H^+$, $H_2^+$, $OH^+$, $HO_2^+$, $H_2O^+$, $O_2^+(H_2O)$, $H_3O^+$, $H_3O^+(H_2O)$, $H_3O^+(OH)$, $H_3O^+(H_2O)_2$ negative ions $O^-$, $O_2^-$, $O_3^-$, $H^-$, $OH^-$, atoms O and H, molecules $H_2$, $O_2$, $H_2O$, $O_3$, free radicals OH, $HO_2$, $H_2O_2$, excited states $O(^1D_1)$, $O(^1S_0)$, $O_2(^1\Delta_g)$ electrons and molecular species - including nitrogen from the system of reactions developed by us for dry air. The estimated number of all reactions (including those of dry air) is 280-300. Besides reactions with these components, it is necessary to consider ion recombination reactions of each positive ion with each negative ion, whereby rate constants for these reactions are to be estimated, because these reactions are not yet completely investigated for all ion combinations. These rate constants were determined according to the Flannery method [14-15]. These reaction rates were normalized by the typical mobility value of these ions, namely 2.5 $cm^2/(V \cdot s)$ and taken from [16]. The model includes reactions of

three-body attachment to the molecule $O_2$ in the presence of $H_2O$ as the third body, and charge-exchange reactions [17-18]. The energy costs of water and propane molecule production were taken from [19-21]. The excitation velocity W in air is connected with the parameters of the relativistic electron beam (with electrons energy $E_b$ = 200-500 keV) by the relation $W = 10^{22} J_b \cdot P$, where the current density $J$ is expressed in $A/cm^2$, and pressure in atmospheres. In the case of the non-relativistic electron beam (at $E_b$ <150 keV) $W = 4 \cdot 10^{22} J_b \cdot P$. For the conditions of our experiments, estimates give $W = 10^{17}-10^{18}$ eV/($cm^3 \cdot s$) (at an corresponding electron beam current density $10^{-5}$ -$10^{-3}$ $A/cm^2$).

### Results

The ignition time of an initially-cold, stoichiometric propane-air mixture calculated by the model of a "dry" propane-air mixture gives $9 \cdot 10^5$-$1.0 \cdot 10^5$ ms under electron beam impact with excitation velocity of $W = 10^{18}-10^{19}$ eV/($cm^3 \cdot s$). The gas temperature in this case reaches a value of $T \approx 2600$ K.

In the case of a non-self-maintained discharge at an external electric field strength of $E$ =3 kV/cm and excitation velocity of electron beam $W=10^{18}-10^{19}$ eV/($cm^3 \cdot s$), the model for a "dry" propane-air mixture gives an ignition time of $7 \cdot 10^4$ -$1.0 \cdot 10^4$ ms. The gas temperature in this case reaches a value of $T \approx 2800$ K.

Calculations of the ignition time of an initially cold stoichiometric propane-air mixture calculated by the model for a "humid" propane-air mixture gives $2.0 \cdot 10^6$ -$3.0 \cdot 10^5$ ms with the influence of an electron-beam, having an excitation velocity of $W = 10^{18}$ - $10^{19}$ eV/($cm^3 \cdot s$). The gas temperature in this case reaches a value of $T \approx 2600$ K.

In the case of a non-self-maintained discharge with an external electric field strength of $E = 3$ kV/cm and electron beam excitation velocity of $W = 10^{18}$ - $10^{19}$ eV/($cm^3 \cdot s$), the model of a "humid" propane-air mixture gives an ignition time of $7 \cdot 10^5$ - $1.0 \cdot 10^5$ µs, i.e. it decreases by a factor of three. The gas temperature in this case reaches a value of $T \approx 2700$ K. Computations show that, at the given rate constants in the case of 2 and 4 % percent of propane, the delay time for ignition takes place during the times of $7.50 \cdot 10^5$ µs and $7.5 \cdot 10^5$ µs, respectively.

Our calculations show that in real conditions the ignition time of the mixture at the given excitation with only the electron beam will lie in the range $10^5$ -$10^6$ µs, and for the non-self-maintained discharge will lie in the range $10^4$-$10^5$ µs. The scatter of the calculation data is connected with the decrease of the temperature of the humid propane-air plasma because a high temperature defines the speed of chemical reactions.

### Acknowledgement

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# Plasma Combustion Nature of a Fireball with a Metallic Core

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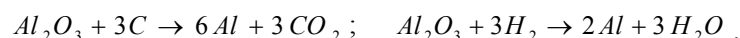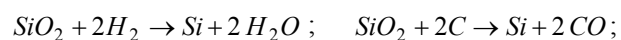
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Questions related to the phenomena of natural fire balls – so-called ball lightning (BL) – involve long-lived luminescent objects in the atmosphere and are lacking scientific explanation for more than a century. Modeling of the BL phenomena have been carried out in different laboratories. Owing to the absence of an unequivocal model and the complexity of modeling related to the given object of interest to BL, progress for explanation of the phenomenon has sharply fallen. However, in experiments [1] in discharge tubes and erosive discharges, long-lived objects of small size (up to 1 cm in diameter) and lifetime in the range of a few seconds, consisting of both organic inorganic nature have been obtained. In [2] in the erosive discharge with insertion of organic materials, luminescent objects with visible size up to 2 cm and a life time up to 2 seconds have been observed. Article [3] has appeared to be an important work for the understanding of the possible BL nature. It was proposed in [3] that BL appears as a result of a linear lightning stroke in the earth. Thus, there is a reduction of silica to metal silicon in fulgurite-containing areas, which results in the formation of metallic chains, and those chains appear, in air, to create a ball of a type predicted in [4]. However, experiments [5] have not confirmed this hypothesis, although in the experiments nano silicon chains were found. This work has been continued in [6-9]. In those investigations, for different electric and discharge conditions, long-lived objects based on silicon have been observed. The largest (up to 4 cm) and long-lived (up to 8 s) objects have been realized using doped silicon. It is well-known that metal particles, such as Si, Al, Fe, Sn, are easily oxidized by oxygen in air. Therefore the results of experiments [1, 2, 6-9], where the burning of metals in a plasma was realized, for which the simulated BL energy-release properties of BL were realized are not surprising. The observed objects, in most cases, have a spherical form, but the destruction of objects with an explosive clap, which is typical of BL [1] was rarely observed.

**Model**

Let us consider a model which enables us to understand the features of BL. Following [3], we consider that a hit of usual linear lightning onto earth (or some melting object) creates a so-called a cavern in the earth or a fulgurite region. For average lightning parameters, this strike transfers about $10^{10}$ J to the earth, creating a high pressure of up to several hundreds of atmospheres in the cavity. After that, ejection of a modified material takes place.

Inside the cavern, the creation of a region takes place where, for high temperature reactions of metal reduction from silica, $SiO_2$, Alumina $Al_2O_3$ or their mixtures accompanying the destruction of organic components of soil occur:

$$SiO_2 + 2H_2 \rightarrow Si + 2H_2O \; ; \quad SiO_2 + 2C \rightarrow Si + 2CO \, ;$$

$$Al_2O_3 + 3C \rightarrow 6Al + 3CO_2 \; ; \quad Al_2O_3 + 3H_2 \rightarrow 2Al + 3H_2O \, .$$

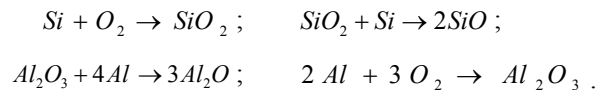Here, C means atoms of carbon, and $H_2$ means molecules of hydrogen.

In this region, gas pressure and temperature rises result in appearance of metallic particles and gases. This process is analogous to the creation process of powders as observed in the electric explosion of wires. The hot region becomes electrically charged due to the charge transferred from the linear lightning - note that a linear lightning stroke carries a non-compensated electric charge.

Because the soil conductivity around the hot region is very small, electric processes develop inside the hot region. The electric charge has time to move to the outer boundary of the hot region over the metallic particles during a time less than that for the ejection of the hot metal from the cavern during gasdynamic times. There, the oxidizing processes accelerate under the influence of electrical charges and their fields, and oxide films of $SiO_2$ or $Al_2O_3$ are created. These oxide films are charged. The oxide film strongly retards metal oxidation due to a decrease of oxygen penetration inside the region. These films have rather high tensile strength. The tensile strength for $Al_2O_3$ is $\sigma = 21$ MPa and that of $SiO_2$ is $\sigma = 40\text{-}60$ MPa in quartz glassy state. This cover can withstand a pressure charge on the surface or gases appearing inside the object.

These processes result in the appearance of an oxide cover, arising from above, with metallic powder particles inside the volume. A slow combustion takes place inside the reservoir (using small amount of penetrating oxygen through the cover or captured inside). It ensures an illumination of the fireball.

After that the ejection of [the particles/matter in] charged reservoir, a ball plasma-discharge from the earth takes place under the influence of pressure. A charged heavy object - the ball lightning - appears in air. It does not fall down due to Coulomb repulsion from the charged surface of the Earth.

Due to the large charge of the object, a plasma layer originates on its surface. The surface layer heats up the ball surface. Oxygen diffusion into the reservoir sharply increases at the surface layer and heating, oxidation and release of gases takes place in chemical reactions such as:

$$Si + O_2 \rightarrow SiO_2 ; \qquad SiO_2 + Si \rightarrow 2SiO ;$$
$$Al_2O_3 + 4Al \rightarrow 3Al_2O ; \qquad 2\,Al + 3\,O_2 \rightarrow Al_2O_3 .$$

Pressure rises inside the object and cracks appear in its outer surface. Oxygen freely penetrates inside. Combustion takes place. And the object explodes and tears apart.

**Experiments**

Obtaining fire spheres by means of an electric discharge in a closed volume at parameters of the current pulse close to those of linear lightning pulses was our purpose. As a discharger, we used a gap between end faces of the rod electrodes filled with a tested substance. Electrodes were located axially and placed in a piece of a polymeric tube (see Fig. 1).



*Fig. 1. The polymeric tube with a hole for conducting experiments*



*Fig. 2. An image of the arising fireball*

The tube was located in a metal enclosure, which had a short lateral hole of small diameter, allowing for a fast release of the discharge products into the atmosphere or the chamber for the further processing. The electrodes were fixed in positions. The capacitor (3.55 mF) stored an

energy of 44 kJ at the greatest-employed voltage of 5 kV and was discharged through a choke of inductance 20 μH. For obtaining discharge images, a digital video camera with an f-50 stop was used. Dynamics of the discharge current and radiation of the ejected object were detected by means of a two-channel oscilloscope. In Fig. 2, an image of an arising fireball is shown. In the case of an aluminum discharge, products are ejected into the atmosphere in a stream, which in a process of gasdynamic stagnation, forms a vortex, and a fireball originates. A maximum luminescence is reached after ~ 5 ms after the emission of discharge products. The short-pulse creation of a large current (a lightning pulse, short circuit in the electric system) from the vapor-gas phase, which results in the emission of discharge products into the atmosphere, is separated by a period of condensation and thermal relaxation of vapor-gas phase release of discharge products in the atmosphere. This should be separated from the periods of condensation and thermal relaxation. As shown in [1], objects of small size can be realized by a delay of emission or with the help of throttling (evaporating throttling) through the thin, long-channel, porous, loose substance. Our video recording has detected an emission of several small-sized objects after the release of the main object possessing at low density. One of these objects s exploded upon hitting the wall of a turbonit–plastic. This part of the results of our experiments is available on the Internet in the form of photo frames. These frames are made from a istance of 3.1 m with a time interval of 5-ms from a distance of 3.1 m [10]. Experiments show that it was possible to realize objects similar to natural ball lightning, but still the question of their charging still stands.

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# Deeply-Subcritical Microwave Discharges System in a Supersonic Flow

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A gaseous electric discharge ignited in a quasi-optical electromagnetic (EM) beam of MWs in a range of wavelengths $\lambda$ is investigated. The apparatus for such a discharge contains the MW generator and the elements forming the quasi-optical electromagnetic beam in space, remote from these elements, and from surrounding subjects. The gas pressure p is in a range from several tens of Torr to atmospheric pressure. Experiments have shown that the properties of such discharges are qualitatively identical in the $\lambda$ range from several centimeters to tens of centimeters. The discharge can be ignited both in a pulsed mode, at MW impulse duration $\tau_{pul}$ of some tens of microseconds and power of MW beam $P_{MW}$ to about a megawatt, and in a continuous mode at $P_{MW}$ of kilowatt magnitude [1-4].

Experiments have shown, that in various ranges of initial level of the field $E_0$ electric component and gas pressure p, such a discharge is realized in essentially different forms.

