3rd International Workshop and Exhibition on Plasma Assisted Combustion (IWEPAC)

18-21 September 2007
Best Western Falls Church Inn
Virginia, USA

Applied Plasma Technologies
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Synopsis

The 3rd International Workshop and Exhibition on Plasma Assisted Combustion (IWEPAC) will be held 18-21 September 2007 in Falls Church, Virginia, USA. (Washington, DC area).

The IWEPAC will provide a forum to present and discuss scientific and engineering aspects of plasma assisted ignition, flame control, fuel conversion and activation, coal gasification, waste disposal for power generation, propulsion, and production of hydrogen-enriched gases. Participants will demonstrate the operation of technical and engineering prototypes and commercial equipment. Among expected exhibits will be a 55 kW power plant for plasma reformation of coal and bio-diesel into synthesis gas; a hybrid type plasma torch (RF + transient DC) with reverse flow; plasma assisted triple vortex combustors; subsonic and supersonic plasma igniters; and plasma spark plugs for IC engines.

Several innovative technologies for municipal waste, plastic and automotive tires processing into liquid and gaseous fuels will be presented in the Waste - into - Energy session. Comprehensive solutions for liquid and solid fuel reformation and further syngas conditioning will be reported. Prospective plasma technologies and approaches for subsonic and supersonic aerospace applications will be demonstrated and discussed.

Several round tables with researches and industry representatives will discuss methods for overcoming obstacles on the path to plasma technology development and implementation.

We plan to establish several International Research Teams for the major directions of activity.

Round table discussions will facilitate an exchange of ideas in an open forum.

Over 30 technical papers will be presented on the following topic areas:

- Waste – into – Energy Processing
- Fuel Reformation and Activation
- Plasma Ignition and Flame Control
- Plasma Generation and Modeling
- Advanced Industrial Processes

IWEPAC – 3
Tentative Agenda

Monday, 17 September

16.00 – 18.00	Registration, Best Western Falls Church Inn Lobby 6633 Arlington Blvd, Falls Church, VA 22042, USA Phone: (1-703) 532-9000, fax: (1-703) 532-3887

Tuesday, 18 September

8.00 – 10.00	Registration, Ball Room
9.00 – 9.30	**IWEPAC-3 OPENING** Welcome remarks from *Dr. Igor Matveev* (Applied Plasma Technologies) *Dr. Louis Rosocha* (Los Alamos National Laboratory) *Dr. Phillip Westmoreland, Program Director* (National Science Foundation)
9.30 – 13.00	**WASTE - INTO - ENERGY PROCESSING** Chaired by *Dr. Edberto Leal-Quiros* (Full Circle Energy, USA)
9.30	**Plasma Catalytic Module for Utilization of Oil Residuals Based on High-Frequency Discharge** *Dr. A. G. Karengin* (Tomsk Polytechnic University, Russia), *Professor Yu. D. Korolev* (Institute of High Current Electronics of the Russian Academy of Sciences, Russia)

10.00	**Hydrogen Production Using Plasma Torches and Plasmatrons for Plasma Gasification and Plasma Magmavication of Organic and Inorganic Materials** *Dr. E. Leal-Quiros* (Full Circle Energy, Inc., USA)
10.30 -10.45	Break
10.45	**Thermoplastic Waste Processing into Alternative Liquid Fuels** *Professor B.Tymoshevskyy, Professor M.Tkach, Dr. Y.Kharitonov* (National University of Shipbuilding, Ukraine)
11.15	**Rubber Waste Processing into the Alternative Fuels** *Professor B.Tymoshevskyy, Professor M.Tkach, Dr. Y.Kharitonov* (National University of Shipbuilding, Ukraine)
11.45 – 12.00	Break
12.00	**Energy from Waste Using the Plasma Resource Recovery System (PRRS)** *Pierre Carabin* (PyroGenesis Inc., Canada)
12.30	**Plasma Applications to Utilization of Municipal Solid Waste for Energy: Pollution Control and Fuel Conversion** *Dr.L. Rosocha (*Los Alamos National Laboratory, USA), *M. Zollinger, M. Elliott* (CobCreations, LLC, USA), *Dr. Igor Matveev* (Applied Plasma Technologies, USA)
13.00 – 15.00	Lunch
15.00	Round Table on Waste - Into - Energy Processing
16.30	Welcome Party

Wednesday, 19 September

9.00 – 11.30	**EXHIBITION** Transportation from Best Western Falls Church Inn provided (5408 Port Royal Rd., Unit S, Springfield, VA 22151).
12.00 – 13.00	Lunch
13.00 – 13.30	**The Emerging Energy Environment in the 21st Century** Invited speaker *Mr. Robert Gentile,* Past Assistant Undersecretary of Energy, United States Government, President and CEO of Leonardo Technologies, Inc., USA

13.30 – 18.30	**FUEL REFORMATION AND ACTIVATION** Chaired by *Dr. Louis A. Rosocha,* Los Alamos National Laboratory, USA
13.30	**Bituminous Coal Plasma Gasification** *Dr. Igor Matveev* (APT, USA), *Prof. V.E. Messerle, Dr. A.B. Ustimenko* (Research Department of Plasmatechnics, Kazakhstan), *Prof. Serhiy Serbin* (National University of Shipbuilding, Ukraine)
14.00	**Thermal Efficiency of a Hybrid Type Plasma Reformation System** *Dr. Igor Matveev* (APT, USA), *Prof. Serhiy Serbin* (National University of Shipbuilding, Ukraine)
14.30	**On-Board Fuel Reforming for Better Combustion and Exhaust Emissions in the Internal Combustion Engine** *Dr. Myoungjin Kim* (University of Texas at El Paso, USA)
15.00 – 15.15	Break
15.15	**Plasma Production of Hydrogen-Enriched Gases From Ethanol** *Prof. Chernyak V.Ya., Yukhymenko V.V., Solomenko E.V., Slyusarenko Yu.I., Olzhevskij S. V., Prisyazhnevich I.V., Martysh E.V.* (Taras Shevchenko Kyiv National University), *Naumov V.V.* (Institute of Fundamental Problems for High Technology, Ukrainian Academy of Sciences), *Demchina V.P., Kudryavzev V.S.* (Institute of Gas, Ukrainian Academy of Sciences, Ukraine)
15.45	**CO_x-free Hydrogen Production by Combination of Plasma Reforming and Cyclic Water Gas Shift Technologies for the Fuel Cells Application** *Dr. V.V. Galvita* (Chemical Engineering Department, University of California, USA), *Prof. V.E. Messerle, Dr. A.B.Ustimenko* (Research Department of Plasmotechnics, Kazakhstan)
16.15	**Fuel Reforming Using Dielectric Barrier Discharge and Micro-Cavity Plasma Array and Reformed Fuel Effects on BUNSEN Flame** *Dr. Myoungjin Kim, Atul Ambhore* (University of Texas at El Paso, USA), *Sungjin Park, James G. Eden* (University of Illinois at Urbana-Champaign, USA)
16.45 – 17.00	Break
17.00	**Decomposition of Ethane in Atmospheric-Pressure Dielectric Barrier Discharges: Model** *Dr. L. Rosocha, Dr. Yongho Kim* (Los Alamos National Laboratory, USA)

17.30	**Temperature Effects on Gaseous Fuel Cracking Studies Using a Dielectric Barrier Discharge** *Richard Renneke, Dr. L. Rosocha, and Dr. Yongho Kim* (Los Alamos National Laboratory, USA)
18.00	**Carbon Gasification in Hydrogen Dielectric Barrier Plasmas** *Dr. Yongho Kim, Sean Brannon, Hans Ziock, and Dr.L. Rosocha* (Los Alamos National Laboratory, USA)
18.30 – 18.45	Break
18.45	Round Table on Fuel Reformation and Activation

Thursday, 20 September

9.00 – 12.15	**PLASMA IGNITION AND FLAME CONTROL** Chaired by *Dr. Igor Matveev*, Applied Plasma Technologies, USA
9.00	**Plasma Ignition System for Internal Combustion Engines "Plasma Drive"** *L. Lenarduzzi* (Plasmatronics, LLC, USA)
9.30	**Transient Plasma Discharge Ignition for Internal Combustion Engines** *Saro Memarzadeh, Jennifer Colgrove, Prof. P. D. Ronney* (University of Southern California, USA)
10.00	**Combustion of Lean Gaseous Fuel Mixture Stimulated by a Microwave Discharge** *Dr. I.I. Esakov, L.P. Grachev, Prof. K.V. Khodataev* (Moscow Radio Technical Institute of the Russian Academy of Sciences, Russia), *Prof. V.L. Bychkov* (Moscow State University, Russia)
10.30 – 10.45	Break
10.45	**Plasma-Assisted Combustion and Flame Holding in High-Speed Flow** *Dr. Campbell Carter* (Wright Patterson Air Force Base, USA), *Dr. Sergey Leonov* (Joint Institute of High Temperature RAS, Russia)
11.15	**First Test Results of the Transient Arc Plasma Igniter in a Supersonic Flow** *Dr. Igor Matveev* (APT, USA), *Dr. Sergey Leonov* (Joint Institute of High Temperature RAS, Russia)
11.45	**Triple Vortex Plasma Assisted Combustor** *Dr. Igor Matveev, Svetlana Matveev* (Applied Plasma Technologies, USA), *Prof. Serhiy Serbin* (National University of Shipbuilding, Ukraine)
12.30 – 14.00	Lunch

14.00 – 18.00	**PLASMA GENERATION AND MODELING** Chaired by *Professor Yu. D. Korolev,* Institute of High Current Electronics of the Russian Academy of Sciences, Russia
14.00	**Plasmatron with Regenerative Carbon Nano-Structured Electrodes** *V.I. Golish, V.G.Lukyashchenko, V.E. Messerle, V.Zh. Ushanov, A.B. Ustimenko* (Research Department of Plasmatechnics, Kazakhstan), *Dr. E.I. Karpenko* (Applied Plasma Power Technologies Centre of the Russian J.S.Co. “UPS of Russia”, Russia)
14.30	**Investigation of a Non-Steady State Discharge in a Pilot for Ignition and Flame Control** *Professor Yu. D. Korolev, O. B. Frants, N. V. Landl* (Institute of High Current Electronics, Russia), *Dr. Igor Matveev* (Applied Plasma Technologies, USA)
15.00 – 15.15	Break
15.15	**Three-Temperature Model of Nonequilibrium Air Plasma** *Dr. A.A. Tropina* (Kharkov National Automobile and Highway University, Ukraine)
15.45	**CFD Calculations of the Reverse Vortex Reactive Flows** *Dr. Igor Matveev* (Applied Plasma Technologies, USA) *Prof. Serhiy Serbin and MS Anna Mostipanenko* (National University of Shipbuilding, Nikolaev, Ukraine)
16.15 – 16.30	Break
16.30	**Mathematical Modeling of Argon Plasma in ICP Torch by Non-Equilibrium Model** *Prof. S. Dresvin, Dr. D. Ivanov* (St.-Petersburg State Polytechnic University, Russia), *J. Amouroux* (LGPPTS, ENSCP, France)
17.00	**Chemical Reactions in Heat and Mass Transfer Between Small Particles and Plasma** *J. Amouroux* (LGPPTS, ENSCP, France), *Prof. S. Dresvin, Dr. D. Ivanov* (St.-Petersburg State Polytechnic University, Russia)
17.30	**Numerical Analysis of High-Speed Flows with Combustion of Fuel Ignited by a Plasma Torch** *Dr. Dmytro M. Voytovych, Prof. Charles L. Merkle* (Purdue University, USA)
18.00 – 18.15	Break
18.15	Round Table on Plasma Ignition and Flame Control

Friday, 21 September

9.00 – 10.00	Round Table on Plasma Generation and Modeling
10.00 – 12.15	**ADVANCED INDUSTRIAL PROCESSES** Chaired by *Professor V. Bychkov,* M.V. Lomonosov Moscow State University, Russia
10.00	**Application of Erosive Plasma Generator Over Flammable Liquids** *Prof. V. Bychkov, V.A. Chernikov, A.A. Kostiuk, V.Yu. Sergienko* (M.V. Lomonosov Moscow State University, Russia)
10.30	**New Plasma Technologies for Fuels Utilization** *Dr. E.I. Karpenko* (Applied Plasma Power Technologies Centre of the Russian J.S.Co. "UPS of Russia", Russia) *Prof. V. Messerle, Dr. A. Ustimenko* (Research Department of Plasmatechnics, Kazakhstan)
11.00 – 11.15	Break
11.15	**Plasma Clean – a Non-Thermal Plasma Approach to Air Quality Improvement** *Kui Zhang* (Plasma Clean Ltd, UK), *Alice Harling, John Christopher Whitehead* (School of Chemistry, The University of Manchester), *Dr. David Glover* (Plasma Clean Ltd, UK)
11.45	**New Solar Cell Manufacturing Processes and Equipment Using Atmospheric Plasma Technology** *B. Piwczyk* (BPP Technology Consulting, USA)
12.15 -12.30	Break
12.30	Round Table on Advanced Industrial Processes

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Plasma Catalytic Module for Utilization of Oil Residuals Based on High-Frequency Discharge

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Institute of High Current Electronics, Tomsk, Russia

This paper presents the results of construction and investigation for a plasma catalytic module based on high-frequency discharge. As one of the examples of applications for such a module, we demonstrate the utilization technology for oil residuals derivable in the process of oil production. The module includes in itself a plasma generator unit and a unit for feeding the discharge region with oil-water emulsion. A schematic of the plasma generator unit is shown in Fig. 1.

The high-frequency discharge in this system represents so-called one-electrode torch discharge. The discharge is powered from power supplier *1* with maximal average power of 60 kW, and oscillation frequency of 13.56 MHz. Under the effect of high voltage, the discharge originates and is sustained inside the quartz tube *5*. The characteristic feature of such type of discharge is that the plasma fills up the volume of the discharge tube rather uniformly and the current closes to the anode *4* in a form of displacement current. Average power, dissipated in the discharge plasma, is mainly determined by the discharge current, which is varied from 2 A to 3.5 A as applied to the described module. In turn, when the discharge current is increased the length of the plasma increases as well. Typical plasma length for the power of 40 kW with quartz tube diameter of 5 cm is about 1 meter.

The high-frequency torch discharge is able to generate a non-equilibrium plasma with moderate gas temperature and high electron temperature. For example, typical air flow for discharge feeding was from 1 g/s to 3.5 g/s and maximum gas temperature was 3,800 K.

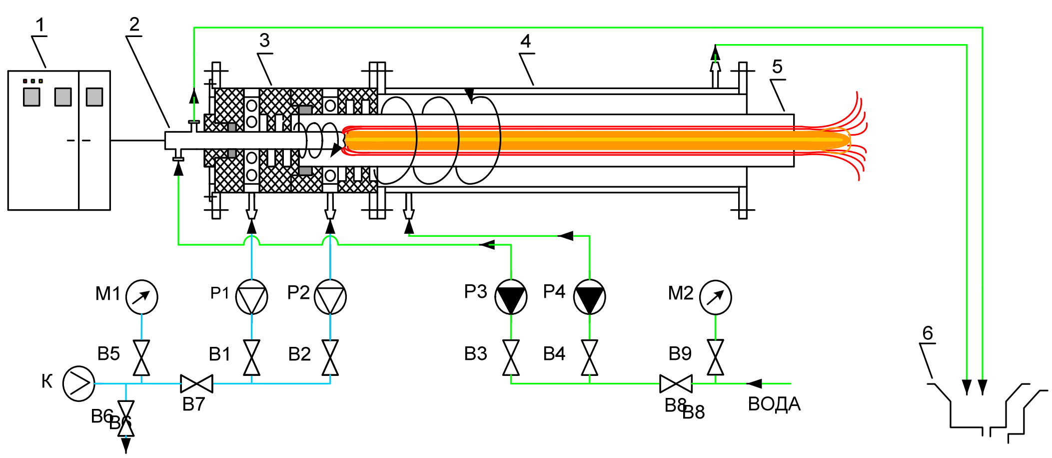

Fig. 1. Schematic of plasma generator unit.
1 - High-voltage high-frequency power supplier; 2 - Water cooling cathode; 3 - Construction unit for obtaining a vortex gas flow inside and outside of the quartz tube; 4 - Metal housing of plasma generator (anode); 5 - Quartz tube (plasma reactor chamber); 6 - Water outlet; K - Compressor; M - Manometers; B - Valves

The area of the plasma chemical reactor is located at the end of the plasma torch. Schematic of the unit for providing the plasma catalytic utilization of the oil residuals is shown in Fig. 2. Here the composition of oil residuals and water is delivered via sleeve 7. Then the viscous composition is turned into oil-water emulsion in the preliminary chamber *4* and after that is delivered to the chamber *3* and to the disk-rotating nozzle *2*.

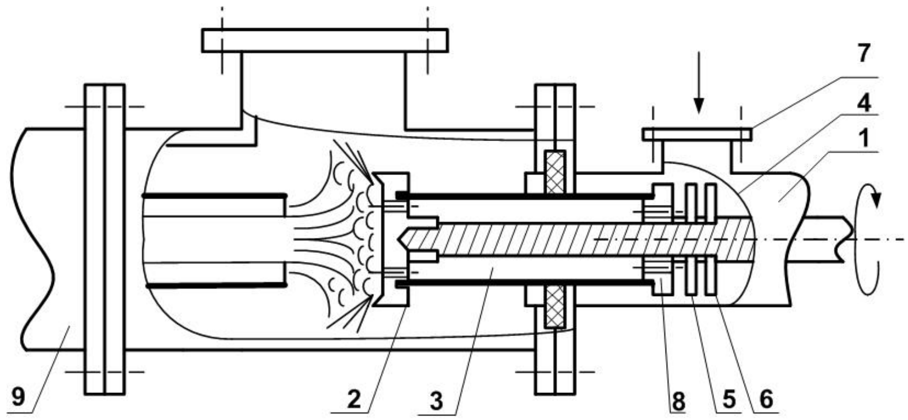

Fig. 2. Unit for feeding the discharge region with oil-water emulsion. 1 - Envelope; 2 - Rotating disk of fuel nozzle; 3 - Secondary chamber for oil-water emulsion; 4 - Primary chamber for preparing the oil-water emulsion; 5, 6, 8 - Unit for oil-water mixing and feeding the chamber 3 with oil-water emulsion; 7 - Injection of water oil composition into the primary chamber

One of the problems for such systems is to decrease the size of microdroplets at the exit of disk *2*. In most cases, it is achieved due to increasing a velocity of disk rotation. In our case, we have achieved small-size droplets due to increasing the gas temperature of the disk *2* with a moderate velocity of disk rotation (about 50 Hz).

In the whole, the recommended rating characteristics for the described module are as follows:

Average power dissipated in plasma	45 kW
Water-oil residuals composition	Water - 60 % , oil residuals - 40 %
Expenditure of Water-oil composition	1,000 liters/hour

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

Hydrogen Production Using Plasma Torches and Plasmatrons for Plasma Gasification and Plasma Magmavication of Organic and Inorganic Materials

*Edbertho Leal-Quiros, Ph.D.**
Full Circle Energy, Inc. Fresno, CA, USA

The interaction of the high density and high energy plasma from Plasma Torches and Plasmatrons with organic compounds through the cascade collision phenomenon produces synthetic gas mainly comprised of CO and H_2. One very important result is the absence of CO_2 in the synthesis gas due to the fact that the CO_2 molecule dissociates at less than 1500 ^oK, and the plasma temperature generated from the torches is more than 5000 ^oK. This synthesis gas can be used to generate power but also can be separated in its components, and so far is the less expensive method to generate hydrogen. H_2 will be needed for the generation of electrical power with fuel cells.

A large variety of organic materials have been used including coal, plastics, used oils, agricultural feedstock's, municipal solid waste, wood, paper, and other biomass materials. On the other hand, the interaction of high density and high temperature plasma generated from plasma torches with fine grains of inorganic materials will melt the grain materials producing a kind of magma similar to the volcanic lava. This phenomenon called Magmavication has been used to process salts, sludge, and different kinds of soils.

After cooling the magma a vitrification process happens and these new materials have in many cases the appearance similar to semiprecious gems. Several examples will be shown.

Fig. 1. Like emerald gem

Fig. 2. Like onyx gem

**Edbertho Leal-Quiros, Ph.D.*
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Edbertho Leal-Quiros, PhD. *Dr. Edbertho Leal-Quiros has a B.S. in Physics from National University of Colombia (1973); M.S. in Physics, in Atomic Collisions, from National University of Colombia, Bogotá-Colombia (1976); a second M.S. in Plasma Physics from University of California Los Angeles (UCLA) (1986), and a Ph.D. in Nuclear Engineering from University of Missouri-Columbia (1989). He is well-known for his experience in research in plasma physics and its applications in Municipal Solid Waste, as well as research with Ultra Clean Coal-Plant Technology using plasma. He has been a university professor for more than 30 years, of Nuclear Engi-*

neering, Physics, Electrical, and Mechanical Engineering programs, teaching at universities of South America Colombia, Venezuela, United States, and Puerto Rico. He was for 9 years Director of Scientific Research and Development Department at Polytechnic University of Puerto Rico (PUPR) where he continue as Adjunct Professor. He developed and directed the Plasma Laboratory and the Laser and the Modern Physics Laboratories at PUPR. He participated in a research project for NASA in the PUPR Plasma Laboratory where materials to be used in the Solar Probe were tested.

He was for more than six year Nuclear Power Operations System Instructor of the engineers, managers and technical staff, at North Anna Nuclear Power Plant that has two PWR Reactors of about 1000 MW electrical power each. In addition, he has participated in several plasma experiments with the plasma group of National Research Laboratory (NRL) at Washington, D.C, and Los Alamos National laboratory. He has directed several projects and has been Principal Investigator (PI) and Co-PI of grants/projects for Department of Energy (DOE), Department of Defense (DOD), NASA, and National Science Foundation (NSF) in collaborations with several national laboratories and universities including University of Missouri-Colombia, University of Puerto Rico, and John Hopkins, among others. He has presented papers in multiple international meetings, in Plasma Physics Applications and Nuclear Science, and has authored more than 200 publications. At present he is the Vice-President of Engineering and Chief Scientist for Full Circle Energy in Fresno, California.

Thermoplastic Waste Processing into Alternative Liquid Fuels

Prof. B. Tymoshevskyy, Dr. M. Tkach, Dr. Y. Kharitonov
National University of Shipbuilding, Nikolaev, Ukraine

The scientific team of the National University of Shipbuilding and the R&D Company "Energy & Technology" have developed advanced technology for thermoplastic waste processing into liquid fuels. The primary raw material for processing is a mixture of unsorted thermoplastics. The results of processing are the following alternative fuels: gasoline, light diesel fuel and heavy diesel oil. A small amount of carbon black is the remainder. The latter is environmentally safe and can be used as admixture in asphalt for highways.

Fig. 1. Municipal Plastic waste

Fig. 2. Medical plastic waste

The experimental facility with a 300 kg per day capacity has been created in the Center for Advanced Energy Technology. It has passed a number of tests to obtain important technical and operational parameters. Ecological and environment protection data were determined as well.

Fig. 3. Experimental facility for thermoplastic waste processing into fuel

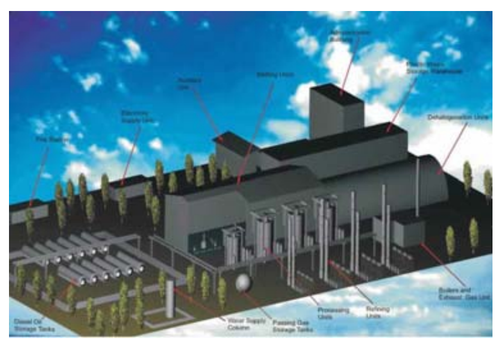

Fig. 4. General view processing plant capacity of 35.000 t/year

The main principle of this technology is a continuous and controlled thermo-cracking process without the use of air (oxygen). It results in the production of a complex organic liquid, which includes a mixture of a large fraction of light hydrocarbons. After distillation and rectification, gasoline and diesel oil can are produced. The technology can be adapted for producing mainly one of the named fuels, according to a product preference. Processing equipment does not require external or additional energy, except during the start-up period. A small amount of about 7-15% of produced fuel is used for the production of energy required for the process.

The approximate product's output in % of feedstock, depending on the tuning options, is given in the table below:

The process technology is environment friendly. The results of ecological, sanitary and hy-

	Gasoline	Light Diesel Oil	Heavy Diesel Oil	Process Supply	Hard Remainder
Version I	60	15	5	15	5
Version II	35	40	10	10	5
Version III	15	55	19	7	4

gienic measurements have shown, that the content of the harmful substances emitted do not exceed 30 % of the maximum permissible concentration in air in the area of operation .

Insignificant amounts of polluting exhaust from a system for chemical halogen removal and final exhaust gases will be treated by an advanced plasma technology system developed by Applied Plasma Technologies (APT) Corporation.

The project for the thermoplastic waste processing plant with feedstock capacity of 35,000 t/year is described.