At low p, this discharge is diffuse and interacts rather poorly with the exciting MW field. At rather high p, the discharge is realized in the form of high-temperature plasma channels and effectively interacts with MW field exciting it. In particular, such discharges have wider range for their possible practical applications.

For the realization of a free-localized, self-maintained discharge in gases, the field $E_0$ should be greater than some critical discharge field $E_{cr}$. So in air at rather high pressure p, the amplitude of the field $E_{cr}$ can be estimated as $E_{cr} = 42$ p V/cm, where p is in Torr. So at p = 100 Torr, the field $E_{cr} = 4.2$ kV/cm. This field, even in a focused EM beam at $\lambda \approx 10$ cm, can be created only in the pulse mode at $P_{MW}$ in the megawatt range. At $E_0 < E_{cr}$, gas breakdown should be initiated. In our research, a linear EM vibrator is used. With its help, the MW discharge can be ignited, both in a subcritical field at $E_0 < E_{cr}$, and in a deeply subcritical field at $E_0 \ll E_{cr}$.

Experiments have shown that the effective area of power interaction $S_{eff}$ for a deeply subcritical MW discharge initiated by the EM vibrator at high gas pressure (with exciting it EM field) essentially exceeds the area of the discharge region. As a result, plasma streamer channels appear in the motionless air and are attached to the edges of the EM-initiator and have high gas temperature. Such a deeply subcritical EM discharge can be ignited in air at pressure values of hundreds of Torr and a field level of $E_0 \leq 100$ V/cm. This field can be provided in a quasi-optical EM-beam with $P_{MW}$ scale of 1 kW. Such a discharge has been considered in the present research.

In the research carried out, this discharge was ignited not only in the motionless air, but also in a high-speed stream of air and a gaseous mixture of propane $C_3H_8$ and air. Photos illustrating the results are presented in Fig. 1.

In the photos, the gas stream has a direction from the left to the right. The discharge burns in the stern area of the cylindrical EM vibrator, placed in a stream. Its length was $\approx 5$ cm. From the photo images, one can obtain the length scale of the discharge. The linearly-polarized radiation in the form of a quasi-optical EM-beam with $= 12.3$ cm arrives at the vibrator from above. Its vector $E_0$ - is horizontal, and the amplitude of the field $E_0 \approx 100$ V/cm. In Fig. 1 to the left of the photos, the speed of a stream $v_{fl}$ is indicated. To the right of the photos, the waveforms from the thermocouple instrument, placed in a discharge trace, for measuring the stream temperature are represented.
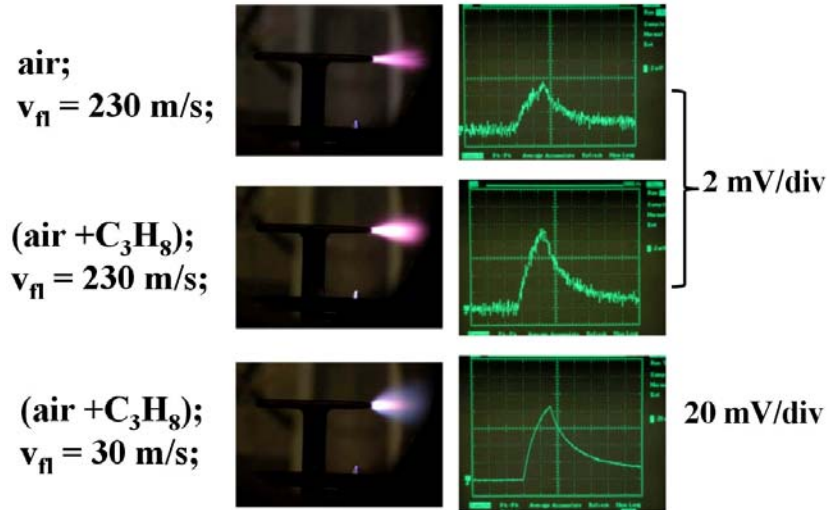
*Fig. 1*

Experiments have shown that the discharge initiated by the vibrator was not blown off by the air stream up to a speed of $v_{fl} = 500$ km/s. At all times it remains attached to the stern area of the vibrator. For the case of a burning propane-air mixture, the area of burning is stabilized in space. Igniting this mixture by such a discharge allows the operational range of ignition to be extended. A lean mixture, of composition several times smaller than its stoichiometric value also ignites. Experiments have shown that a plasma for such a discharge provides ignition of the mixture at a gas temperature much smaller than the temperature of ignition achieved by traditional ways. Besides, the propane combustion time is also reduced. At the same time, as is shown in the lower photo of Fig. 1, the typical size of the plasma area $d_{dis}$ has a scale of 1.0-1.5 cm.

The last also set the purpose of researches. In the case for which the cross-section size of the gaseous mixture stream $D \gg d_{dis}$, then most of the mixture will not pass through the plasma area. A possible variantion for solving this problem consists in ignition using a deeply subcritical initiated MW discharge system so, that $\Sigma \, d_{dis}$ would be approximately equal to D. In this case, the transverse distance between EM vibrators should have a scale of 1.0-1.5 cm

To check the realization of such a possibility, we employed a flat submerged air jet. The stream had a transversal section area of $S_{fl} = (10 \times 70)$ mm$^2$, and the Mach number at the exit of the Laval nozzle was M = 2 at an air speed in the jet of $v_{fl} = 500$ m/s. Thus, the static temperature of air in the jet was $T_{stat} = 150$ K and the static pressure was $p_{stat} = 100$ Torr. The stream leaked into the hermetic chamber, in which the air pressure $p_c$ also was maintained at a value of 100 Torr.

In the stream, as is shown in Fig. 2, across its cross section were located linear EM vibrators. On the vibrators, the linearly-polarized EM radiation arrived from above. In this MW beam, the metal sheet-screen was located transverse to the Poynting vector. Thus falling on it and reflected waves formed a field loop at a distance from a screen plane of h = 30 mm = $\lambda/4$.

In these experiments, the distance between the parallel EM vibrators $\Delta$ was varied. Our results have shown that discharges are simultaneously initiated by these vibrators only at $\Delta \geq 30$ mm. At smaller $\Delta$, only one discharge usually was ignited.

In this report, we have shown that as the electromagnetic vibrator approaches the screen, its ability to initiate an electric air breakdown in the subcritical field of quasi-optical EM beam increases. The field induced by the vibrator starts to be localized between the surface of the vibrator and the screen for a value of the distance between an axis of the electromagnetic vibrator and the screen smaller than some threshold value.

The linear system of weakly electrodynamically-connected deeply subcritical initiated MW discharges in the high-speed air stream is experimentally realized. Their plasma areas completely cover the cross-section section of the stream.



N=3;
h=30 mm=($\lambda$/4);
$\Delta$=30 mm;
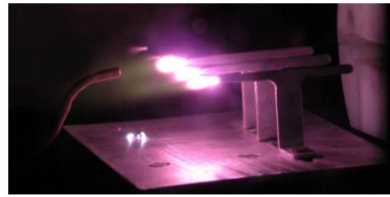
Air;  $S_{fl}$=(10x70) mm²;  M=2;  $v_{fl}$=500 m/s;
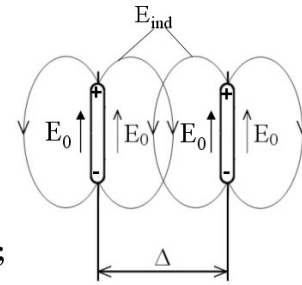$T_{stat}$=150 K;  $p_{stat}$=$p_c$=100 Torr;

*Fig. 2*

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# Cylindrical Flame Kernel and Flame Propagation Induced in Air-Propane Mixtures by a Single Corona Discharge

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One growing topic of interest in non-thermal plasma field is the use of pulsed corona discharges for ignition [S. M. Starikovskaia 2006 J. Phys. D: Appl. Phys.]. The purpose of this work is a better understanding of the physical mechanisms implied in the ignition of lean mixtures of air and hydrocarbons at high pressure using nanosecond range discharges. Such kind of discharges could improve the energy release in the mixtures, promoting the creation of radicals and excited species instead of direct heat, and the ignition efficiency. A positive high voltage (40-50 kV) is applied between a pin electrode and a grounded plane over a short nanosecond range pulse (10-15 ns). The energy of the discharge can be modified by changing the amplitude and the duration of the voltage pulse. The diffuse regime in which the discharge develops at atmospheric pressure in pure air disappears in mixtures with propane and the discharge becomes filamentary [P.Tardiveau, N.Moreau 2009 J. Phys. D: Appl. Phys.]. In this filamentary regime, the ignition of propane-air mixtures and the propagation of a self-sustained flame, as shown on figure 1, can be realized with a single nanosecond range pulse. Compared to the conventional car spark plug ignition which occurs in a very small volume, the single nanosecond pulse discharge can ignite a mixture all along a plasma channel, i.e. more than one centimetre. It gives, for a comparable electrical energy release of about 70 mJ, a cylinder-shaped flame kernel, as shown on Fig 2. Regarding the combustion at 2 bar, the ignition occurs very near the anode electrode with an energy limit of 10 mJ. Ignitions of propane-air mixtures at atmospheric pressure are possible for an equivalence ratio limit of 0.75 with a few tens of millijoules.
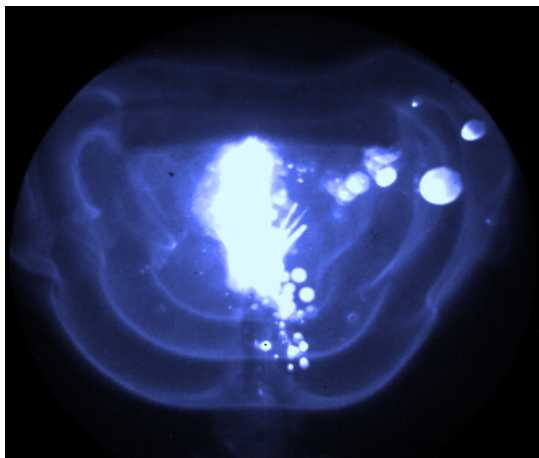


*Fig. 1. Fast CCD imaging of the flame propagation (1bar and stoechiometric conditions) in a burst mode (3 images integrated over100 µs and delayed by 50 µs)*
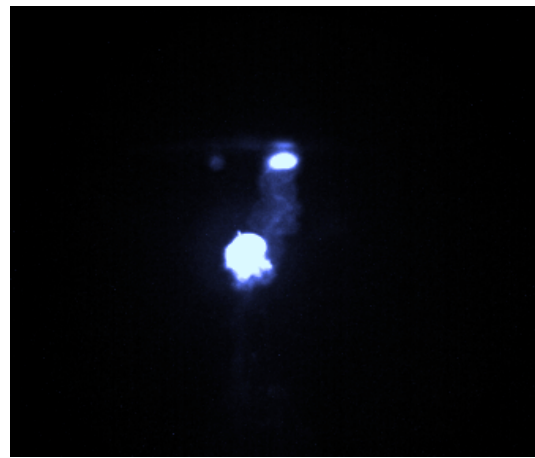


*Fig. 2. Ignition along a plasma channel and cylindrical flame kernel integrated over 100 µs.*

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**Pierre Tardiveau** received a postgraduate degree in Electronics from Supelec (Orsay, France) in 1994, a master science degree in teaching of applied physics in 1995, a PhD degree in physics from the University Paris-Sud (Orsay, France) in 2002 on the study of car engine ignition by non-equilibrium plasmas and the effects of pressure and two-phase mixtures. He recently passed in 2009 his habilitation for research in Physics at the University of Orsay, on the characterisation of pulsed discharges in dense and inhomogeneous media and its application to air treatment and combustion. He is now associate professor in plasmas, optics and electronics at the University Paris-Sud of Orsay and he works in the DIREBIO group of the Laboratoire de Physique des Gaz et des Plasmas. His current research interests are focused on the physics of pulsed nanosecond range discharges at atmospheric and higher pressures for combustion release applications, and on the physics of pulsed discharges in porous materials and its application to the removal of gaseous pollutants. Since 2009, he is advisor of two PhD students (combustion and air treatment applications).



**Stéphane Pasquiers** was born in Paris in November 1962. He graduated from the South Paris University (Paris 11) in 1985 and achieved is PhD degree in 1987 at the Laboratoire de Physique des Gaz et des Plasmas (LPGP, CNRS U), Paris 11 (Orsay). He joined the CNRS in 1988 to work as a research scientist in the team of Dr. V. Puech (LPGP), working on high power XeCl lasers energised by pulsed discharges, and thereafter on HF/DF lasers (photo-triggered discharge equilibrium and stability, plasma kinetics and chemistry). Since 1999, he is involved in researches about pollution control by non-thermal plasmas and coupling with catalysis (de-$NO_x$ and de-VOC processes), reforming and ignition of combustion. At the present time his main scientific interests, for various applications, are : pulsed discharge physics at high pressure (0.1 – 10 bars), non-thermal plasma kinetics in atmospheric gases, decomposition processes and kinetics of hydrocarbons and VOCs. He is now Research Director in CNRS and manager of the DIREBIO research team at LPGP.

# Numerical Investigation of Plasma Ignition Process in a Utility Boiler

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The value of plasma ignition and combustion stabilizing (PICS) systems to reduce oil consumption during low load, start-up, and commissioning periods has been demonstrated by its installation in over 500 coal-fired utility boilers worldwide. Despite the ability to maintain a stable flame for most coals, however, PICS systems do encounter difficulty to ignite some lignite and anthracite. Computational fluid dynamics (CFD) can be a useful tool for the development and customization of PICS systems to address this problem, provided a reliable approach to model coal/plasma reactions can be established. Previously, a modeling approach to simulate coal reactions with the presence of plasma was proposed and found to provide reasonable results when compared to the limited available measurements from ignition tests. In the study described here, the CFD modeling approach was used to explore a hypothetical PICS installation in a tangentially-fired utility boiler. Three pseudo-steady cases of the boiler were simulated that represent three successive conditions during the start-up period. The operating conditions were determined according to the boiler start-up curves. The four coal burners at the bottom level of the boiler were replaced by four coal/plasma burners of the PICS system, which also function as regular coal burners during normal operation.

The CFD method was to first simulate the plasma burner of the PICS system and then to use these results as input to the boiler simulation. The previously established modeling approach was used for the coal/plasma reactions in the burners and a standard coal combustion model was used to calculate the reactions of the partially-gasified coal inside the boiler. Even with the plasma system applied, the model predicted that the coal particles lose only 5-11% of their combustible material within the plasma burner, leaving the remainder of the combustion process to occur inside the boiler. The correct trends in temperature and burnout were obtained for the burner and the boiler, suggesting that, with further refinement, this approach can be used to optimize the design and operation of the PICS system, and can also be used to optimize the operation of the boiler during ignition process. Although the flame remained stable, the model results indicated that the behaviour of both the PICS system and the boiler vary significantly during the start-up period, especially regarding the coal burnout and the temperature distribution. Significant bottom ash and significant carbon in the bottom ash were predicted for the boiler, indicating that there is not enough fluid dynamic suspension for the coal particles during the start-up period. This underscores the importance of properly customizing the entire plasma/boiler system for low firing rates, not just the plasma system. Modification of operating conditions is suggested to address this problem.



*Haining Gao has been working on computational fluid dynamics modelling as a Research Engineer in CanmetENERGY since 2001. Before 2001, he worked with Thermal Power Research Institute (TPRI) in Xi' an, China, where he gained 10+ years of experience on boiler retrofitting, combustion testing, emission control and equipment developments in the utility industry. At CanmetENERGY, he has conducted many modelling investigations on utility boilers. This has led to improvements of efficiency and availability for utility boilers in China and in Canada. Haining has also been involved in coal gasification modelling and is also involved in creating a new easy-to-use modelling tool targeting utility boilers. Haining's current interests include equipment developments, and using modelling tools to develop clean coal technologies including the development of low-NOx coal burners, low-NOx firing systems, and plasma coal gasification reactors.*

# Plasmic Initiation of Detonative Combustion of Preheated Supersonic Hydrogenous Flows

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Prior numerical investigations show that the hydrogen detonative combustion in an axisymmetric convergent-divergent nozzle can lead to an arising of a propulsion force, which is acceptable for the supersonic flights with a high Mach number [1-2]. Hydrogenous mixture is supposed to be incoming into the nozzle with a supersonic velocity. There is a problem to initiate the hydrogen detonation in the supersonic hydrogenous flow compressed and preheated in the convergent nozzle part without placing any additional equipment. Under these requirements a plasma spot is seemed to be the valid ignition source.

In this paper the plasma spot is obtained as a result of laser radiation focusing. The laser-based ignition of a hydrogenous mixture in supersonic flows is modeled by experiments in a shock tube. Conditions behind an incident shock wave model the temperature regime in the high parameter zone of the flow in a convergent-divergent Laval nozzle. The pressure and flow velocity behind the shock wave are lower than those in the nozzle case. A hydrogenous gas ignition behind the incident shock wave is produced by the impulse Nd: YAG-laser with the wave length 1.06 мкм and pulse duration 30 ns. The radiation energy is varied from 100 to 300 mJ. It is experimentally shown the reality of the laser-based initiation of a detonative combustion of supersonic hydrogen-oxygen and hydrogen-air flows behind incident shock waves.

Numerical calculations consider a stimulated ignition of hydrogenous mixtures in a rest state, in a homogeneous supersonic flow and also behind an incident shock wave in the shock tube used in above mentioned experiments. The located supply of the laser energy is modeled by the instantaneous local increasing of the thermal gas energy. Numerical simulations are fulfilled on the base of unsteady Euler's 2D-equations for a multi-component inviscid and non-heat-conducting gas. The used prior approbated kinetic model of chemical transformations includes 10 components, participating in 116 non-equilibrium chemical reactions. The enthalpy and the entropy of each component are calculated using applicable approximations of Gibbs function. Calculations are made using the first-order Godunov's scheme for a fixed mesh.

It is experimentally shown that the successful detonation initiation is generally connected with the gas temperature. The detonation combustion of hydrogenous mixtures in the supersonic flow is realized with the initiation energy, which is more than in the case of the rest gas.

Results of experimental and numerical modeling allow hope for successful laser-based plasmic initiation of the detonative combustion of hydrogen-air mixtures under conditions of supersonic flow compressed in the convergent section of Laval nozzle.

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# Convergent (Cumulative) Shock Wave Generation and Its Application as Igniter of Flammable Gas Mixtures

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In an aviation engines with high-speed fuel/air mixtures the flame initiating system has a critical influence on misfire or cycle-to-cycle variations. For improve of igniters action various ignition systems have been proposed and tested [1-4]. These include high-energy spark plugs, plasma jet igniters, rail plug igniters, laser-induced ignition, torch jet igniters etc. Over last decade, considerable progress has been made in studies of non-equilibrium plasma assisted combustion. A review of recent experimental work in this field is given in [5-7].

The aim of the present paper is to study the processes of ignition of gas mixtures under the action of still untapped and non understood axisymmetric (ring) electric discharges. A particular feature of the action of ring discharges on a gas medium is that the possibility exists of initiating combustion of the gas mixture not only in the immediate vicinity of a ring discharge, but also near the axis of the ring through the presence of a converging toroidal wave generated by the discharger.

The cumulative effect of convergence of a non-one-dimensional shock wave was first demonstrated by the example of a ring-shaped shock wave in air, in experiments performed at the General Physics Institute [8, 9]. The experiments have shown that the geometry of the wave (i.e. whether it is one-dimensional or non-one-dimensional) is not essential to the end results. Shock waves investigated in those experiments were ring-shaped (toroidal), apparently non-one-dimensional. It was found that the amplitude of a shock wave generated by a ring electric-discharge increases gradually as it approaches the center of the ring. Generally, the effect of cumulative amplification of a noncylindrical (nonspherical) shock wave converging toward the axis is nontrivial, because in contrast to a one-dimensional wave, there may be hydrodynamic energy outflow along the axis.

Theoretical analysis performed in [10] has shown that the amplitude of a ring shock wave (as with spherical and cylindrical waves) increases without bound if dissipative processes are ignored. An unbounded increase in the energy of a convergent shock wave, which is indicative of a cumulative process, still remains a key problem in both theoretical and experimental research. In other words, it is necessary to identify mechanisms that limit the values of the gas temperature $T_g$ on the focus in real experiments.

The further step toward the solution of the above problem has been taken in recent experiments [11-13] for studying a toroidal shock wave generated in atmospheric-pressure air by ring electric discharge. It was shown that the shock wave converges at the axis of the ring. A mathematical model describing the focusing of a non-one-dimensional shock wave was constructed, and the results of calculations were compared with the experimental results. The energy released in the ring discharge was estimated from calculations given a good fit to the experimentally observed dynamics of both a toroidal shock wave convergent toward the axis and axial shock waves (Mach waves) accompanying the cumulative process of focusing. With the assumption that the model

adequately describes actual gas flows at a given level of released energy, the gas temperature was estimated near the cumulation region located on the axis at some distance from the center of the ring. In particular, for a ring discharger of radius ~5 cm with released energy of about 200 J, the gas temperature on the axis of the ring at a distance of about 1 cm from its center was estimated as 6000 K. The energy is transferred from a discharge toward the axis through gas-dynamic perturbations caused by the discharge itself.

The results obtained in [11-13] allow us to make an assumption that, with a ring discharger employed as an initiator, the ignition may be induced not only in the region of energy release (an annular plasma layer), but also outside of this region – at the center of the ring. In the present paper, we report on results of the first experiments with the use of a ring discharge in a combustible (methane—oxygen) mixture in closed volume and describe characteristic features of the initiation of combustion in a gas medium by this discharger.

Both the above experiments and the calculations, being important for fundamental physics, were stimulated by the applied problem – the initiation of combustion of fuel-air streams in the axial region of a ramjet aviation engine. Schematically method of supersonic gas ignition is shown on the Fig. 1. Considering the obtained in [11-13] results from this scheme viewpoint, we note that the heating of a gas to the mixture ignition temperature occurs in relatively small volumes, while the temperature remains high for a short (microseconds) time. For this reason, we are not in position to assert that the ignition of a fuel-air stream is realizable. However, this possibility must not be ruled out, especially as a success was achieved in a series of experiments on the initiation of combustion of gas mixtures by laser sparks, microwave discharges and gliding surface discharges [14-17]. It has been found that high-temperature microscopic plasma objects generated by discharges have an abnormally long lifetime, eventually causing combustion of a gas mixture throughout the gas volume.
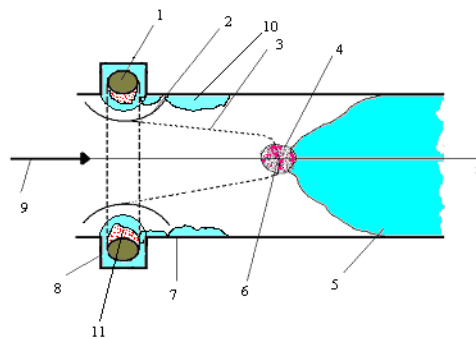


*Fig. 1. Scheme of supersonic gas ignition by cumulating shock wave*

*1-annular electric discharger; 2- toroidal shock wave; 3- trajectory of toroidal shock wave front; 4- region of combustion ignition; 5- burning gas; 6- point of toroidal shock wave focusing; 7- combustion chamber; 8- annular slot; 9- inflammable gas mixture flow; 10 – periphery combustion wave initiated by annular gliding surface discharge; 11 – gliding surface discharge*

Analysis of experimental results obtained in the course of this work allows us to conclude that the geometry of the electric-discharge initiator, namely its ring geometry, plays a decisive role in the process of ignition of a combustible gas mixture as well as in the dynamics of the flame propagation inside the combustion chamber.

As we might expect, the ignition of a gas mixture begins near the annular plasma layer. In this case, the flame advances into the surrounding gas at low velocities, which do not exceed the velocity of usual deflagration waves. As a consequence, the flame initiated by the annular plasma layer is confined to this region during the time interval under observation. A peculiarity of the phenomenon under study is that an extremely fast process of flame propagation throughout the

reactor starts in the region situated at a distance from the annular region of energy release – at the axis of the ring, near its center.

The present experiments have demonstrated the effect of ignition of a stoichiometric mixture at a certain distance from the initiator – a multielectrode discharge system generating an annular plasma layer which is a source of gas-dynamic perturbations converging toward the axis.

The gas-dynamic processes of the ring discharge in a methane-oxygen medium are more intricate than those in chemically inactive gases. The distinctive feature of this discharge is generation of the second wave of strong gas-dynamic perturbations, which is also converging toward the axis. The ignition occurs when the second wave is approaching the axis.

The induction times at initiation of combustion by a ring discharge turn out to be much shorter in comparison with linear gliding discharges, microwave discharges at plane targets, and lasers sparks with nearly the same energy released.

Results of calculations in the framework of developed computer model are presented.