The main advantages of the alternative fuels from the thermoplastic waste are the following:

- Ultra-low sulfur content
- Low heavy metals and paraffin content
- Low total contamination
- Good oxidation stability and copper strip corrosion
- Low cold filter plugging and cloud points

Average Main System Performance

1. Capacity of the Plastic Waste Processing, t/year	35.000
2. Gasoline, t/year	5250
3. Light diesel oil, t/year	19250
4. Heavy diesel oil, t/year	6650
5. Hard remainder, t/year	1400

The processing plant includes the following main units:

- Storage for thermoplastic waste.
- Preliminary treatment (cleaning and crushing) and transportation of the thermoplastic waste to the processing equipment;
- Melting and halogen removal from the mixture of the plastic waste, separation from the mineral, and organic (coke) additions;
- Thermo-cracking of the melted thermoplastic mixture and separation from the carbon black;
- Separation of the cracking products, condensing of liquid hydrocarbons into crude oil and extraction of the uncondensed hydrocarbon gases;
- Crude oil refining and fuel production;
- Fuel transportation and storage.

The main processing units are shown in the following photos.

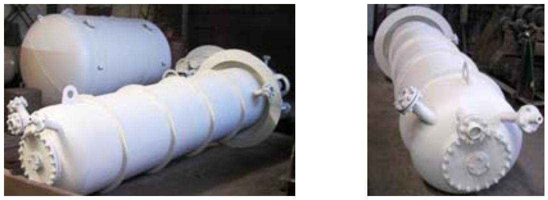

Fig. 5. Melting and halogen removal devices

Fig. 6. Thermo-cracker

Fig. 7. Deflegmer

Fig. 8. Condensers

Fig. 9. Filter

There are several methods for thermoplastic waste processing. The simplest one is uncompleted plastic waste processing where the output product is a form of crude oil. This crude oil can be transported to the petrochemical oil refineries for standard gasoline, diesel oil and heavy oil production. Another method is complete plastic waste processing where the end product products are gasoline, diesel oil and heavy oil. The third method is plastic waste processing into the diesel oil of wide fractional content. This fuel is not standard and cannot be used directly for low and mid power automotive engines, but its properties are sufficient for middle and large size stationary (electricity power station) and marine engines. A choice can be made depending on the specific product needs.

Prof. B. Tymoshevskyy

Dr. M. Tkach

Dr. Y. Kharitonov

Rubber Waste Processing into the Alternative Fuels

Prof. B. Tymoshevskyy, Dr. M. Tkach, Dr. Y. Kharitonov
National University of Shipbuilding, Nikolaev, Ukraine

Utilization of the rubber waste, including automotive tires, is one of one of the important problems in the world. Expert's estimation that 1 billion tons of the used automobile tires are currently stored in the world: Approximately 300 million tons in the US, 150 million tons in the EU and 2 million tons in the Ukraine. This waste is not processed and is a huge burden on environment.

Fig. 1. Used Tires near Farmer House in Ukraine

Fig. 2. Tires Fire in California

Simple burning of the rubber waste and electricity production is not cost effective and ecologically undesirable: The cost of power the cost of electricity from natural gas and coal by a factor of two. In the burning process huge amounts of carcinogenic substances such as furanes, chlorinated dioxins, phenyl-benzene, anthracene, fluorobenzene, fluoro-olefins, pyrenes and benzo-pyrenes are formed.

The mechanical or cryogenic crushing of rubber and automotive tires into small chips is expensive and their use for highway paving or other purposes is inefficient.

At the same time, rubber waste is raw material consisting of organic hydrocarbon polymers and can be processed by applying thermo-cracking technology. R&D shows that one of the best methods of rubber processing is controlled thermo-cracking. The resulting products of rubber waste processing are the following: Gasoline – 35%, light diesel oil – 10%, carbon black – 45%, flame cracking gases – 5% and metal scrap – 5%, approximately. Output products of the rubber waste processing vary and depend on temperature.

##	Products	400°C	500°C	600°C	700°C
1.	Pyrolysis gas	5,0	7,1	7,5	8,0
2.	Liquid hydrocarbons	32,0	47,8	50,6	52,6
3.	Solid (Carbon black + metal scrap)	61,5	43,9	40,9	38,6
4.	Losses	1,5	1,2	1,0	0,8

Rubber processing has special features. One of the most important is initial crushing. This process is energy intensive and decreases processing cost-efficiency. A better method is rubber waste decomposition into a liquid substance by a chemical solvent under special conditions. This solvent can be produced within the plastic waste processing at a low cost. Decomposed and dissolved in a special continuously operating facility rubber waste is then sent to a thermo-cracking reactor. This processing is energy and cost effective.

Rubber processing gases include the following at optimal treatment temperature:

##	Gases	Mass,%	##	Gases	Mass,%	##	Gases	Mass,%
1	Ethylene	5,2	6	Isoprene	0,6	11	Pentanes	0,3
2	Propylene	4,5	7	Methane	23,7	12	Hydrogen	35,1
3	Butylenes	3,8	8	Ethane	12,6	13	Carbon oxide	1,0
4	Pentene	0,4	9	Propane	4,2	14	Carbon dioxide	3,2
5	Divinyl	0,5	10	Butane	1,3	15	Caloric capacity, kJ/м^3	45100

These gases may be used as alternative fuel instead of natural gas in different industries and for municipal needs.

Alternative gasoline properties are as follows:

##	Indexes	Data
1	Octane index	76
2	Fraction content: Start temperature of refining, ^{o}C 10% recovered vol. ºC 50% recovered vol. ºC 90% recovered vol. ºC Finishing of gasoline boiling, ^{o}C Reminder in bomb, % Remainder and losses, %	 35 56 99 163 190 1,3 3,8
3	Pressure of the saturated vapors, kPa	68,0
4	Acidity, mg KOH for 100 cm^3	1,0
5	Concentration of tar, mg for 100 sm^3	3,0
6	Induction period, sec	1250
7	Sulfur content, %	0,005
8	Cooper plate test	OK
9	Water soluble acids and alkali content	No
10	Admixtures content	No
11	Water and sediments content	No
12	Density at 20^{o}C, kg/m^3	711
13	Caloric capacity, kJ/kg	45100

Alternative diesel oil properties are as follows:

##	Indexes	Data
1	Cetane index	45
2	Fraction content: 50% recovered vol. ºC 96% recovered vol. ºC	 270 350
3	Kinematics viscosity at 20ºC, cst	3,4
4	Temperature of freezing, ^{o}C	- 18
5	Flash point (PMCC), ^{o}C	43
6	Paraffin content, pct, weight (%)	2,7
7	Sulfur contents, pct weight (%)	1,1
10	Cooper plate test	OK
11	Water soluble acids and alkali content	No
12	Concentration of tar, mg for 100 sm^3	35
13	Acidity, mg KOH for 100 cm^3	4,5
14	Iodine number – g/ 100 g	4,5
15	Ash content in wt %	0,005
16	Coking, weight (%)	0,9
18	Admixtures content	No
19	Water and sediments content	No
20	Density at 20 ^{o}C, kg/m^3	810

The feasibility study for the rubber waste project, including automotive tires processing plant are described and a general view and facility layout are presented.

Fig. 3. General view of the rubber processing plant.

##	Indexes	Data
1.	Capacity, t/year	50.000
2.	Gasoline, t/year	17500
3.	Light diesel fuel, t/year	5000
4.	Carbon black, t/year	22500
5.	Passing gas,	2500
6.	Metal scrap, t/year	2500
Processing energy supply		
1.	Carbon black, t/year	15500
2.	Gasoline, t/year	1000
3.	Passing gas,	2500
Commercial output		
1.	Gasoline, t/year	16500
2.	Light diesel fuel, t/year	5000
3.	Carbon black, t/year	10000
4.	Metal scrap, t/year	2500

The rubber processing plant does not need an outside energy supply. All product gases and 73% of the carbon black could be used for a thermal power generating to facility.

Energy from Waste Using the Plasma Resource Recovery System (PRRS)

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PyroGenesis' Plasma Resource Recovery system (PRRS) can treat a wide array of waste types by combining gasification with vitrification. Vitrification produces inert slag that can be used as a construction material. Gasification produces a fuel gas containing carbon monoxide (CO) and hydrogen (H_2) that can be used for cogeneration of electricity and steam. In many cases, the electrical energy produced will exceed the energy required for the generation of the plasma. The PRRS can therefore produce clean energy while producing virtually no secondary waste.

The PRRS is a two step process that combines an electric arc furnace for vitrification of the inorganics and volatilization of the organics, and a plasma eductor for the gasification of the organics and syngas cleaning. The plasma-driven eductor is used to mix the raw syngas with air and steam and expose the highly reactive mixture to the extreme temperatures of plasma. In the eductor, the gasification reactions are completed within fractions of a second. This innovation allows the Plasma Resource Recovery System to be much more compact than most other thermal treatment alternatives.

The core technology of the PRRS, namely the plasma fired eductor (Figure 1), is presently being used commercially on shipboard systems. The shipboard system was developed in collaboration with the US Navy, is operating on a cruise ship since 2003, and is now in its final stages of design for installation onboard the next generation of US aircraft carriers.

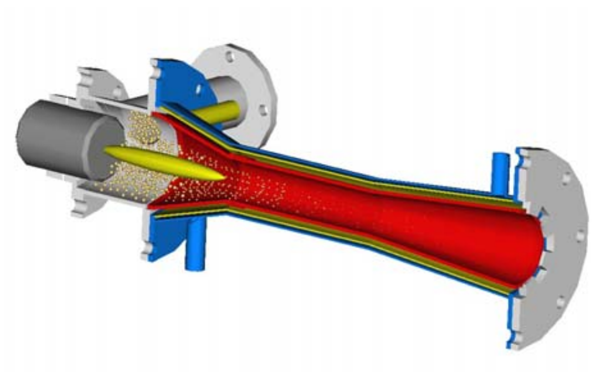

Fig. 1. Plasma Eductor

Fig. 2. PRRS Pilot Plant

The capabilities of the PRRS technology have been demonstrated in a pilot plant, at a rate of up to 2 TPD of waste. Pilot runs have demonstrated the PRRS' ability to convert various types of waste into syngas and inert slag, such as ASR (Automobile shredder residue), MSW (Municipal Solid Waste), and flammable hazardous waste.

Projections show that a system processing 240 TPD of MSW will produce 7 GJ of syngas energy or 700 kWh of electricity per tonne of waste fed to the system. For hazardous flammable waste, which has a much higher heating value, as much as 16 GJ of syngas energy could be produced per tonne of waste fed to the system.

Because of the high intensity of the plasma flame and the reduced amounts of gases produced in a gasification system, compared to traditional combustion systems, the PRR system is typically very compact. As such, the PRR technology opens the door for a decentralized, small scale approach to waste management.

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Plasma Applications to Utilization of Municipal Solid Waste for Energy: Pollution Control and Fuel Conversion

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We are currently exploring the possibility of adapting plasma technology to enable the clean and efficient utilization of municipal solid waste (MSW) for electrical-energy generation. Two issues are associated with this idea: 1) air pollution control from the burning of MSW-derived fuel and 2) the conversion of MSW-derived fuel into a form that can be used in gas-turbine-based electrical power generation.

To address the issues of exhaust-gas pollution control, we are examining concepts for implementing a novel non-thermal plasma technology (developed by the Los Alamos National Laboratory – LANL) to treat exhaust gas from boilers and burner-based power generation equipment that use MSW-derived fuel. To addresses the issue of conversion of MSW-derived fuel to gas-turbine feedstock fuel, we are examining an innovative plasma 'tornado' combustor (developed by Applied Plasma Technologies – APT) for finely-processed MSW-derived fuel conversion.

Cob Creations, LLC is adapting an innovative technology for processing municipal solid waste (MSW) into energy-rich fuel. In this technique, MSW is converted into briquettes and pellets, which can be burned in boilers or electrical power-generating stations or converted into feedstock for gas-turbine power-generation equipment.

This talk will provide an overview of the MSW-to-fuel process and will describe power-generation systems which can possibly utilize the non-thermal plasma pollution control technique and the plasma combustor for conversion of MSW-derived fuel to gas-turbine feedstock.

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Bituminous Coal Plasma Gasification

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The world's petroleum reserves are limited. Based on current global consumption, it has been estimated that this reserve will be depleted in approximately 40 to 60 years. Coal is worldwide the most abundant energy resource and the least expensive fossil fuel. In connection with this, the development of coal utilization technologies, which would be environmentally friendly and efficient, is of a primary importance. Plasma coal gasification is one of the most promising technologies for effective utilization of coal [1]. Plasma-steam gasification of coal enables the production of high quality synthesis gas designated for high-efficiency thermal power plants with steam-gas facilities, production of inexpensive methanol and hydrogen and use as a restorer instead of expensive metallurgical coke.