**Acknowledgement**

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# Subcritical Microwave Coupling to Laser Ionization for Ignition

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High speed combustion systems are highly constrained by a number issues associated with the short residence time of the combustor. Most existing schemes to accelerate the ignition process are characterized by discharges created by super-critical fields (10 kV/cm for air) that may be applied to varying systems. Plasma assisted combustion and ignition have shown potential benefits through two alternate pathways: controlled thermal energy deposition and an increase in the radical pool available to initiate and sustain reaction. [1, 2] Recent work at Princeton has demonstrated the use of a laser for designation and a subcritical microwave pulse for ignition of methane/air mixtures. [3, 4] In addition, multipoint ignition and volumetric gas heating over a long focal volume were observed. Work by Stockman, et al. at Princeton also demonstrated an effective increase in the laminar flame speed with the application of continuous and pulsed microwaves. [5]

We present work on the use of a seed laser to localize energy deposition in a designated region. The volume filling subcritical microwave field is used to deposit sufficient energy into those locations to initiate combustion. We demonstrate ignition of methane/air mixtures with a small amount of seed laser energy (< 1 mJ) in combination with a microwave pulse of with an energy of 50 mJ. We achieve significant heating of gas in both air and methane/air mixtures evident in the shadowgraph images of Fig. 1. In addition, we are able to couple microwave energy into an expanding spherical flamefront. The shadowgraph images in Fig. 2 depict the increase in kernel growth rate due to successive microwave pulses at 1 µs and 2 µs. Kernel growth without and with additional microwave pulses is shown in the upper and lower set of images, respectively.

These subcritical microwave applications to ignition and combustion systems offer the potential to localize interactions with flame fronts. The ability to designate the region of interaction with a low energy seed ionization laser and to drive gas heating with a subcritical microwave field offers the opportunity for ignition and combustion enhancement. The potential for localized energy addition during the ignition process or in very lean combustor applications hold significant promise for the development of more reliable high speed combustion systems.

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# Flow Pattern Around Targets of High-Porosity Cellular Material in the Supersonic Pyrolytic Reactor

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Natural-gas resources form one fourth of the world energy balance. Energy-efficient use of natural-gas reserves is an important issue since, according to British Petroleum Statistics 2009, the world natural-gas resources in today consumption level are expected to get almost exhausted in nearest sixty years. It is a well-known fact that natural gas consists, for the most part, of methane, whose content in the gas, depending on the particular field from which the natural gas was obtained, amounts to 65-98%. For this reason, methane can be considered as a most significant component for subsequent gas conversion. Among the existing means for natural-gas conversion, plasma reactors take a special place. Cormier and Rusu [1] gave a comparative analysis of presently available methods for syngas production, this product being an intermediate one in obtaining hydrogen from natural gas using steam reforming process. In the analysis of [1], ordinary chemical processes were compared to processes intended for obtaining syngas in plasma reactors. The comparison was performed in terms of such factors as maintenance advantages, energy effectiveness, and cost. Plasma reactors were noted to offer such obvious advantages over their chemical rivals as simple design, small total dimensions, and low cost. Estimations show that, with allowance for design and productive investments, the production cost of hydrogen per one working hour amounts to 750-900 euro in the case of chemical reactors, whereas the same cost for plasma reactors is just 65 euro. It was concluded that plasma processes for hydrogen production show considerable potential in industry. Other workers have arrived at similar conclusions. Simultaneously, as of today, catalytic reactors are still more efficient in comparison with plasma reactors. The development of novel processes for methane conversion using non-equilibrium discharge plasma is under way worldwide (see, e.g., [2]). In [3-7], a new pyrolytic process for natural-gas pyrolysis was introduced. In this process, energy input into supersonic flow was proposed to be organized via inputting part of discharge-plasma energy into the stream kinetic energy. After the flow is decelerated in the normal shock, for instance, at a blunt target, and the temperature is recovered, the thermal pyrolysis mechanism comes in operation. Here, there arises a possibility to have the energy input zone and the reaction zone separated in space and time, this circumstance being of importance for tonnage plants. In the presently known Huels and DuPont processes the energy input is organized in an electric arc, where the natural gas suffers partial decomposition due to overheating.

During deceleration of a supersonic flow at a blunt body, unsteady flow regimes may arise, with the normal shock suffering large-amplitude oscillations. The frequency and intensity of the oscillations depend on the flow Mach number and on the body and nozzle geometry. The oscillatory regime may result in reduced yield of the useful product, and may lead to reactor's abnormal operation with damages inflicted to structural components.

Results of an experimental study of the action of an electric discharge on the shock-wave structure of a supersonic overexpanded jet of methane or air (M=3.5) impacting onto an impermeable target (obstacle) or onto an target prepared from a high-porosity cellular material (HPCM) are reported. The impermeable obstacle was a small-height steel cylinder of varied diameter. The diameter ranged from 0.3D to 2.0D, where D is the nozzle outlet diameter. The cylinder was installed so that to face the impact jet with its base. The HPCM obstacle of diameter 2.3D was prepared from foam nickel, whose pore content per inch was 10 ppi to 30 ppi. A short-duration d.c. electric discharge was initiated in the gap between the nozzle and the obstacle (Fig. 1).
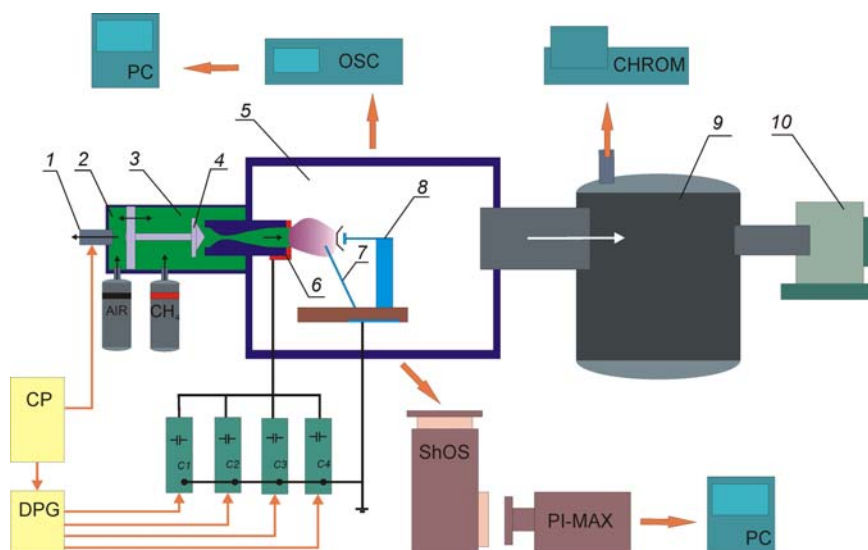
*Fig. 1. Experimental scheme*

*1 –pressure release valve for secondary gas; 2 – secondary-gas chamber; 3 – primary-gas chamber; 4 – fast-operating valve; 5 – working chamber; 6 – orificed anode; 7 – auxiliary electrode - cathode; 8 – pylon carrying the blunt body(electrode); 9 – low-pressure chamber; 10 – backing pump; PC – computer; OSC – oscilloscope; CHROM – chromatograph; CP – control panel; DPG – delayed-pulse generator; AIR – compressed-air flask; $CH_4$ – methane flask; C1, C2, C3, C4 – four capacitor banks; ShOS – Schlieren optical system; PI-MAX – PI-MAX photo camera or high-speed video camera PCO 1200hs*

The experiments were carried out on a plasma-chemical facility of ITAM SB RAS. The typical running time of the facility was 300 ms. A visualization study of the flow was performed using a traditional-arrangement shadow technique. Non-stationary effects were registered with a high-speed video camera.

It is a well-known fact [8-12] that during the interaction of a supersonic jet with a normally installed impermeable obstacle under certain conditions unsteady regimes may arise, in which normal-shock front oscillations emerge. In the present study, we examined the influence of the electric discharge, the geometric parameters of the nozzle-obstacle system, and obstacle-permeability value on the oscillation frequency of the normal compression shocks. It is shown that, on electric-discharge initiation, the oscillation frequency of the bow shock wave and that of the Mach disc changed their values. The flow structure and the oscillation frequency of the fronts depended on the permeability of the target (obstacle).

The data obtained may prove useful in the development of new flow control methods, in the design of high-speed plasmochemical reactors and spray processes for application of functional coatings.

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# Computer Simulation of Gas-Discharge and Chemical Processes in a Non-Steady-State Plasmatron

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The work is aimed to a study of chemical species formation in typical conditions of non-steady state plasmatron operation. To this end we have developed the computer model of the plasma chemical processes in the non-steady-state discharge that is capable to take into account electric circuit parameters. The individual parts of this model are described below in more details.

Initial data block

This block includes:

- Initial diameter of the discharge plasma column at the prebreakdown stage and initial plasma density inside the column.

- Initial gas mixture composition, electrode configuration, electric circuit parameters.

- Rate constants for gas-phase reactions.

Electron energy distribution function

This part of the code provides solution of Boltzman equation for electron energy distribution function every time when gas discharge voltage changes by 5% of its preceding value. This procedure determines the main plasma parameters during discharge evolution process.

The particle kinetics and plasma parameters

This part includes the particle kinetics in plasmas, electron and ion densities, rate constants for electron-impact processes, electron temperature, drift velocity and diffusion coefficient. The calculations are based on electron energy distribution function.

Electric parameters

This routine calculates the voltage at the gap and the current in accordance with the plasma column parameter variations in the course of discharge development. The voltage and the current waveforms demonstrate the principal features of discharge behavior, which earlier were observed in our experiments.

Output data on plasma composition

This block provides output data on evolution of chemical species densities.

Output data on gas discharge waveforms

This block delivers the plasma column current and voltage across the gap.

Overall, the model operates in a self-consistent mode to obtain more reliable data on the gas discharge behavior and output plasma composition. An example of chemical species calculation for the gas discharge in air is shown in the Fig. 1. The principal idea of this graph is to demonstrate a typical lifetime of the chemically active particles, when the plasmatron operates in a spark gap mode with a high repetition rate [1].

We can see that typical lifetime of important chemically active species falls into the time interval of less than 10 ms. For example, it is characteristic for excited metastable molecules of nitrogen $A^3\Sigma_u^+$, for atomic oxygen $O(^3P)$, and atomic oxygen ion $O^-$. At the same time, there exist chemically

active species that have a rather long lifetime ($O_3$ and $O_2^-$).

If the plasmatron operation corresponds to conditions, when the sparks are superimposed on the glow type discharge, the picture changes radically. The modeling results indicate, that due to the glow type discharge the radicals do not decay, but are permanently generated in the gap. It is noticeable that in this case $A^3\Sigma_u^+$ and $O(^3P)$ densities exceed the plasma density in a glow type discharge. So, the active neutral particles can leave the area of the discharge column and carried away by the gas flow. These particles will facilitate origination of a weak prebreakdown current and generation of weakly ionized background plasma outside of the main plasma column [1, 2].
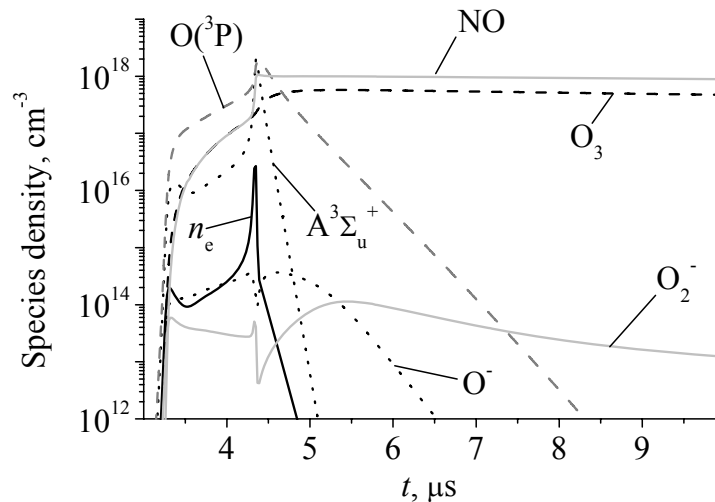


*Fig.1. Temporal evolution of the main discharge species, when a glow type discharge is not sustained in the breaks between current kicks.*

At the current stage the model allows an approximate consideration of the gas dynamic effects in plasmatron nozzle related to some stable particles with a long lifetime. In this case, we can suppose an average gas velocity to be associated with the plasmatron flow and consider the temporal evolution of particles drifting along gas stream. Under these conditions some stable species like NO, $O_3$, and $O_2^-$ are able to leave the area of plasmatron nozzle.

Thus, the model allows us to obtain the data on the main chemical species composition in the course of discharge development. The principal result at this preliminary stage lays in the fact that the model has maintained our premise on the advantages of the non-steady-state discharge mode in plasmatron.

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**Acknowledgement**

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# Theoretical Investigations of the Working Processes in a Plasma Assisted Afterburner with Reverse Vortex Flow

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The necessity to recycle different types of plastic wastes leads to the designing of various facilities for their conversion. Most existing systems use pyrolysis as the recycling method. The syngas obtained from the pyrolysis process is a mixture of hydrocarbon gases, carbon monoxide, carbon dioxide and water vapor, and other different gases with usually low calorific value. In some cases (when it is not possible to use it directly in power plants) this syngas should be burned anyway because the quantity of hazardous substances in it is much higher than statute-permitted values. Thus, the design of a high efficiency syngas afterburner is very real problem.

The syngas afterburner is designed based on a plasma assisted reverse vortex combustor [1-3]. The following initial data were taken under consideration:

- syngas mass flow rate of 25 g/s with temperature 700 K;

- calorific value of dry syngas in the range 18000-20000 kJ/kg;

- air mass flow rate of 400 g/s with temperature 350 K;

- atmospheric operating pressure.

For the solution of the problem of rational afterburner parameter selection, corresponding optimization calculations using a mathematical model developed earlier [4] are carried out. More than ten afterburner cases were calculated using the CFD ANSYS Fluent program to obtain the best geometric characteristics (Fig. 1.) and the most prospective methods of syngas injection. A mixture of propane and carbon dioxide ($C_3H_8$ – 40 % vol. + $CO_2$ – 60 % vol.) was taken as the fuel for calculation. The moisture in the fuel is absent, the calorific value of the mixture is 18270 kJ/kg, and the total air excess coefficient in the afterburner is 2.586.
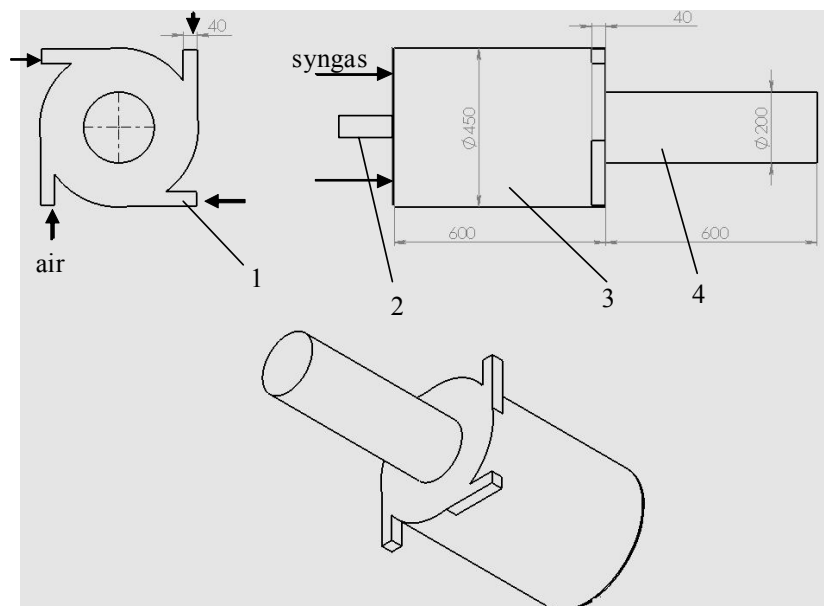


*Fig.1. Geometric parameters of the afterburner:*

*1 – air injection channels; 2 – plasma pilot; 3 – reverse vortex combustor; 4 – outlet tube*

Some interesting features of the working process in the reverse vortex afterburner were obtained during the CFD calculations. The first is that the diameter of the flame is approximately equal to the outlet tube diameter (Fig. 2.).
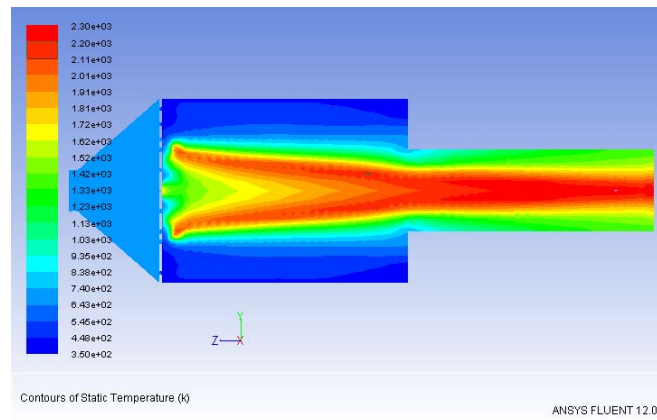


*Fig. 2. Temperature field in the afterburner*

Furthermore, the combustion efficiency depends on the distance of the syngas injecting holes from the afterburner axis. The syngas holes or gaps should be located on  diameters  larger than the diameter of the outlet tube. This provides good mixing and increases residence time, which ensures high combustion efficiency but decreases the range of the afterburner stable operational range.

On the other hand, the less distance between syngas holes and the combustor axis, the lower is the gauge pressure  needed to support the syngas mass flow rate due to a suction effect created by the main vortex inside the afterburner. The area of the negative pressure near the afterburner bottom is a bit less than the area of the main vortex in the chamber. This fact was proven (Fig. 3) not only by the CFD calculation but with experimental measurements by E. Kirchuk from APT, LLC.

Thus, for our proposed afterburner, the syngas holes should be located a) on the diameters just behind the diameter of the outlet tube, and b) inside the plasma pilot (Fig. 1) for stabilizing the burning processes and reducing  harmful emissions [5-7].

The recommended diameter of the outlet tube is 200 mm and the length is 500-600 mm, for an air mass flow rate of 400 g/s and fuel mass flow rate of 25 g/s. Increasing  the outlet tube diameter will cause  backflow at the afterburner outlet sections.
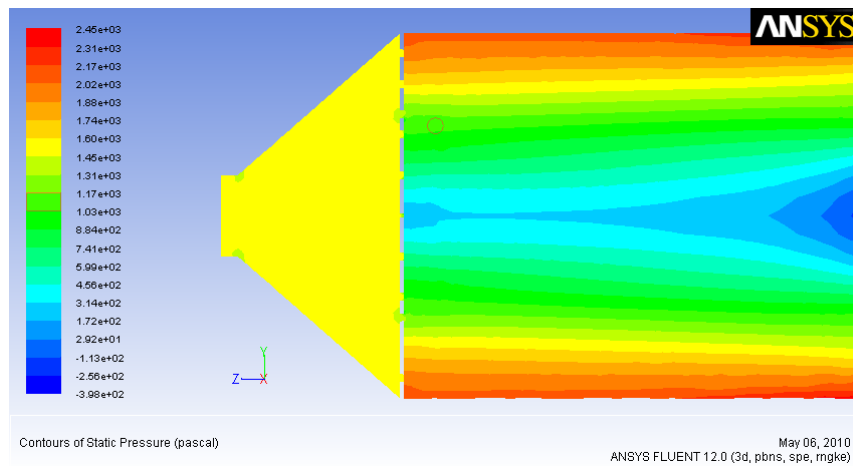


*a)*
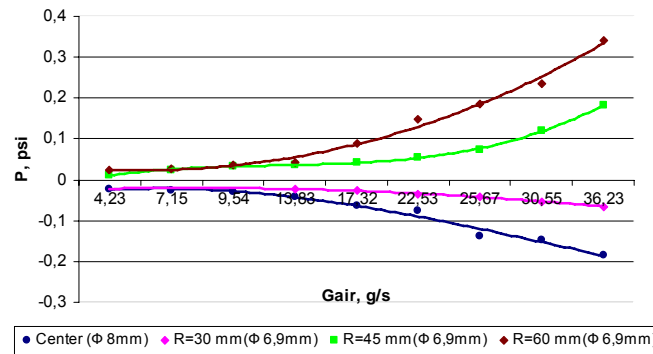
*b)*

*Fig.3. Gauge static pressure in the afterburner near the bottom:*

*a - experimental; b – calculated*

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# Plasma Instabilities as Instrument for Supersonic Mixture Formation

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This work is devoted to plasma – flow interaction under condition of supersonic high Reynolds flow and not equilibrium discharge plasma. It was focused on investigation of gas dynamic properties of flow variation in relation with plasma instabilities. Direction analysis was determined by problem of mixture preparation in high speed engines and flow control. Experiments were carried out in duct with nozzle of Mach number M=2. Cross longitudinal arc discharge (CLAD) was used as plasma source, located in area of duct sudden expansion (Fig. 1).
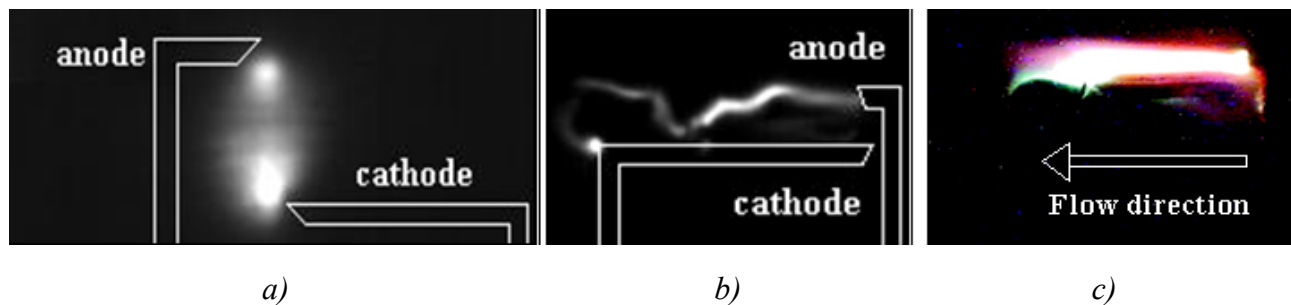


| a) | b) | c) |

*Fig. 1. Shot of CLAD discharge*

*a) Quiescent air. b) Flow, exposition is 20 µs. c) Flow, exposition is 1 s.*

Parameters of discharge were varied: 101-176 V (voltage) and 7-15 A (current). Static air pressure in duct was 0.08 Bar under condition of supersonic flow. Initial stagnation temperature and pressure of air was 300 K° and 2.4 Bar correspondingly. Three types of diagnostics were used for analysis of plasma influence on statistical parameters of flow. First type is spectral analysis of pressure disturbances realized with help of pressure transducers mounted on upper wall of plasma chamber. Fast Fourier transform of signals combined with noise analysis and filters gives understanding of spectral changing under influence of plasma. Second type of diagnostics is picture processing and receipt of cathode spot luminescence maximum coordinate. This method omitted to validate results of first method and to detect low frequency components. Third type of diagnostics was based on statistical R/S analysis of pressure signal. It was used for determination of fractal dimension of flow and it's relation to chaos transition (developed turbulence), i.e. determination of flow in range between laminar and turbulent state.

R/S analysis has shown that mean electric field (E/N parameter) increase leads to appearance of new effective degrees of freedom in flow and intensification of mixing. Minkovsky dimensionality (D) that is used as fractal characteristic of flow is represented on Fig.2. Number of freedom degrees can be determined as $(2 \cdot D + 1) \cdot 2$. I.e. field input leads to shift of flow state into turbulent region at the expense of gas excitation.
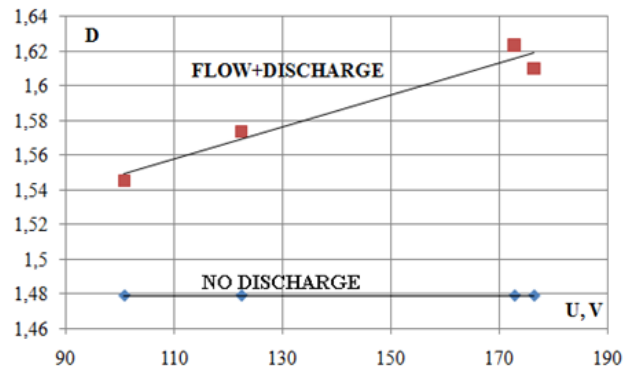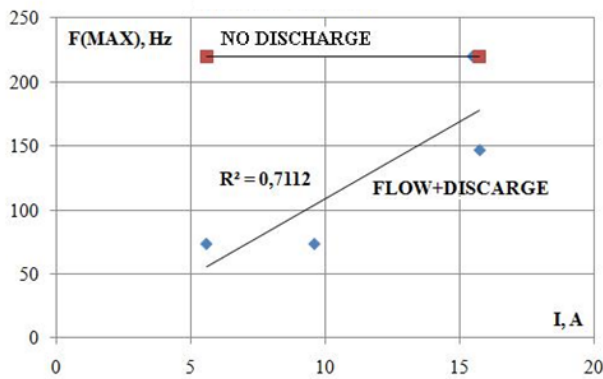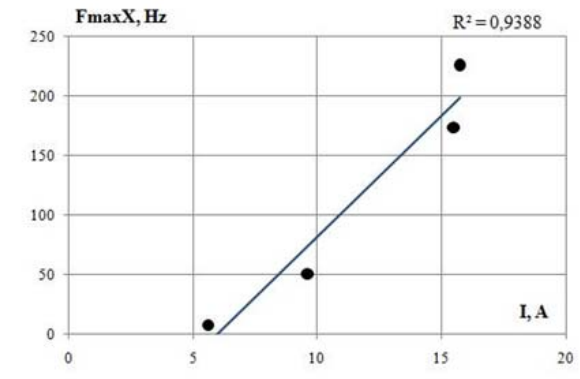
*Fig. 2. Dependence of Minkovsky dimensionality from mean field*

Spectral analysis of pressure signals has shown that frequency of maximum spectra component was shifted into "ultraviolet" region under condition of current increase. This data was validated by visual processing procedure (Fig.3).