This paper represents thermodynamic and kinetic mathematical modeling for plasma gasification of a bituminous coal. First gasification of the mixtures of the coal with air and water steam was investigated numerically with the aid of code TERRA [1] validated for thermal equilibrium calculations. The calculations allowed optimizing of the mixtures and an acceptable content of an initial mixture for the process was found. Then the found mixture was investigated numerically using kinetic mathematical modeling with the aid of code Plasma-Coal [1]. Powder River Basin bituminous coal 6.8% of ash content, 5 % of moister and 29.9 % of volatile matter was used for the investigation. Software code TERRA has been developed to calculate high temperature processes. It has a database of thermodynamic properties for more than 3500 chemical compounds over a temperature range of 300 to 6,000 K. The database includes thermodynamic properties of organic and mineral components of hydrocarbon fuels. The calculations were performed over a range of temperatures (300-4,000K) and at a pressure of 0.1MPa. As a result of the optimization the following initial thermodynamic mixture was found: Coal is 1 part, air blown through the plasmatrons is 0.94 parts, and water steam (H_2O) is 0.75 parts. At this mixture processing the main part of the gaseous phase consists of synthesis gas ($CO+H_2$). At 2,000K, the carbon monoxide (CO) concentration is 39.6 vol.%, the hydrogen (H_2) concentration is 42.5 vol.%. Concentrations of oxidants CO_2 and H_2O are less than 0.1 vol.%. The nitrogen-containing compounds are basically molecular nitrogen (N_2) with a concentration of 16.9 vol.%. The concentration of NO_X is less then 0.1 vol.%, even at 4,000K. There are no sulphur oxides and the fuel sulphur is represented as oxygen-free compounds such as hydrogen sulphide (H_2S), and silicon sulphide (SiS). At temperatures of more than 1,650K in the gaseous phase, components of the mineral mass of coal appeared. They are silicon monoxide (SiO), SiS, aluminum (Al) etc. Thus this mixture is chosen for kinetic calculations with the aid of Plasma-Coal code [1].

The plasma vortex fuel reformer or gasifier is the subject for kinetic modeling. It is a cylinder with four plasma torches on the gasifier bottom plate. The plasma torches fulfill several functions, including fuel feeding, it's preheating by variable temperature, chemical reactivity and power plasma flow, and reagents mixing and distribution in the gasifier reaction zone. Total maximal electric arc power for short term operation could be up to 5 kW. The plasma torches work using air as plasma forming gas. Water in the form of steam for the coal gasification is supplied through special steam pipes in the upper part of the gasifier. Steam spreads along the wall of the gasifier down to the coal/air mixture input by way of the vortex effect. Slag produced during the coal gasification is withdrawn through ash crater below the plasma torches. From the thermodynamic calculations it was found that 5 kW is not enough for initialization of the gasification process. The coal/air/steam mixture is additionally heated with the aid of an inductive heater with 10 kW of electric power, which is installed in the first 0.1 m of the reformer. It is supposed that kinetic modeling could give the size of the reformer, temperatures, velocities and gas phase species concentrations along the experimental unit. To calculate the process of the coal gasification in this specified plasma vortex reformer a one dimensional mathematical model and a specially developed Plasma-Coal code for flow plasma reactors calculations was used.

The diameter of the gasifier is 0.073 m and its length is 0.3 m. The process of gasification has to be mainly completed in the gasifier volume. The products received in the gasifier are withdrawn through the pipe with the inner diameter of 0.05 m. Its length can vary. The average diameter of the coal particles was taken as 60 μm. The temperature of the coal particles on the inlet of the gasifier was 300 K and the water steam temperature was 423 K. The plasma gasifier efficiency was taken as 90%. In accordance with the thermodynamic investigation coal consumption through the reformer was taken as 7.668 kg/h, air rate was 7.2 kg/h, and steam rate was 5.76 kg/h. Table 1 summarise results of calculation on the outlet of the reformer (2 m).

Table 1. Results of calculations

H_2O	CO_2	CO	CH_4	C_6H_6	H_2	N_2	O_2
Vol.%							
5.09	5.0	34.64	0.37	0.31	35.15	19.43	0

Xc, %	Tg, K	Ts, K	Vr, m/s	Time, s	Gas heat power, kW
94.8	1090	1062	13.1	0.2	55.2

A 94.8 % carbon gasification (Xc) was achieved, at a 13.1 m/s of reagents velocity (Vr), 1,164 K gas temperature (Tg) and 1,109 K solids temperature (Ts), and a 69.8 vol.% synthesis gas yield. Time of reagent residence was 0.2 s and gas heat power was 55.2 kW.

On the base of the calculations a plasma vortex fuel reformer was designed and constructed.

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Thermal Efficiency of a Hybrid Type Plasma Reformation System

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Coal gasification offers one of the most versatile and clean ways to convert coal into hydrogen rich gas, electricity, and other energy forms. Plasma coal gasification looks like the best solution for portable and small to media-scale coal processing facilities.

Applied Plasma Technologies (APT) is developing a highly energy efficient, robust, durable, universal and an electrodeless, hybrid plasma reformation system mainly for waste remediation and coal gasification. This product will combine several key features such as an inductive type plasma torch, an innovative reverse vortex reactor and a non-equilibrium plasma pilot developed by APT as well as a plasma chemical reactor [1-4]. The scheme of a recently patented hybrid plasma reformation system is shown in Fig. 1 [5].

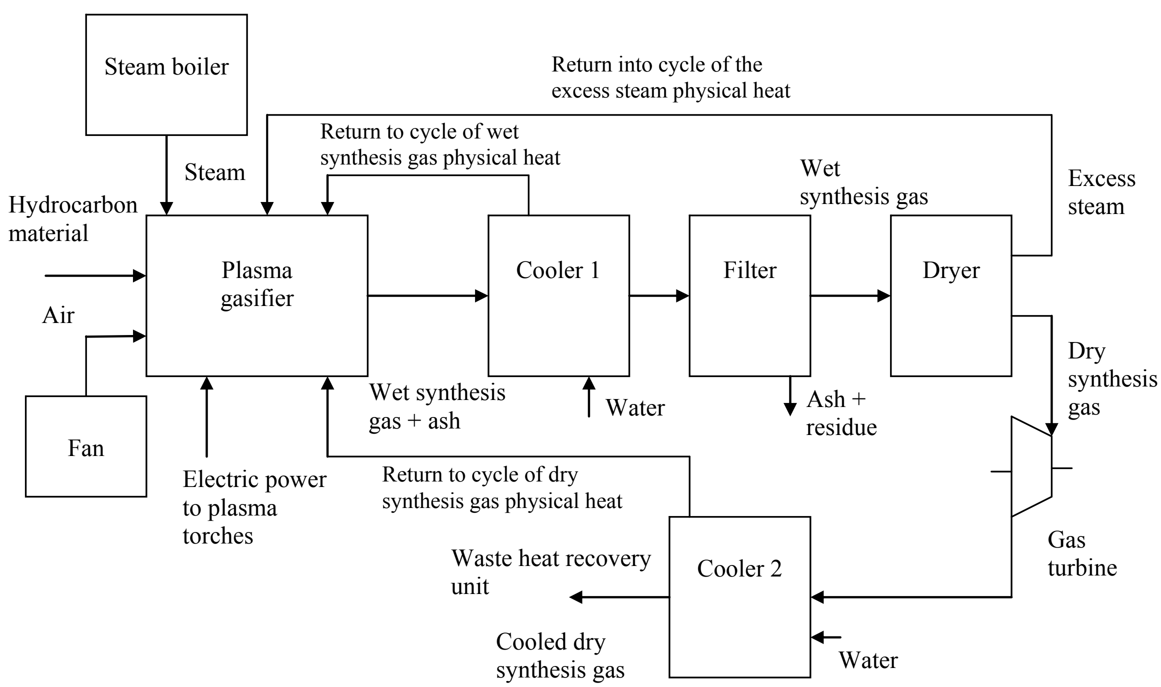

Fig. 1. Scheme of a hybrid plasma reformation system

The plasma gasifier consists of an inductive RF heater and a number of bottom placed high voltage DC plasma torches. These torches serve to initially ionize media inside the reactor and to feed fuel and additional reagents. The system will operate as a multi-mode, multi-purpose reactor in a wide range of plasma feedstock gases and turn down ratios, convenient and simultaneous feeding of several additional reagents, for example coal and air, into the discharge zone.

Heat admission (input) and rejection (output) balances are calculated for coal consumption of 7.668 kg/h, air consumption of 7.2 kg/h, and steam consumption of 5.76 kg/h for the bench-scale power plant and pressure in the gasifier of 0.1 MPa and are shown in Fig. 2. Here Q_{1in} is the potential gasified coal heat, Q_{2in} is the physical air heat, Q_{3in} is the heat for steam generation, Q_{4in} is the plasma torches power, Q_{1out} is the potential dry synthesis gas heat, Q_{2out} is the physical dry synthesis gas heat, Q_{3out} is the excess steam physical heat, Q_{4out} is the heat losses with ash and residue, Q_{5out} are the heat losses by balance difference. Calculations are carried out for Powder River basin bituminous coal. The calorific heat of gasified coal is 30.20 MJ/kg corresponding to heat power of 64.33 kW.

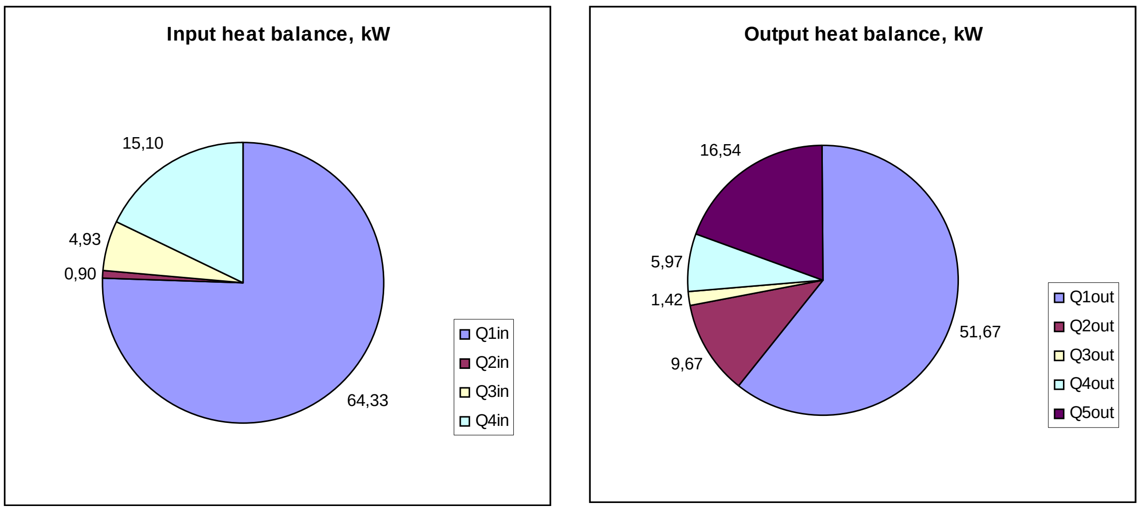

Fig. 2. Heat balances at system operating pressure 0.1 MPa

The heat power for water vapor generation and air compression is insignificant, 5.83 kW, in comparison with the total input heat power of 85.27 kW. Power consumption of the plasma devices is equal to 15.1 kW (17.7 %), i.e. this is more significant and assumes selection of the most efficient plasma torches.

For the selected working media the operating pressure inside the plasma gasifier does have a significant influence on the wet synthesis gas heat power. The averaged level of synthesis gas heat power for the investigated pressure range from 0.1 to 3.5 MPa is approximately 52.5 kW.

The gasification efficiency calculations for the above pressures in the reactor based on the fuel lower calorific value show achievable efficiency of 76-81 %, an efficiency of 57-61 % for the hybrid type plasma gas generation system, and a system efficiency of 60-70 % with internal heat recovery.

If steam consumption increases the synthesis gas temperature for constant plasma torch power of 15.1 kW decreases. When steam consumption decreases the oxygen deficiency for carbon gasification (both in air and vapor supplied to the reactor) results. The relative steam mass flow rate of 0.45-0.55 corresponds to a maximum efficiency for the plasma gasifier.

A hybrid plasma reformer could be suitable for mobile and autonomous small to mid-size coal gasification and hydrogen-rich gas generation systems as well as waste processing systems and plasma chemical reactors. Obtained refined synthesis gas can be efficiently used in internal combustion engines, gas turbines, boilers, fuel cells, etc.

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Igor B. Matveev *was born on February 11, 1954 in Russia. He received his Master of Science degree in mechanical engineering from the Nikolaev Shipbuilding Institute in 1977 and earned his Ph.D. degree in 1984. The Ph.D. theses were entitled "Development and Implementation of The Plasma Ignition Systems for Naval Gas Turbines". From 1977 to 1990 he was a researcher, teacher and associate professor of the Nikolaev Shipbuilding Institute. In 1990 established a privately owned company Plasmatechnika (Ukraine) for development and mass production of the plasma systems. From 2003 is with Applied Plasma Technologies (USA) as President & CEO. Over 1,200 plasma ignition and flame control systems, developed under his supervision are in operation worldwide.*

In 1989 has organized the first in the former Soviet Union conference on Plasma Ignition and Flame Control. From 2006 organizes annual International Workshop and Exhibition on Plasma Assisted Combustion. He is a guest editor for the IEEE Special Issue on Plasma Assisted Combustion from 2004.

Serhiy I. Serbin *was born on April 29, 1958, in Mykolayiv, Ukraine. He received the MS. (DipI. Mech. Eng.) and Ph.D. (Cand. Sc. Tech.) degrees in mechanical engineering from the Mykolayiv Ship-building Institute, Ukraine, in 1981 and 1985, respectively, and the Dipi. D. Sc. Tech. and DipI. Prof. degrees from the National University of Shipbuild-ing, Ukraine, in 1999 and 2002, respectively.*

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

Dr. Serbin is the real member (Academician) of Academy of Shipbuild-ing Sciences of Ukraine and International Academy of Maritime Sciences, Technologies and Innovations.

On-Board Fuel Reforming for Better Combustion and Exhaust Emissions in the Internal Combustion Engine

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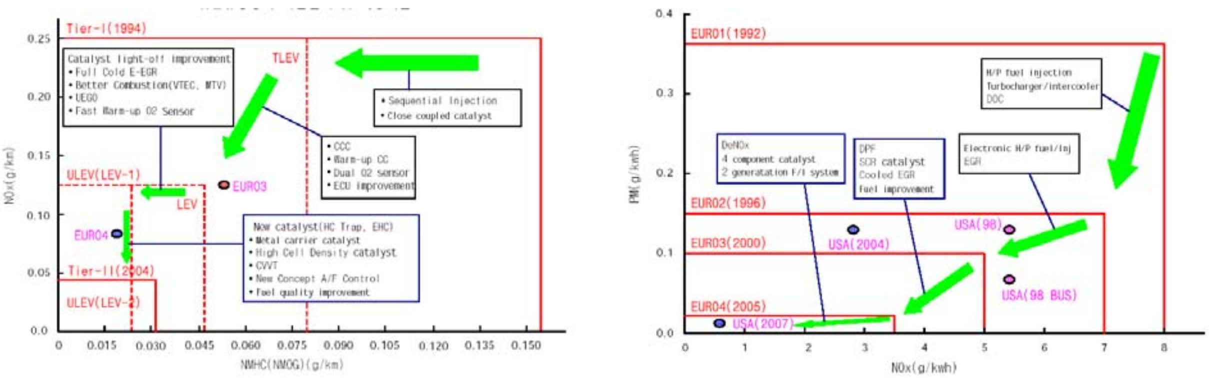
INTRODUCTION

Since German engineers invented internal combustion engine late 1800s, internal combustion engine has been the main power plant for transportation over more than 100 years. In recent decades, however, the internal combustion engine has been faced with several challenging problems which include stringent regulations of exhaust emissions (even zero emission requirements), market's demand for higher energy conversion efficiency (should compete with fuel cell), degraded fuel qualities, emerging alternative fuels such as bio-fuels, syngas, etc. New concept combustion technologies (i.e. ultra lean burn combustion, low temperature combustion, high EGR (Exhaust Gas Recirculation), HCCI (Homogeneous Charge Compression Ignition), etc) developed for reducing exhaust emissions and fuel consumptions have not been mass-produced yet because of combustion instabilities and combustion phasing control issues at highly lean operating conditions. Moreover, as renewable and alternative fuels are drawing attention due to high gas price and limited oil resource in more recent years, it is essential to develop clean and highly efficient combustion technology which ensures stable combustion irrespective of operating conditions and fuel qualities.

This report proposes new combustion technology in the internal combustion engine using the syngas generated by on-board plasma fuel reforming technology. The reformed fuel mainly composed of hydrogen and carbon monoxide has been made from the modification of the fuel composition using a reverse vortex reactor with spatial arc. The reformed fuel may affect initiation and propagation characteristics of the combustion in gasoline and diesel engine.

CHALLENGING ISSUES IN THE INTERNAL COMBUSTION ENGINE

Challenges in current internal combustion engine such as spark ignition or compression ignition engine are strict emission regulation and market demand for higher thermal efficiency. Figure 1 shows emission regulation for gasoline engine. Emission reduction of the internal combustion engine can be achieved via in-cylinder combustion control and after-treatment of exhaust emissions. In the gasoline engine, higher thermal efficiency is more important than the reduction of exhaust emission. Although target regulation for the future is zero emission in the gasoline engine, automakers have already developed ZLEV (Zero Level Emission Vehicle) where the emission level is almost nothing. However, the thermal efficiency of the gasoline engine is quite lower than that of the diesel engine or the fuel cell. Brake thermal efficiencies of the conventional gasoline engine range from 25% to 30% depending on engine operating conditions while the diesel engine has around 50% brake thermal efficiency. Low thermal efficiency of the gasoline engine is attributed to high pumping loss (due to throttling loss) and lower compression ratio (due to knocking). Although new combustion concept in the gasoline engine including ultra lean burn, high EGR, HCCI engines may have high thermal efficiency equivalent to diesel engine, combustion instabilities and phasing control problems make it difficult to apply in mass produced engine.



a) Gasoline engine *b) Heavy duty diesel engine*

Fig. 1. Emission regulation for gasoline engine and heavy duty diesel engine

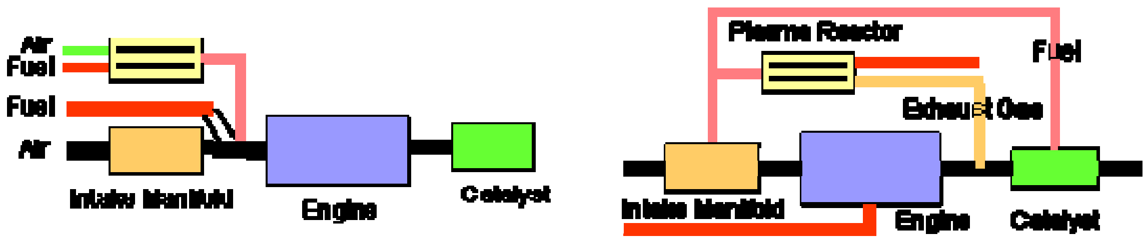
The diesel engine has a high thermal efficiency due to its non-premixed lean combustion and high compression ratio. Ironically, because of non-premixed lean combustion in the diesel engine it is hard to reduce the exhaust emission only using three-way catalyst as in the gasoline engine. Therefore, it is needed to install several exhaust catalysts (de-NOx catalyst, oxidation catalyst) and particulate filters to remove NOx, hydrocarbons, CO, and particulate emissions. Since increased number of after-treatments in the diesel engine caused increased costs, durability issues, and control issues, the best policy reducing exhaust emissions in the diesel engine is to prevent harmful gas emission from generating in the cylinder by using combustion control. However, combustion control in compression ignition engine is also a challenging problem.

Besides strict emission regulations, another challenging issue for the internal combustion engine is emerging diverse alternative fuels. Resources of fossil fuels are limited and world oil production would reach maximum within 10~20 years under current technology. For these reasons, we need a new energy source for the future and potential future fuels could be liquid or gaseous fuel. Alternative fuels are various sources of synthetic and bio-fuels including gaseous alternative fuels, hydrogen, natural gas, LPG, liquid fuels, etc. It is hard to say which fuel would become a main energy source for the future at this time, but it is clear that no single fuel would dominate since any single source of energy cannot substitute for current energy demand. Various fuel sources in the future are a big challenge for the internal combustion engine since combustion and emission of the engine is dependent on the fuel species.

ON-BOARD FUEL REFORMER IN THE INTERNAL COMBUSTION ENGINE

Hydrogen addition into the internal combustion engine is a promising technology to control combustion characteristics and reduce exhaust emissions. Since hydrogen has high flammability limit, fast laminar flame speed, and high mass diffusivity, it has been proved that small amount of hydrogen addition may have an important impact on the combustion. However, storing and refueling hydrogen with the conventional fuel is not realistic for passenger cars. Therefore, hydrogen generation using on-board fuel reforming technologies is an alternative option that can break through technical barriers in the internal combustion engine. In particular, plasma fuel reforming is a promising technology in on-board hydrogen generation since it is prompt, controllable, and energy efficient reaction. The reverse vortex plasma reactor developed by Applied Plasma Technologies, Inc., is promising as an on-board fuel reformer because of its compactness, high conversion efficiency, low power consumption, etc.

Figure 2a shows a simple schematic which can be applied in the internal combustion engine for on-board fuel reforming. The fuel has been inducted into the cylinder head via two different ways in the conventional internal combustion engine. One is port injection and the other is direct injection. Most of mass produced gasoline engine uses port injection even if recently direct injection gasoline engine has been developed for better fuel economy. Current diesel engine uses direct injection for better thermal efficiency. Reformed fuels can be inducted into the cylinder through three different paths: intake port, exhaust recirculation line, direct cylinder injection. Figure 2b only presents former two ways, i.e., via intake port and exhaust recirculation line.



a) Reformed fuel in the intake port *b) Reformed fuel in exhaust recirculation*

Fig. 2. The schematic for on-board fuel reforming applied in Intake port and exhaust recirculation

Direct injection of the reformed fuel into the cylinder needs a high pressure pump to pressurize reformed gases.

TECHNICAL BARRIERS ON THE ON-BOARD FUEL REFORMER

Although plasma fuel reforming is a promising technology which may break through technical barriers in the internal combustion, it has also drawbacks and technical barriers. Plasma fuel reforming generates hydrogen and carbon monoxide by partial oxidation of the conventional fuel using electrical discharges. Thus, the loss of low heating values of the fuel is indispensable and plasma reaction for fuel reforming needs a power for electrical discharge. Moreover, direct injection of the reformed fuel means an additional parasitic loss. In addition to the power loss for plasma fuel reformer, it is needed to study the effect of the reformed fuel species on the combustion of gasoline, diesel and other alternative fuels.

CONCLUSION

Although on-board plasma fuel reformer is a promising technology to breakthrough technical barriers in current internal combustion engine, it should be evaluated based on energy balance between the energy requirement of the reformer and the saved energy. In addition to the energy balance, the effect of reformed fuels on the combustion characteristics should be investigated thoroughly to evaluate the feasibility of the plasma fuel reformer.

Plasma Production of Hydrogen-Enriched Gases From Ethanol

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Until today very great advances have been made in the search for alternative biofuels (biomass-derived liquid fuels, synthesis gas, etc) which can replace traditional fossil fuels, petrol and natural gas. However, the main question is the quality of biofuels [1]. Thus, well-known ethanol has a number of limitations including relatively low specific heat of combustion and poor storage properties due to high volatility and water absorption. Therefore, it is very timely topic to investigate the methods for the reformation of biofuels with the aim of enhancing their combustion efficiency.

From the physics and chemistry of fuel combustion it is known that addition of highly inflammable light components improves the combustion of heavy oil fuels [2]. One of the promising approaches is to use the plasma reformation of heavy hydrocarbons, which permits the production of free hydrogen (H_2), carbon oxide (CO), acetylene (C_2H_2) and other fractions. For plasma reforming various methods using thermal and non-thermal plasma are known [3-7]. This work is related to the new method of the plasma reforming of ethanol using the electric discharge in the gas channel with a liquid wall [8, 9]. The process of production of the hydrogen enriched gases in this plasma system was studied and the energy efficiency of the plasma conversion of ethanol into the synthesis gas was compared with other known plasma-fuel reforming methods. Although there is some more work needed before such technology can be made commercially viable, this new plasma-fuel reforming process looks promising.

Fig. 1 shows the scheme of the plasma reactor used to produce the electric discharge in the liquid fuel. The DC discharge burned in the gas channel formed by two counterflow air streams in the liquid ethanol between copper electrodes. The photo of the reactor is given in Fig. 2.