*a)*



*b)*

*Fig. 3. Dependence of maximum spectral component frequency from mean current*

*a) Pressure signal data. b) Video image data*

Described experimental facts permit to speak about influence of electrons on formation of gas dynamic spectrum. There are several mechanisms that could be responsible to this phenomenon: ion sound instabilities and increase of streamer propagation velocity and determination of charged particles concentration will help to clarify nature of phenomenon.

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# Thermal Plasma Gasification of Organic Waste

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## 1. Introduction

The gasification of biomass and organic waste to produce syngas is a specific process of plasma waste treatment, which has not been so far intensively studied. The main purpose of the process is not destruction of treated material, but the production of gas composed mostly of CO and $H_2$, which is called syngas. Syngas is a key intermediate for the production of renewable transportation fuels, chemicals and electricity. Thermal plasma offers possibility of decomposition of organic materials by pure pyrolysis in the absence of oxygen, or with steichiometric amount of oxygen (gasification) to produce high quality syngas, with high content of carbon monoxide and hydrogen and minimum presence of other components. The process acts also as energy storage – electrical energy is transferred to plasma energy and then stored in produced syngas. The main advantages are better control of composition of produced gas, higher calorific value of the gas and reduction of unwanted contaminants as well as wide choice of treated materials.

This paper presents experimental results obtained in medium scale thermal plasma gasification reactor equipped by the gas-water dc plasma torch. The computations of syngas composition and analysis of the energy balance are made for the conditions in this reactor.

## 2. Experimental system

Investigation of plasma assisted gasification of organic materials and production of syngas was studied in plasma reactor PLASGAS with dc arc plasma torch. High enthalpy steam plasma was generated in an arc torch with water stabilized (Gerdien) arc. Reactions of mixtures of oxygen and $CO_2$ with polyethylene, plastic waste, wooden pellets and saw dust were studied for arc power 100 - 140 kW. The wall temperature in the range of $1100^0\,C$ to $1400^o\,C$ could be regulated by the torch power and feeding rate of the material. The gas produced in the reactor flowed to the quenching chamber, where it was quenched by a spray of water.

## 3. Results

Syngas with high content of hydrogen and carbon monoxide and very low content of carbon dioxide was produced. Very low content of complex hydrocarbons and tar was detected. Effect of composition and flow rate of oxidizing gases was studied. While for oxygen and air the energy from oxidation of surplus carbon contained in wood increases maximum throughput of material for given plasma jet power, use of $CO_2$ or steam leads to reduction of throughput as some energy is spent for dissociation of molecules of added gases. Complete energy balances for various combinations of conditions were determined. Energy balance of the process is discussed. In optimal conditions the calorific value of produced syngas was about 2.5 times higher than electric energy spent for plasma generation. Possibility of usage of the process is discussed for treatment of waste with production of high quality syngas as well as for energy storage during excess of electricity available from power plants with fluctuating output.
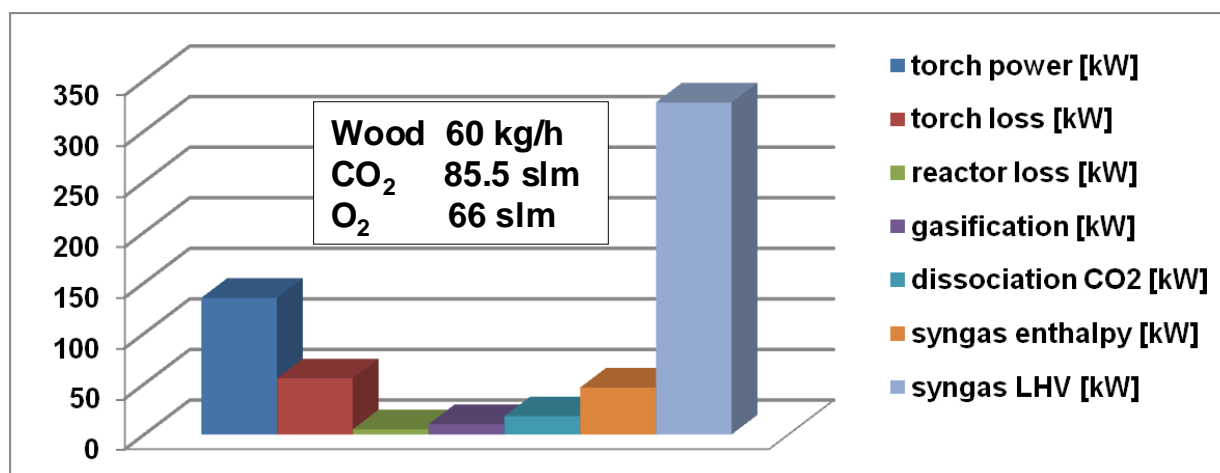
## Acknowledgement

*Fig. 1.  Power balance of gasification of wood in plasma reactor PLASGAS*

# New Approaches to Plasma Waste Gasification

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Waste disposal has long been a problem throughout world history for societies and their governments. With 2.02 billion metric tons generated in 2006, the world's landfills now contain well over a trillion tons of municipal solid waste (MSW)[1].

The United States produced 230 million metric tons of MSW in 2006[2], and on average, each resident of the United States produces just over 2 kilograms of household waste per day[3], an amount that is the highest per capita in the industrialized world[4]. Only 33% of this MSW is recycled and most of the remaining 67%, or about 124 million metric tons, is dumped in landfills[5]. Currently in the United States there are 1,754 active landfill facilities, plus approximately 10,000 old and inactive facilities[6]. The environmental impact of landfills is quite high: in addition to being a major source of methane emissions into the atmosphere (which has 21 times the global warming impact of CO2), leachate from landfills is a constant threat to groundwater supplies. Most facilities also contain unknown quantities of many toxic and hazardous substances in spite of extensive environmental regulation[7].

An overview of the global waste-to-energy (WTE) industry reveals that only about 130 million tons of MSW worldwide are combusted annually in over 600 WTE facilities that generate electricity and also heat for both district heating and for the recovery of materials for recycling. Located in 35 nations, mostly in Europe, these facilities utilize relatively old and inefficient technologies that provide an estimated 650 kWh of electricity per ton of MSW combusted. The most common grate technology, developed by Martin GmbH (Munich, Germany), has an annual installed capacity of about 59 million metric tons. The Martin grate at the Brescia (Italy) plant is one of the newest WTE facilities in Europe. The Von Roll (Zurich, Switzerland) mass-burning process follows with 32 million metric tons combusted worldwide. All other mass-burning and refuse-derived-fuel (RDF) processes together have a total estimated processing capacity of perhaps 40 million tons [1].

It needs to be pointed out that MSW-fired facilities do not eliminate waste, but change the form of waste into generally more hazardous air emissions and toxic ash, which need further treatment to be rendered harmless. Incinerator fly ash and, to a lesser degree, bottom ash contain leachable heavy metals, including lead, chromium, arsenic, mercury, cadmium and zinc. In addition, these ashes can also contain very hazardous persistent organic pollutants (POPs), such as dioxins and furans.

During the past decade, scientific and engineering efforts, mainly in the U.S., Canada and the UK, have led to the development and testing of small-scale prototypes of plasma waste gasification technology. Its key element is a plasma gasifier, which provides much higher process temperatures, about 2,500° C, in comparison with even the highest temperatures, 1,200-1,400° C, now employed in classic incineration for hazardous waste. These much higher temperatures allow

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[1] www.epa.gov/msw

[2] http://www.epa.gov/epawaste/nonhaz/municipal/pubs/msw07-rpt.pdf

[3] http://www.epa.gov/epawaste/nonhaz/municipal/pubs/msw07-rpt.pdf

[4] www.epa.gov/msw

[5] http://www.epa.gov/epawaste/nonhaz/municipal/pubs/msw07-rpt.pdf

[6] www.epa.gov/msw/facts

[7] http://www.ncbi.nlm.nih.gov/pubmed/15626384

waste conversion with total destruction of all organic chemical constituents, generating pure synthesis gas (syngas: primarily CO and H2), and a chemically inert, fully vitrified slag (similar to basalt rock). Subsequently, the syngas is used for power generation through combustion in IC engines, power boilers or gas turbines. The major players in this field are: Advanced Plasma Power, Ltd. (UK), Plasco Group (Canada), GeorgiaTech (USA), and PyroGenesis Canada Inc. (Canada) [5-7]. The current status of their efforts could be characterised as a phase of scaling up from a demonstrated 2-3 tons per day capacity to a commercial level of 250-500 t/day.

Advanced Plasma Power in November 2007 and by Plasco Group in January 2008 announced the successful initiation of commercial operations for their full-scale 100 t/d modules The success of these installations so far have not been supported by publication of practical positive results. A careful review of the facts reveals that each firm has encountered significant technical problems and obstacles during their attempts to scale up their small-scale units by a factor of 10 or more. These problems include high operation and maintenance costs, a variable composition syngas with low caloric value, which result in difficulties with its combustion and conversion into electrical power. Moreover, all plasma gasification technologies are based on three main principles, which are: (1) the application of electrically inefficient, short-lived, high maintenance DC torches, or DC arcs, for plasma generation, (2) performing plasma gasification in air, and (3) syngas quenching by water. This results in a relatively low power efficiency (a low total export power generation of 0.8-1.1 MW per ton of MSW), a high internal power consumption (about 500 kW per ton plus power for auxiliary systems), and high facility operation costs ($70-80 per ton). These high costs make these processes technically and economically unfeasible, and ultimately impractical for wide implementation as a national, or global, waste management strategy.

The detailed analysis of existing PGWTE technologies has proven their advantages over incineration, but also has revealed a substantial potential for improvements, both for reduced capital and operating costs [8-18]. As a result, an alternative schematic for a much improved plasma gasification plant has been developed and discussed at scientific forums [16-18] and numerous meetings with industry experts, waste managers, and venture capitalists. The schematic shown in Fig.1 is a significant step change in the technical and the economic feasibility for waste processing, delivering as much as twice the final electricity export product at a lower capital and operating cost. Such improvements are essential for practical implementation of global waste processing. This improved technology is based on three key innovations: (1) the hybrid type plasma generator having an almost endless lifetime, (2) the oxygen gasification environment, and (3) the steam catalyst treatment of raw primary syngas. The hybrid type plasma generator is a combination of radio-frequency (RF) and direct current (DC) modules, coupled with reverse vortex plasma stabilization, as recently patented by APT [11-12]. Powered by a newly designed, highly efficient solid-state power supply, this power-efficient plasma system with electrode-less design runs reliably for thousands of hours without maintenance or interruption. The current state of power electronics makes available such a plasma source power level up to 1.8 MW per unit. The switching from air to oxygen becomes affordable due to recent progress in air separation technology. With 0.3 kW/kg of $O_2$, we can eliminate the inert nitrogen (which behaves as an enthalpy ballast), dramatically reducing overall power consumption, $NO_x$ emissions, and the volumetric and gravimetric parameters of the entire waste gasification system. The total power output could reach up to 1.9MW per ton of MSW. Replacement of syngas water quenching by steam catalyst conversion and syngas heat recovery dramatically improves the process thermal efficiency and increases hydrogen yield. This, in turn, leads to higher syngas caloric value and its simpler conversion in existing heat engines, including gas turbines. An upgraded, high quality syngas could also be used for synthetic fuel production, other sustainable chemistry synthesis, hydrogen separation, and other applications..