Two modes of the discharge burning were investigated with the constant airflow ($G \neq 0$) and without airflow ($G = 0$), i.e. flow was stopped after the discharge initiation. Figs. 3-4 demonstrate the stable plasma column in the central part of the gas channel.

The optical emission spectroscopy (UV-VIS-NIR 3648-pixel-CCD optical multichannel analyzer SL-40) was used for diagnostics of the gas-liquid discharge plasma in the reactor. The mass-spectrometry (monopoly mass-spectrometer MX 7301) and gas chromatography (6890 N Agilent) was used for determination of the output gas-phase products of the ethanol conversion. The data of chromatographic analysis for both modes of the discharge burning are given Table 1.

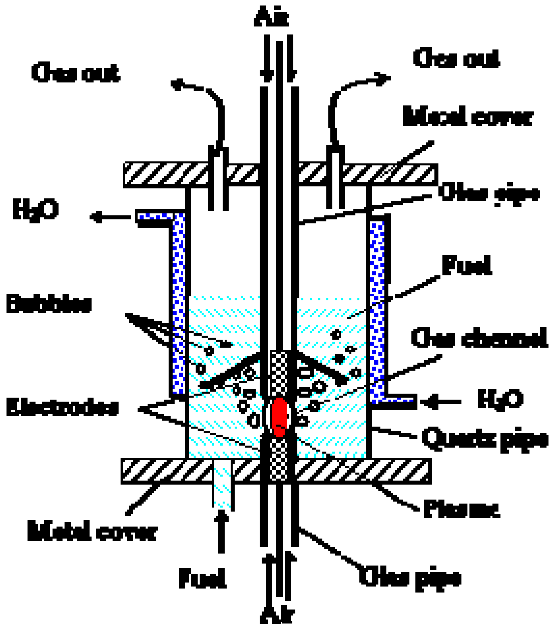

Fig. 1. Plasma reactor design

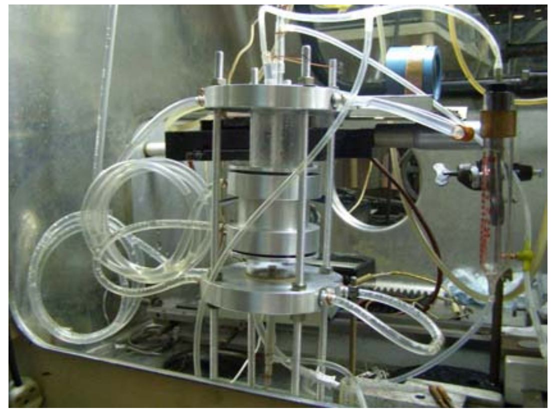

Fig. 2. Photo of plasma reactor

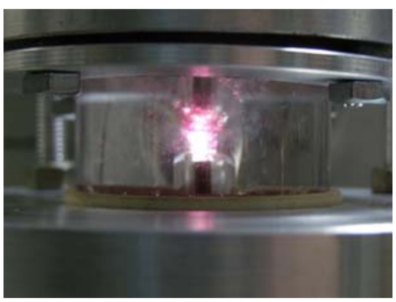

Fig. 3. Discharge pictures at constant flow of air in water

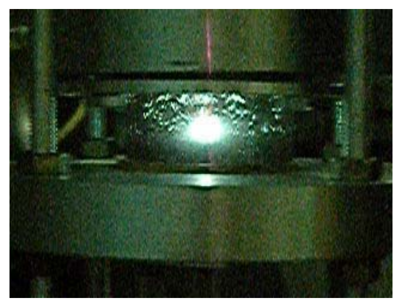

Fig. 4. Discharge pictures at constant flow of air in ethanol

Table 1

I=200 mA	Gas-phase products of conversion (%)										
	H_2	O_2	N_2	CO	CH_4	CO_2	C_2H_4	C_2H_6	H_2O	C_2H_5OH	C_2H_2
G=38 cm^3/s	5.92	14.48	64.64	5.16	1.37	2.26	0.99	0.56	1.85	2.09	0.68
G = 0	40.38	12.48	18.0	14.48	5.7	1.00	2.3	2.62	2,08	0.28	0.68

The estimation of the conversion efficiency of liquid ethanol by electric discharge plasma in the gas channel with a liquid wall and other known methods of plasma-fuel conversion: high-voltage discharge (HMTI, Belarus), arc plasmatron (MIT, USA), GARC (Chosun University, Korea), and Tornado (Drexel Plasma Institute, USA) was conducted on the basis of thermochemical calculations: (1) conversion efficiency of one cubic meter of syngas and hydrogen; (2) productivity of conversion; and (3) total output power of combustion of one cubic meter of syngas. These calculations were made taking into account thermochemical constants of hydrocarbons [10] and experimental data available in the literature [3-7]. Comparison of results of our calculations (*) and experimental data are presented in Table 2.

Table 2

	IHMT, Belarus [4]	**Chosun University, Korea [5]**	**Drexel Plasma Institute, USA [3]**	**MIT, USA [7]**	**KNU, Ukraine (this work)**
Initial fuel mixture	CH_4 + H_2O	C_3H_8 + CO_2 + H_2O	CH_4 + 1/2 (O_2 + 3.76 N_2)	Diesel	C_2H_5OH + 0,22H_2O + y(O_2 + 3.76 N_2)
Electric power, kW	2	1.37	0.5¸10*	0.2	0.1
Conversion efficiency kWh/m^3, Syngas	-	2.28*	0.06	0.17*	~1.5
Conversion efficiency kWh/m^3, H_2	≤ 3	4.09*	-	2.19*	-
Productivity H_2, m^3/h	0.48*	0.26*	-	0.091*	-
Productivity syngas, m^3/h	-	0.60*	-	1.2*	0.1
Output syngas power, kWh /m^3	-	4.2*	2.9*	4.71*	5.3*

Fig. 5 and 6 shows the conversion efficiency of one m^3 of syngas in the discharge in the gas channel with ethanol wall.

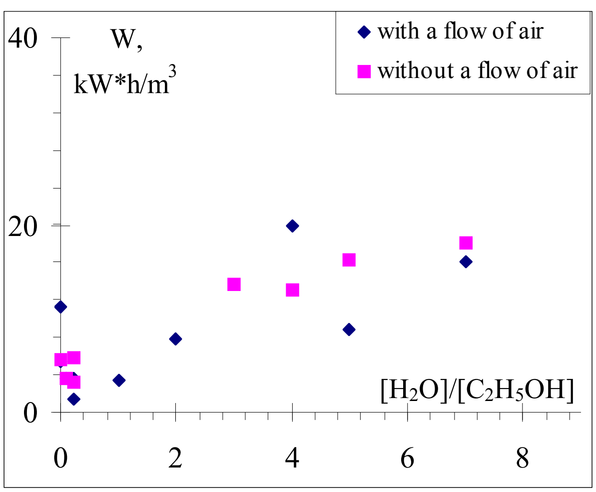

Fig. 5. Conversion efficiency of one m^3 of syngas. G=55 cm^3/s; I=200 mA

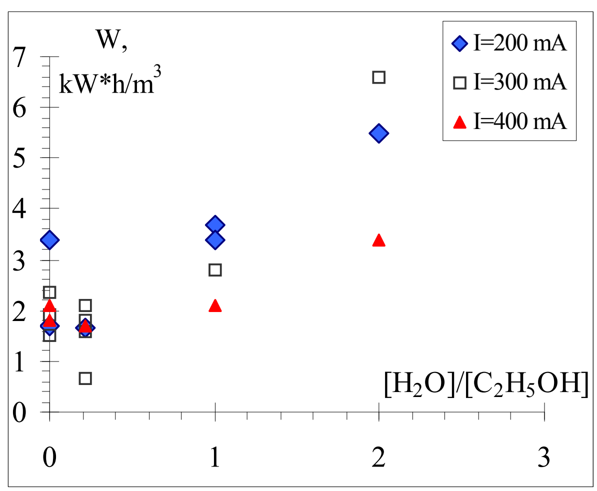

Fig. 6. Conversion efficiency of one m^3 of syngas. G=83 cm^3/s; I=200, 300, 400 mA

Our study has shown that:

1.The main stable gas-phase components in the outlet of the plasma reactor under the ethanol conversion are H_2, CO, CH_4, C_2H_4, C_2H_6, and H_2 content increases with increasing of electric discharge power.

2.The composition of gas-phase products of conversion and the power inputs on conversion of ethanol into syngas in the discharge in the gas channel with a liquid wall depend on the gas that forms the plasma channel.

3.The minimal value of power inputs in the investigated discharge modes is ~1,5 kWh/m^3 of syngas at the output syngas power ~ 5 kWh /m^3 that specifies possibility of this method.

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CO_x-free Hydrogen Production by Combination of Plasma Reforming and Cyclic Water Gas Shift Technologies for the Fuel Cells Application

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Fuel cell energy systems have attention due to their high efficiency and zero-emission. According to the operation temperature, fuel cells can be divided into different groups. The low-temperature fuel cells, such as proton exchange membrane and alkali fuel cell operates at temperatures from 343 to 363K and from 343 to 473 K, respectively, and high-temperature fuel cells, such as melting carbonate fuel cell and solid oxide fuel cell operates at temperatures from 923 to 973K and from 1073 to 1273 K, respectively. Proton exchange membrane and solid oxide fuel cell in the stationary power units are the most promising approaches to convert chemical energy to electrical energy. The ideal fuel for the fuel cell is hydrogen, which can be produced from different resources.

Within the next 20 years, the production amount of oil and natural gas are expected to decrease and in the future their cost will increase continuously. Renewable energy sources will not be able to cover the total energy demand in the world: some countries will replace oil and natural gas with nuclear energy, some others with coal. Coal reserves are larger than oil and gas reserves together and coal can give some time for our civilization to accommodate to the post-fossil fuel world and to fully develop renewable sources or nuclear power.

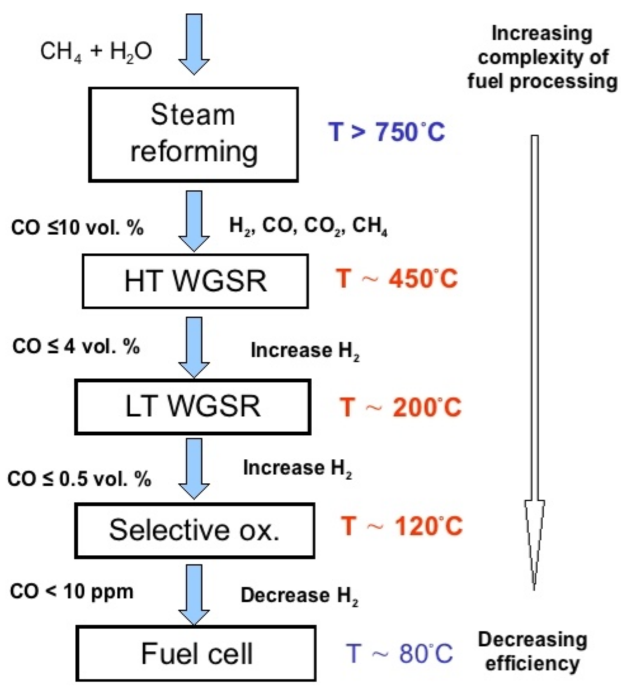


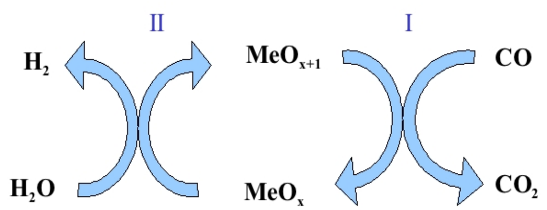
Fig. 1. Simplistic schematic of the methane steam

Coal is the fossil fuel with the highest content of carbon and therefore it is crucial to increase the conversion efficiency and make zero-emission coal technology. Among the renewable fuels the most promising sources of hydrogen are vegetable oils and glycerol. Glycerol is a byproduct in the production of biodiesel by transesterification of vegetable oils. Therefore the increase of biodiesel production results in the accumulation of glycerol, which leads to a price decline. Those sources are particularly attractive because the overall production of the inevitable by-product, CO2, is near zero (since most of the CO2 released would be of biological origin and is thus expected to be recycled in the eco-system).

There exists currently a variety of different gasification technologies. One of most promising one is the coal plasma gasification. The arc plasma can speed up the chemical reactions substantially and initiate some reactions which, otherwise, are difficult to carry out under normal conditions. It is well known that coal, when processed under plasma conditions, can produce hydrogen and carbon monoxide with high yield.

However, for PEMFC, which is the most potential fuel cell, the gasification product CO is a strong poison even when its concentration is as low as 20 ppm. The complete removal of CO to the range of some ppm by two step water gas shift reaction and by preferential oxidation is complex, bulky and expensive (Fig. 1). These drawbacks remain a serious technological obstacle in the practical utilization of these processes.

As an promising alternative to these conventional CO cleaning technologies is the metal oxide redox cycle. This process has been developed to produce hydrogen with a quality that exceeds the requirements of all types of fuel cells and it has recently obtained an increasing attention. This two-phase process can be performed in one single reactor without any post-processing of the gas, such as water gas shift and/or preferential oxidation. The technology is based on periodic reduction/re-oxidation cycles of metal oxides (see Fig. 2). During the first step, gaseous hydrocarbon or syngas reduces the metal oxide to metal. During the second step (metal re-oxidation), steam is used as oxidizing agent for metal, simultaneously producing hydrogen. The produced gas consists of steam and CO free hydrogen which can be directly supplied to PEMFC.



phase I: $MeO_{x+1} + CO \rightarrow CO_2 + MeO_x$ exothermic

phase II: $MeO_x + H_2O \rightarrow H_2 + MeO_{x+1}$ endothermic

Overall : $CO + H_2O \rightarrow H_2 + CO_2$ $\Delta H = -41$ kJ/mol

Fig. 2. Schematic diagram of the novel process for the hydrogen purification by cyclic water gas shift reaction

The purpose in this presentation is to give results of the hydrogen production from solid and liquid fuels (coal, glycerol and vegetable oil) by combination of plasma reforming technology with CWGS reaction for COx-free hydrogen production for different type of fuel cells.

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Scientific interests: *development and investigation of catalysts and catalytic processes, including those for conversion and storage of various kinds of energy, catalysis and photocatalysis in nature and in applications of renewable and non-traditional energy sources.*

Fuel Reforming Using Dielectric Barrier Discharge and Micro-Cavity Plasma Array and Reformed Fuel Effects on BUNSEN Flame

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Sungjin Park, James G. Eden
University of Illinois at Urbana-Champaign, USA

INTRODUCTION

In recent decades the internal combustion engine has been faced with several challenging problems that include stringent regulations of exhaust emissions, market's demand for higher energy conversion efficiency, degraded fuel qualities, emerging alternative fuels such as bio-fuels, syngas, etc. New concept combustion technologies (ultra lean burn combustion, high EGR, low temperature combustion, etc) have been developed to reduce exhaust emissions and fuel consumptions. However, combustion instabilities and combustion phasing control issues at highly lean operating conditions make it difficult to apply into mass production.

Hydrogen is one of the promising future fuel candidates for internal combustion engine since it has high flammability limit, fast laminar flame speed, and high mass diffusivity. In particular, since ideal combustion of hydrogen generates only water, hydrogen can alleviate global warming effect of IC engine combustion. However, hydrogen also has weak points to become a main transportation fuel due to abnormal combustion (premature combustion, backfire, etc), low energy density (per volume), difficulties in storing and delivery on board, etc. Hydrogen addition into conventional fueled IC engine is another approach to control combustion characteristics and it has been proved in many experiments and simulations that small amounts of hydrogen addition can dramatically change the combustion characteristics via extending flammability limit and increasing flame speed. Thus, various on-board fuel reforming technologies have been proposed and reported to generate hydrogen from conventional transportation fuel due to difficulties, risks, and inconvenience in storing and refueling hydrogen gas. Hydrogen can be generated on-board using three different ways: steam reforming (SR), thermal reforming (TR), and plasma reforming (PR). Hydrogen generation using steam reforming is conventional method and the reaction scheme is as follows.

$$\begin{aligned} &C_nH_m + H_2O \rightarrow nCO + (n + m/2)H_2 \\ &CO + H_2O \leftrightarrow CO_2 + H_2 \end{aligned} \tag{1}$$

Thermal reforming generates hydrogen via partial oxidation reaction shown in Equation 2 and exhaust gas heat is mainly used for the reaction.

$$\begin{aligned} &C_mH_n + m/2(O_2 + 3.773N_2) \\ &\rightarrow mCO + n/2H_2 + m/2(3.773N_2) \end{aligned} \tag{2}$$

Reforming processes in SR and TR are dependent on exhaust gas temperature and so, at cold state the fuel reforming efficiency becomes low. Moreover, steam reforming generates CO_2 that causes global warming and delays combustion speed.

Plasma fuel reforming generates synthetic gas using electrical discharge and is prompt, controllable, and energy efficient reaction for fuel reforming. This report uses dielectric barrier discharge (DBD) and micro-cavity plasma array to generate hydrogen and low hydrocarbon fuel species by reforming methane and propane. DBD can possibly be tailored to favor specific reaction pathways in a chemical processing system owing to its non-equilibrium nature. Micro-cavity plasma arrays recently fabricated by Dr. Eden's group in university of Illinois can be operated continuously at high gas pressures with high power loading exceeding 100kW/cm^3. Since gas discharges confined in micro-cavity has high electron densities (10^{13} ~10^{16} cm^{-3}) and highly uniform non-equilibrium characteristics and can be fabricated with low cost and various device structure forms, micro-cavity plasma array can be a good fuel reformer. This letter reports the fuel reforming characteristics of DBD and micro-cavity plasma arrays and shows reformed fuel effects on BUNSEN burner flame.

TEST SETUP

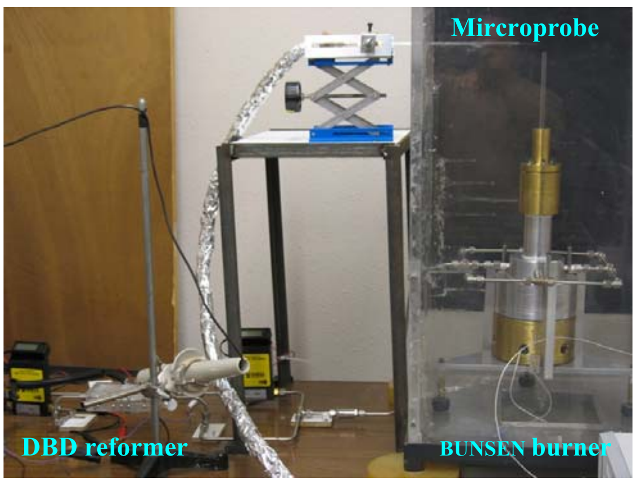


Fig. 1. Fuel reformer and BUNSEN burner

Figure 1 represents test setup for DBD fuel reformer and flame experiment. Methane and Propane reformed at DBD reactor are premixed with air and supplied into BUNSEN burner. DBD reactor is composed of dielectric barrier (alumina plate) and electrodes and is powered by sinusoidal voltage. Reformed fuel species are sampled via microprobe and analyzed at gas chromatography that has 4 channels TCD (Thermal Conductivity Detector). Figure 2 shows the schematic of micro-cavity plasma array applied as a fuel reformer in this report. Figure 3 shows the real reformer sample fabricated using micro-cavity array.

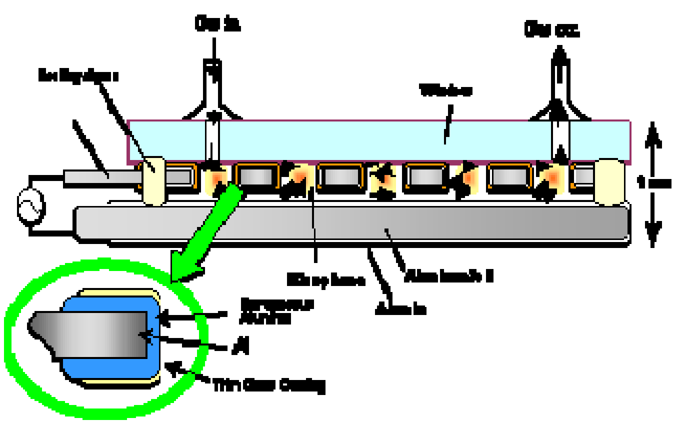


Fig. 2. Micro-cavity discharge array for fuel reforming

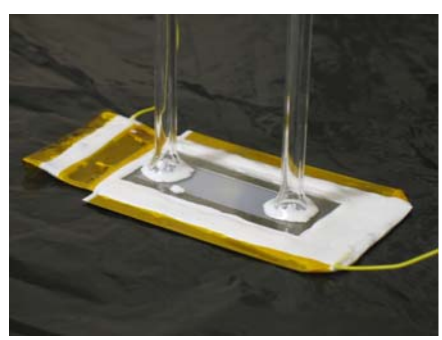


Fig. 3. Fuel reformer using micro-cavity array plasma

TEST RESULT

Figures 4 and 5 present the measured fuel species of reformed fuel using DBD at different power input. The flow rate of methane and propane was set to 0.3 l/min.

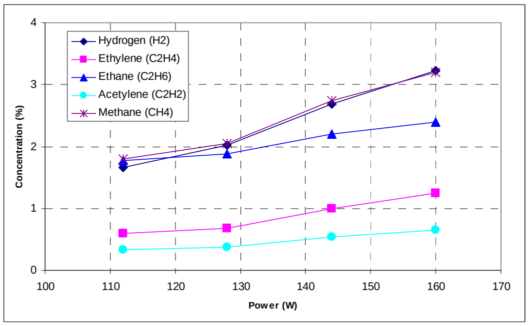


Fig. 4. Reformed fuel species from methane conversion

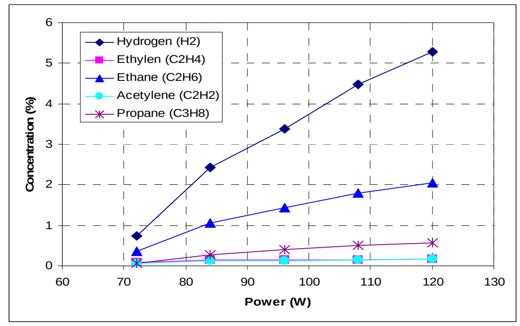
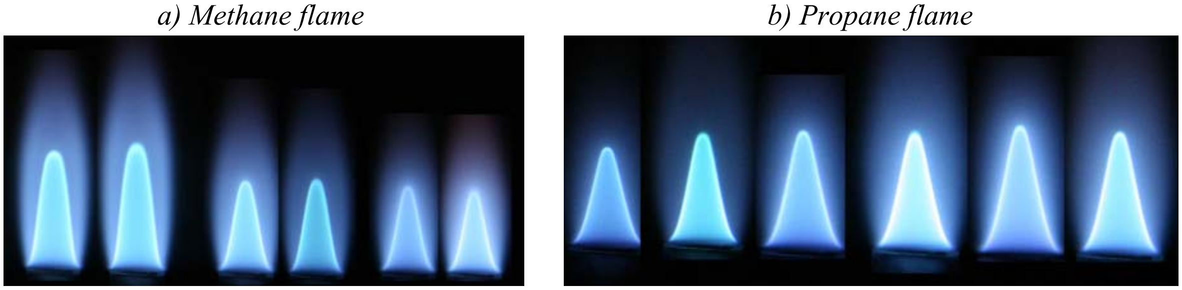


Fig. 5. Reformed fuel species from propane conversion

Hydrogen and ethane are main species generated from methane and propane fuel reforming using DBD. Small amount of acetylene and ethylene are also generated from DBD reactor. Figures 6 shows BUNSEN burner flame structure at different equivalence ratio when using reformed fuel. Equivalence ratio (Φ) 1 represents the stoichiometric air fuel ratio, equivalence ratio greater than 1 means rich and less than 1 is lean. Left flame at each equivalence ratio represents the base flame using pure methane or propane and the right indicates reformed fueled flame. As shown in Figure 6, the reformed fuel makes the flame longer at rich air fuel ratio and at stoichiometric and lean condition BUNSEN flame of reformed fuel is almost same with that of base fuel. CHEMKIN 4.1 is used to analyze the effect of reformed fuel on BUNSEN flame.

a) Methane flame *b) Propane flame*



Φ=1.2 *Φ=1.0* *Φ=0.95* *Φ= 1.1* *Φ=1.0* *Φ= 0.95*

Fig. 6. BUNSEN flame structure at different equivalence ratio

CONCLUSION

DBD and micro-cavity array plasma have been applied to reform methane and propane. The reformed fuel has more impact on the BUNSEN flame at rich flame rather than at stoichiometric and lean flame.