One of the most feasible alternatives for optimizing worldwide implementation of this new technology would be the direct feeding of this raw syngas (CO and H2) into operating fossil fuel-

fired boilers to significantly reduce their $NO_x$ and CO emissions. This proposed technology "Plan B" can operate with significantly lower operating cost, about $20-30 per ton, as compared to $70-80 per ton for the existing technologies for plasma-based waste gasification processing. By installing the RDF plasma gasification facilities adjacent to existing power plants, and feeding the very hot syngas directly into their boilers we can eliminate all the back-end equipment employed for handling the raw syngas: steam reformer, heat recovery boiler, all air pollution control systems, and the motor generators for generating electricity. Existing power plants already have systems for air pollution control and electric power generation, and these are much less expensive due to their very significant economies of scale. Adoption of "Plan B" would allow the processing of MSW into compressed bales at central localized facilities that could then be transported to regional power plants.
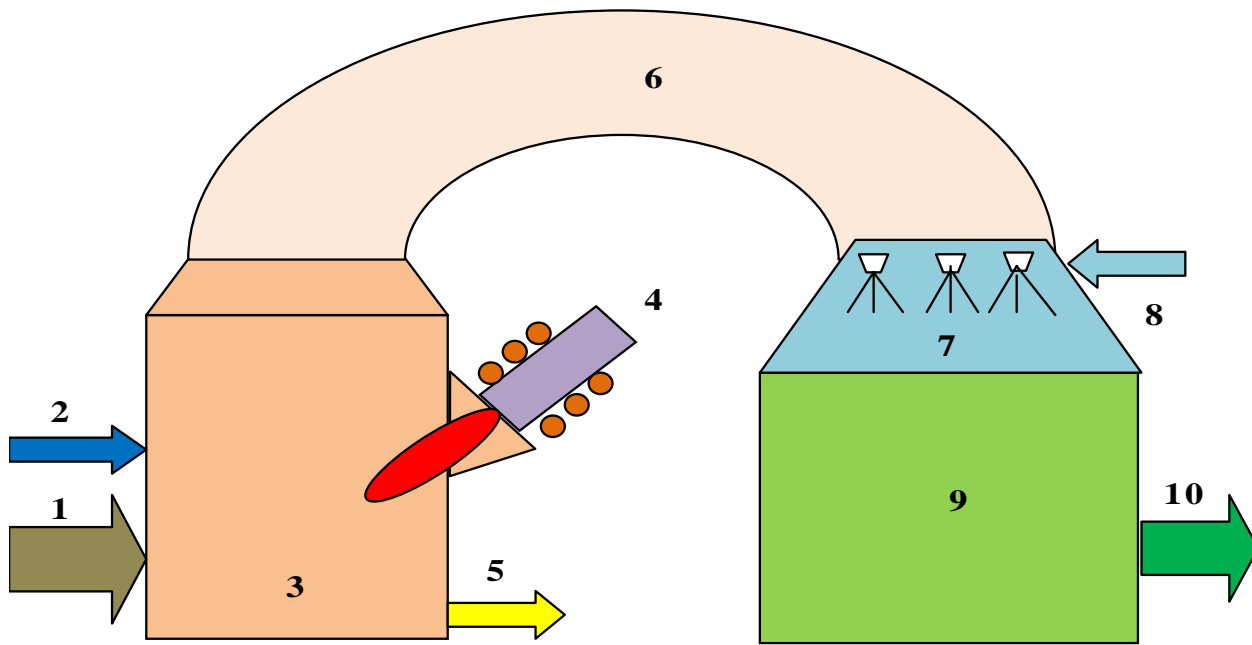


*Fig. 1. Pilot module for plasma oxygen waste gasification:*

*1 – feedstock input,  2 – oxygen input, 3 – gasifier, 4 – hybrid type plasma torch, 5 – slag output, 6 – gasifier output (raw synthesis gas), 7 – contact type steam injector, 8 – water input, 9 - catalyst steam converter, 10 – hydrogen enriched synthesis gas output*

The preliminary feasibility study of the alternative waste processing system for the city of Austin, TX with a population 775,114 and landfill cost ("tipping fee") of $25 per month per household (effective from 1 October, 2008) showed that the city could generate annually up to 594,000 MWh per year of green electricity and the return on investment would not exceed 6 years. In the case of "Plan B" implementation return on investment could be lowered to 4.5-5 years.

The simplified U.S. market evaluation [18] was based on such input data as total annual MSW generation level of 251 million tons, averaged capacity of waste processing plants of 250 tons per day, their cost of ownership at $50 million, and a number of operating days of 330 per year. This leads to total market volume of $155 billion.

It should be noted that the estimated total net power output from MSW plasma processing (oxygen based process) is from 250  to 326 million MWh.  Total national power generation for the US is 4,065 million MWh (2006).  The waste processing (annual amount) would cover from 6% to 8% of the US power demand.  Mining and recycling from old existing landfills would add even more, from another 1 to 5%, annually.  This becomes more important taking into consideration the

DOE's forecast regarding the massive decommissioning of major coal-fired power stations within the next two decades.  Note also that this 6% compares favorably to those contribution percentages for contribution to US national generation, as projected for wind, solar and biomass.

A proposed strategy would be based on seven major principles: (1) gradual scaling up of the core technology from a 2-5 ton/day unit, to a 25-30 ton/day unit, and then to a 250 ton/day unit, (2) immediate implementation of the R&D results as separate market products, (3) international cooperation with leading scientists and engineers, (4) teaming with the industry partners, (5) financial support by government, private and corporate investors (especially for full-scale demonstration units), (6) aggressive worldwide marketing, and (7) flexible and customer oriented financing.  This means that the first plasma-oxygen gasification module with 2-5 t/d capacity for medical, bio- and hazardous wastes will enter the market in 6-8 months, the second with 25-30 t/d in 12-14 months and the third one 250 t/d in 33-36 months.  At the same time within perhaps the first year after project activation, the first development in the form of a continuously operated 300 kW hybrid torch could be available to enter the market and be sold to potential customers in different areas such as silicon melting for solar panel production, scrap metal melting, coal ignition and gasification, coke and cement production, fuel reformation, surface treatment, and so forth. The much larger 1 to 1.5 MW hybrid torches, as well as new catalytic converters, and other project byproducts will become available to be marketed to enable development of other plasma-based technologies worldwide.  (Note that DC torches are inherently dirty, due to electrode consumption, while electrode-less RF torches produce clean plasma, a difference which is critical for many potential plasma applications.)

Global problems need global approaches. Global waste trade, which is mainly illegal, can be eliminated by organizing an international network of high performance and environmentally friendly waste recycling facilities. This will clean up the land and ocean, as well as reduce dependence on fossil fuels. One more related global issue is the emission of greenhouse gases, as per the Kyoto protocol. It expires in 2012 and developed countries should find a compromise in dealing with the growing and polluting economies of countries such as China, India, and Brazil [3]. These countries could not meet our standards and acceptance requirements within several decades. In this case the internationally regulated transfer of the waste-into-energy technologies could be an option to ameliorate these expected Kyoto emission controls' shortfalls.

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# Plasma Gasification of Organic Waste Using a Closed Loop ICP-Driven Facility

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Various plasma sources have been developed for the investigation of atmospheric entries at IRS [1]. The expertise gained in the field and the qualification level of the self-developed facilities led to developments in the field of terrestrial plasma applications such as plasma shock peening or decoating using a pulsed magnetic accelerator plasma source [2] or material coating and synthesis using a high power ICP [3, 4]. In [3] a set of terrestrial applications for which ICP systems can be used is outlined.

Among these applications are spheroidization and nano-scaling of particles and, in particular, plasma pro-cesses where reducing and oxidizing con-ditions are needed. The latter application results from the high flexibility of ICP systems due to the absence of electrodes. Correspondingly, ICP systems are very feasible for pro-cesses where aggressive wastes are treated, too [5]. Here, a concept of a closed loop plasma waste treatment facility that can be operated in a decentralized manner is proposed. Exemplarily the facility is motivated on basis of hospital waste treatment with particular emphasis on emerging markets where the facility's advantages namely the production of additional energy and its small size which is in the order of 1 m$^3$ have a positive effect. The mass of hospital waste created in emerging country hospitals are reported to be between 1 to 7 kg per day and bed. However, this wide value range has to be considered carefully as the interpretation of the waste strongly depends on the existing or non-existing hospital waste law system. Eventually, in Germany a typical value is 2.8 kg/(day·bed).

With the operation of the IPG of IRS with different working gases such as air, oxygen, nitrogen and carbon dioxide at thermal plasma powers of more than 50 kW, see Fig. 1 it becomes evident that design problems of already existing plasma systems can be solved by the use of these IPGs.
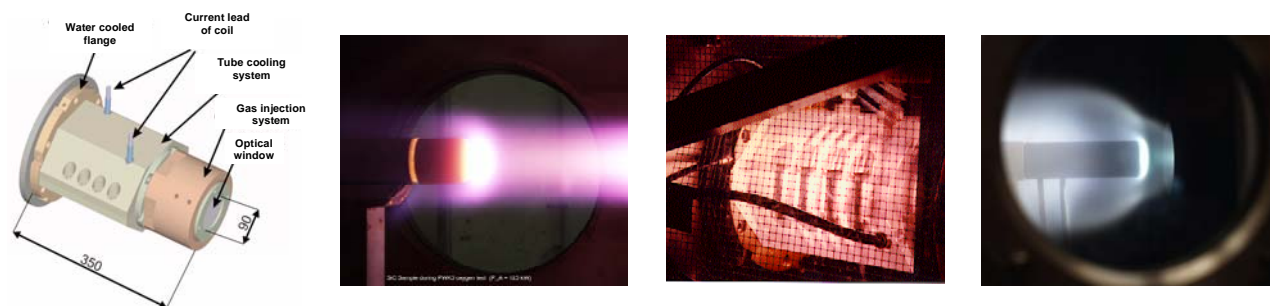


*Fig. 1: IPG3set-up (left) and IPG3 in operation*
*(first: air, View of the transparent cooling system, second: pure oxygen, third: carbon dioxide)*

So far most of the plasma devices to treat hospital waste are realized using electrode based plasma generators although problems with the running time occur due to the sensitivity of the electrodes with respect to the chemically reactive processes [6].

The advantages resulting from the functional principle of the IRS ICP plasma generators led to the conclusion that with such plasma sources infectious, pathological and chemically contaminated

wastes can be treated. The usability of the IPG for almost any working gas leads to the central idea of the concept below. The proposed facility consists of a ring-shaped channel in which the IPG is integrated. The resulting exhaust gases can be recirculated, see Fig. 2.

Solid wastes can be positioned within the channel such that they are thermo-chemically decomposed by the plasma. Gaseous and liquid wastes can be fed directly to the IPG. The process is then continued until the remaining waste 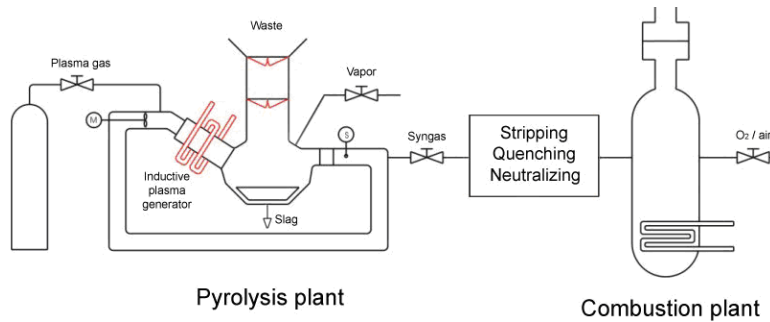material is either elementary or in harmless compounds. Toxic products such as dioxins can be excluded due to the high process temperatures (several 1000 K). This feature in combination with the plasma radiation is lethal to germs and viruses. Therefore, a chemical disinfection of hospital wastes is not necessary anymore. Using inert process gases leads to a pyrolysis. Therefore, the resulting gases are of higher energy (combustile, often



*Fig. 2 Scheme of hospital waste disposal facility (pyrolysis process)*

referred to as "syngas") which allows for a retrieval of energy by the use of a connected burner or mini-gas turbine. This energy in turn can be used to partially supply electric energy for the ICP system and, therefore, contributes to higher efficiency and a decrease of the operating costs. Here, energetic improvements can be achieved adding $H_2$ to the syngas e.g. either by actively adding water vapour or by the use of water that is contained in the hospital wastes. However, the total process is very complex. For example the pyrolysis gases must undergo quenching and stripping processes to prevent both the formation of dioxins and furans and critical substances from surviving the pyrolysis process.

A preliminary analysis was performed in view of the probable power balance. For this purpose an extensive literature research was per-formed [6-10]. Corresponding-ly, esti-mative values for the different energy para-meter could be identi-fied: Most literature reports on a hospital waste heating value of about 14 MJ/kg [8, 9]. The syngas is reported to have heating values around 5 MJ/kg [9]. The heat losses to the channel walls can be estimated to roughly 10 % [10]. Maximum values for the heat loss via the slag are reported to be less than 1 % [10]. The mass flow of the slag is estimated at 5 % of the total mass flow rate of the waste [11]. The required energy that has to be invested to treat 1 kg of waste is roughly 3 MJ/kg [12].

Using 30 kW of plasma power at a working gas mass flow rate of 10 g/s with no water vapour allows for a hospital waste mass flow rate of about 36 kg/h. This goes with losses to the channel walls of roughly 17 kW and losses via the slag of 1.2 kW. About 70 kg/h syngas is produced delivering a combustion power of 97 kW. This is more than the plasma system's operational input power. From this analysis it can be concluded that such a system seems to be profitable in terms of energy. In ref. [5] a market survey analyzing the hospital waste emergence in different countries with a particular focus on developing countries has been performed. It was found that such systems may be feasible for application in such countries to solve the problem of hospital waste disposal at rather low operating costs while the infrastructure needs not be centralized by the use of advanced but large combustors as they are available in developed countries. Most recently a business plan and a cost analysis has been assessed showing that even for an economic worse case scenario such as Germany a break even of the costs can be achieved using such a facility.

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Hypersonic Systems Research Institute is engaged in the development of progressive technologies of hydrocarbon catalytic conversion on the base of highly efficient nanostructured catalysts of a planar and a frame types. Employment of hydrocarbon conversion promotes incorporation of the new resource-and energy-saving technologies in various spheres of human activity. We cite a number of examples.

Fig.1 shows employment of liquid hydrocarbon conversion scheme for production of hydrogenous fuel for internal combustion engines (ICE), air-breathing engines (ABE), gas turbine engine (GTE), fuel cells and other devices.
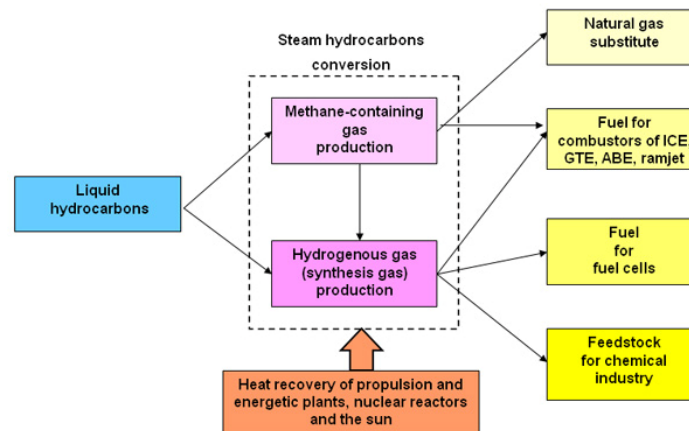


*Fig. 1. Production and usage of liquid hydrocarbons gasification yields*

For conversion purposes heat losses of propulsion-and-power plants are used resulting in the enhancement of their efficiency.

Fig. 2 presents diagram of a gas turbine with steam injection and thermochemical reactor that we have developed.
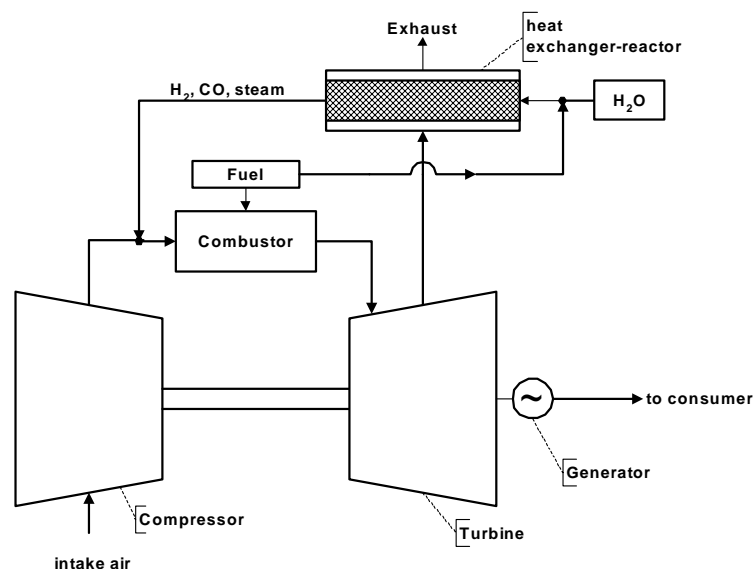


*Fig.2. Gas-turbine with injected steam and chemical heat regeneration*

As a result of the process of natural gas steam conversion, previously lost energy with exhaust gases is absorbed to 10 MJ/kg and it returns to the heat engine' thermo-dynamic cycle. As a result, its efficiency increases by 10 – 20 %, and its economical operation – by 10-15 %. Burning of the converted fuel, the so called synthesis gas (H2 + CO), results in reduction of irreversible energy losses as compared to the natural gas burning and decrease of harmful substances emission by several times.

And lastly, catalytic converter can be a part of the installation designed for gasification of coal, biomass and waste. A catalytic converter is designed for enhancement of calorific capacity of coal, biomass and waste gasification products at the expense of additional hydrogen. The point is that owing to gasification, in the gas content, apart from hydrogen $H_2$, complex organic compounds such as $C_nH_{2n+2}$, $C_nH_{2n}$, $C_nH_n$ can be present, as well as $CO$ and $CO_2$, aqueous vapor and other substances. All these compounds can be further subjected to additional treatment in a catalytic unit to obtain an additional quantity of hydrogen. It can be steam ($C_nH_m + H_2O$) and carbon-dioxide ($C_nH_m + CO_2$) conversion as well as CO shift ($CO + H_2O$). Steam and carbon-dioxide conversion are endothermic reactions providing high hydrogen yield at temperatures $T > 1000K$, while CO shift is an exothermic low-temperature reaction ($T = 500 – 600\ K$). An active element in steam and $CO_2$ (carbon-dioxide) reactions is nickel ($Ni$) while during CO shift it is compounds such as $Fe – Cr$ and $Cu – Zn - Al – Cr$. But knowledge of active elements in any of the reaction does not guarantee yet a successful process. In practice of heterogeneous catalysis the most commonly encountered are fixed-bed catalytic reactors whose catalyst grains can have different shapes.

When initiating catalytic reaction by passage of reacting gas flows through catalyst bed, pure chemical transformation is accompanied by the following physical stages:

- transfer of reacting substances from the gas flow between the grains to the catalyst surface and the products of reaction in the opposite direction;

- diffusion of reacting substances and the products in the pores of catalyst grains;

- heat transfer inside the grains;

- heat exchange between catalyst grains and gas flow.

If speeds of these physical stages are too low as compared to chemical transformation rate, then concentration and temperature gradients appear with respect to catalyst grain and reaction space. This, in turn, will influence basic kinetic characteristics: activity, selectivity, catalyst durability and so on. Therefore, the important research and development task is significant intensification of heat-and-mass exchange process and provision of minimal temperature gradients in respect to the volume of chemical reactor, i.e. a catalytic converter. The solution of this problem can be realized by switching from traditional granular catalyst to the volumetric framework catalytic structures with high thermal conductivity which can ensure turbulent conditions for the flow of chemically reacting mixture in the reactor. Such catalytic structures should be manufactured for both endothermic reactions of hydrocarbon transformation into synthesis gas ($H_2 + CO$) and exothermic reactions of $CO$ conversion.

The potentialities of traditional catalytic materials with equilibrium structure to provide for the catalyst stable overactivity have been practically exhausted. Consequently, it is expedient to use new amorphous or quasicrystalline gradient-functional materials when making catalytic converters. Creation of catalysts with a new structure became possible due to implementation of the technologies of supersonic plasma and cold gasdynamic spraying modified by HSRI plc as a catalysis subgoal.

The photos of thermochemical reactors with different catalytic structures are shown in Fig. 3.
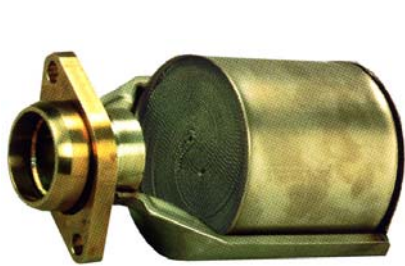
a)                                                          b)

*Fig. 3. The photos of thermochemical reactors*

a) *Reactor with planar catalyst on metallic band*
b) *Panel with catalyst on metallic foam*



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# Plasma Jets Magneto-Inertial Fusion for Space Propulsion

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Electric propulsion is an important in-space propulsion approach primarily due to the high exhaust velocities achieved, enabling higher payload mass fractions and mission resulting in reduced trip times. The objective of this paper is to develop theoretical model for magneto-inertial fusion (MIF) rocket and basic plasma physics research in the system "magnetized plasma - plasma liner" in reactor mode of recently offered concept of using plasma jets for formation of the liner [1]. The feature of a task in view is presence initial seed fields (the imposed external magnetic field) and compression of a magnetic flux by plasma jets (the plasma liner).

Advanced space propulsion using compact torus, namely field-reversed configuration (FRC) is studied. In the given work prospects of using FRC as a target compressed by the powerful external plasma piston for achievement of thermonuclear temperatures theoretically are considered. The driver represents system of the guns forming plasma jets. A few hypersonic plasma jets (Mach number between 5 and 50) with high density (within the range of $10^{21}$-$10^{23}$ m$^{-3}$) must be injected. Closed symmetrical configurations with poloidal field are the most suitable for MIF (Fig. 1). The charged particles are directed out a magnetic nozzle to produce thrust. Direct energy converter may be connected to fusion/ignition chamber.

Such systems may be used for interplanetary and interstellar travel. Concept of magnetized target fusion (MTF) rocket [2] and the scientific basis of MIF/MTF are described. Magnetic fusion rocket model [3] and magneto-inertial fusion engine model are presented. Comparison with other magnetic configurations for high-energy plasma propulsion is made.
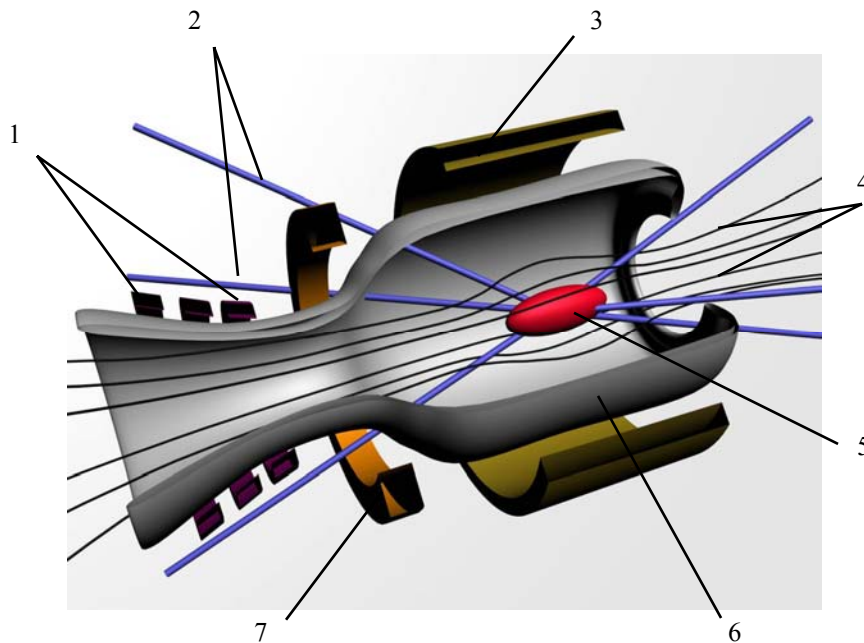


*Fig. 1. Magnetized plasma in magneto-inertial fusion rocket based on a FRC type compact torus:*

## Acknowledgement

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# Prospective Applications for a New Generation of High Power ICP Torches

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Advantages of the newly developed ICP torches are as follows:

- Portable electrodeless design = unlimited life time

- Pure plasma not contaminated by the products of the electrodes erosion

- Unbeatable power range from several Watt up to 10 MW

- Atmospheric pressure operation

- Wide range of plasma gases from noble to air and air based blends

- Possibility to use as a reactor for variety of plasma enhanced processes

- Increased efficiency due to contemporary solid state power supplies

- Possible wave modulation to reduce power consumption.

Possible applications:

- Coal, petro-coke, waste, and hydrocarbons gasification

- Bio mass pyrolysis

- Synthesis of new materials

- Production of nano- powders, fullerenes

- Etching

- Coating

- Melting

- Treatment of hazardous liquids, coal ash, and fly ash

- Contaminated soil recovery

- Hypersonic flight simulation

- Bio weaponry, ammunition, and drugs destruction

- Possible combining with the plasma chemical reactors

**Igor B. Matveev,**
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# Announcing a Special Issue of the IEEE Transactions on Plasma Science Plasma-Assisted Combustion (Scheduled for December 2011)

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 2011.

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 2010) 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, 2011** 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:

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