Decomposition of Ethane in Atmospheric-Pressure Dielectric Barrier Discharges: Model

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Our earlier work in the field of plasma-assisted combustion has demonstrated that dielectric-barrier discharge (DBD)-driven non-thermal plasmas (NTPs) can increase flame speed and extend the combustion of hydrocarbon fuel gases into very lean-burn regimes [1-4]. In this talk, we will present plasma-chemistry modeling results on the decomposition of ethane (C_2H_6) by DBDs at atmospheric pressure. Ethane was chosen for this study because its gaseous electronics properties (electron-impact dissociation cross-sections, drift velocity) are available in the literature. An earlier paper discussed experimental results on the DBD-driven plasma decomposition products of ethane and their estimated yields [5]. In this talk, we present results on calculations carried out to determine the electron energy distribution function, electron transport coefficients, the decomposition products, and their respective energy yields for pure ethane, as excited by a near-atmospheric pressure DBD plasma. The major stable decomposition products, as measured in earlier experiments were H_2, CH_4, C_2H_2, and C_2H_4. In this talk, the calculated results will be compared to the measurements favorable reaction pathways will be discussed. These results are important in assessing the possibility of using NTPs to enhance the combustion of hydrocarbons.

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Temperature Effects on Gaseous Fuel Cracking Studies Using a Dielectric Barrier Discharge

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Fuel cracking using a plasma is one of the methods to enhance combustion by forming lighter hydrocarbons and hydrogen from heavier ones. Lighter hydrocarbons and hydrogen will burn more efficiently and thus more energy can be extracted from the fuel.

Fuel cracking is accomplished at Los Alamos National Laboratory (LANL) by using an annular dielectric barrier discharge (DBD, also called a silent electrical discharge) [1]. This forms a non-thermal plasma between the barrier (a glass tube) and the central electrode, which is typically charged to 5-10 kV. Electrons gain most of the energy input and initiate gaseous fuel cracking. Associated fuel fragments and radical species further crack the fuel. The DBD reactor is run with an AC input waveform at hundreds of hertz. Current and voltage are measured from the reactor and used to calculate the reactor power, which is typically on the order of a few watts. Gas samples are collected from the DBD reactor and analyzed using a Gas Chromatography system.

Thus far, experiments at LANL have been performed at ambient temperature and pressure for Los Alamos [2]. However, certain radical-forming reactions should have enhanced reaction rates at higher temperatures than the ambient case. Consequently, higher temperatures should enhance fuel cracking. The results of temperature increases on the concentration of H_2 (hydrogen), CH_4 (methane), C_2H_2 (acetylene), C_2H_4 (ethylene), C_2H_6 (ethane), and C_3H_6 (propylene) from a C_3H_8 (propane) parent gas will be presented.

Recent experiments at Southwest Research Institute have shown that even a 1 % concentration of hydrogen mixed with gasoline greatly enhances spark ignited engine stability [3]. It is interesting to see if small amounts of oxygen can promote fuel cracking of propane, and thus also enhance combustion. The primary purpose of this oxygen addition is to promote formation of lighter hydrocarbons and not to produce hydrogen primarily. Reaction kinetics suggest that even small amounts of oxygen will promote formation of HO_2 and OH radicals. These radicals should eventually form stable products such as C_2H_5CHO (propionaldehyde), CH_2O (formaldehyde), and H_2O_2 (hydrogen peroxide), all having high energy contents and masses lighter than the propane parent gas. Influences of oxygen on gaseous fuel cracking will be discussed at the presentation.

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Carbon Gasification in Hydrogen Dielectric Barrier Plasmas

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A Zero Emission Coal (ZEC) technology which converts coal into gaseous fuels without CO_2 emissions has been proposed by Los Alamos National Laboratory in collaboration with Louisiana State University [1]. A challenge faced by the ZEC technology is carrying out the hydrogasification reaction ($C + 2H_2$ à CH_4) under a reasonable set of conditions. Although the hydrogasification reaction is exothermic and is thermodynamically favored at ambient conditions, its kinetics are far too slow to be useful. Ideally one could use catalysts to enhance the kinetics of the hydrogasification reaction, thereby reducing the required temperatures and pressures, but the conventional catalysts rapidly degrade in hostile environment of coal gasification (abrasion, sulfur poisoning, relatively high temperatures, etc.). Without catalysts, high pressure process has been practiced to increase the speed of the reaction. However, an innovative technology is still needed to improve the hydrogasification reaction.

We have attempted to increase the reaction speed through the use of a plasma in a catalytic role, where a plasma turns hydrogen molecules into highly reactive hydrogen free radicals and excited species, which are believed to promote hydrogasification reactions by lowing an activation energy required [2]. A dielectric barrier discharge (DBD) has been developed in the mixtures of hydrogen and carbon powders in order to study the hydrogasification of carbon. The hydrogen gas (no plasma) produced no methane at all temperatures; however, the 10 W hydrogen plasma produced varying concentrations of methane as the system temperature increased to 400 °C. After 500 °C, methane production decreased. Nonthermal plasma effects on the carbon hydrogasification will be discussed at the presentation.

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Plasma Ignition System for Internal Combustion Engines "Plasma Drive"

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Plasmatronics has created a thermal plasma ignition system for internal combustion engines called the Plasma Drive Ignition® system (PDI). The output waveform of the PDI is 22 nS in duration with a rise time from zero to 30 KV of 2 nS. The power consumption profile ramps linearly from zero to 19 Amps at 14 VDC over a 1.55 mS duration for each cycle of the PDI.

The relatively low power consumption of the PDI lends it for use in a direct ignition system engine. Experiments were conducted that replaced the coil over spark plug ignition coil found on direct ignition engines with PDI units. Conventional "J" style spark plugs were replaced with surface air gap spark plugs. Road and laboratory tests revealed fuel consumption was reduced by as much as 22%.

Increasingly, engine makers are employing misfire detection circuits built into the ignition coil and the engine computer that controls the ignition coils. These sophisticated engine controllers interpret the installation of any aftermarket ignition coil as a defect and so display the check engine light on the dashboard of the vehicle and record the defect for engine scanner retrieval. In some cases, the engine controller will even shut down the corresponding fuel injector.

In order to allow the installation of the PDI without generating a check engine condition, feedback circuitry was developed that mimics the feedback created by conventional ignition systems. This PDI feedback system employs a proprietary misfire detection system so that the PDI can provide true misfire detection to the engine controller. Since different engine manufactures use different feedback designs, a PDI feedback system is being developed for each one. As of this writing, PDI units compatible with most GM and Ford engines have been created.

Fig. 1. PDI units with misfire detection feedback mounted on a late model GM vehicle.

Fig. 2. Multiple streamers produced by the PDI.

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Transient Plasma Discharge Ignition for Internal Combustion Engines

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The use of non-thermal transient plasma ignition (TPI) as an alternative to the conventional spark ignition method for internal combustion engines was studied. Previous studies in static combustion chambers showed that ignition delays and pressure rise times were shorter by typically a factor of 3 with TPI compared to conventional spark ignition. Consequently, the performance of TPI and conventional spark ignition were compared in a 2.5 liter 4-cylinder engine under identical operating conditions and using natural gas and liquid fuel. Three main parameters, namely RPM, intake manifold pressure and air/fuel ratio, were controlled. An interface was developed using Labview to automatically control the engine, and record data from sensors. Results showed typically 15 - 20% increase in indicated mean effective pressure (IMEP) and shorter burning duration for TPI at the same operating conditions. Moreover, the tradeoff between thermal efficiency and brake specific NO_x emissions was found to improve with TPI. These benefits were shown to be a result of geometrical advantages of TPI (multiple ignition sites) and possibly inherent chemical effects. It is proposed that these advantages of TPI may be exploited by either using leaner fuel-air ratios or designing engines with lower turbulence levels, leading to reduction in heat loss to cylinder walls, thus increasing thermal efficiency, and taking advantage of TPI to obtain sufficiently rapid burning in low-turbulence engines.

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Combustion of Lean Gaseous Fuel Mixture Stimulated by a Microwave Discharge

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This research is devoted to studies of combustion in low-speed flow of previously prepared air-propane mixture initiated by a microwave (MW) undercritical discharge attached to a sharp end of an electromagnetic initiator. Earlier we have investigated the combustion process of propane or an air-propane mixture injection through a thin channel in the body of an initiator into a MW discharge region in a high speed airflow.[12] It was demonstrated that a MW low power discharge is able to create a quasi-stationary torch of the injected combusting propane with high efficiency. In new experiments the behavior of a combustion wave initiated by a MW discharge in a homogeneous flow of a propane-air mixture at low velocity was investigated.

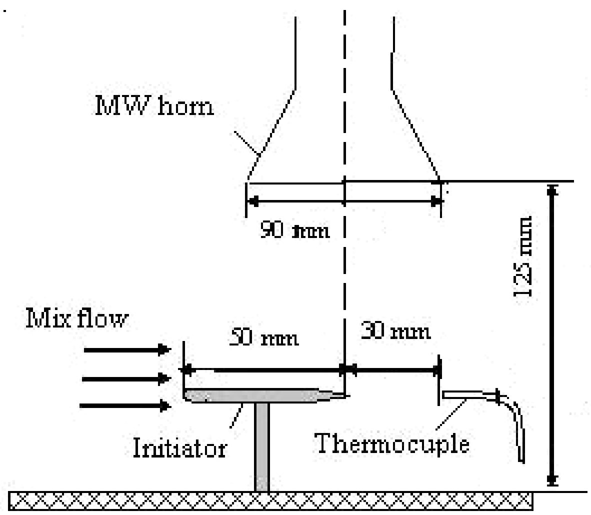

Fig. 1. A sketch of the setup working area

The schematic of the experimental setup is shown in Fig.1. A balloon with previously prepared propane - air mixture at atmospheric pressure is opened to the process chamber evacuated to 114 Torr by a pressure controlled valve. The gas flow is controlled by a small aperture. The mixture flows through the nozzle, creating a submerged jet with a diameter of 3 cm. The stream velocity, controlled by the small aperture located before the nozzle, is 13.2 m/s. The gas temperature in the jet is equal to room temperature.

The initiator is represented by the electromagnetic thin straight vibrator of a resonant length located along the flow axis. It is fed by MW radiation with the wavelength of 12.5 cm at the generator's power ~1 kW. The horn-type antenna directs a radiation to the vibrator. The discharge arises at a stem tip of the vibrator because this tip is the sharpest point. The discharge stays attached to the vibrator tip during the duration of the process (~0.2 s). The thermocouple is located behind the vibrator at the flow axis at a distance of 3.0 cm from the vibrator's tip.

The gas mixture's air excess coefficient was varied. Photos of the discharge area and thermocouple data were recorded.

The images of the discharge area at different air excess coefficient are presented in Fig. 2 and Fig. 3.

One can see in Fig.2 the cone of the flame front is. The cone angle depends on the rate of α. The lower α, the lesser the cone angle becomes.

The angle is insignificantly small at $\alpha < 0.5$, and images of the discharge area are the same not depending on α. The typical image of the discharge area is shown at $\alpha < 0.5$ in Fig.3.

a) *b)* *c)*

Fig. 2. Photos of the attached MW discharge area in air-propane mixture flow at air excess coefficient α: 1.14 – (a), 0.93 – (b) and 0.63 – (c)

Fig.3. Attached MW discharge area photo in air-propane mixture flow at an air excess coefficient α < 0.5

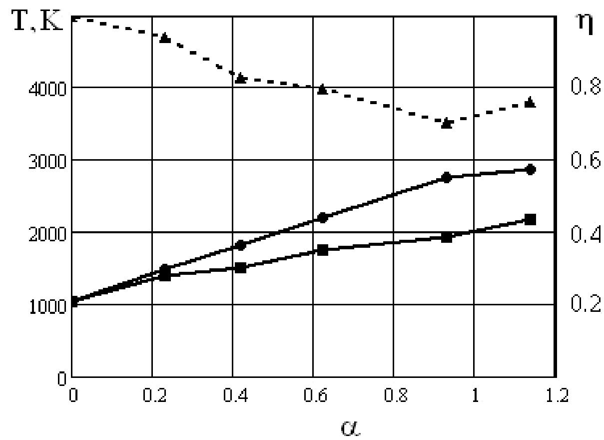

Fig. 4. The temperature T of the burned mixture at the stream axis, boxes represent the measured values and the circles the theoretical values. η is the combustion efficiency (see scale on the right side)

Measured values of the gas temperature at the stream axis are compared in Fig.4 with theoretical values of the combusted mixture temperature in isobaric approximation. The ratio of the measured and theoretic values determines the combustion efficiency

$$\eta = \frac{\mathbf{T}_{\mathbf{measered}}}{\mathbf{T}_{\mathbf{Theory}}}$$

at the stream axis. The magnitude η ≈ 0.75 is observed at 0.4 < α < 1.2.

It is easy to estimate the flame front velocity using the measured values of the burned mixture temperature and known value of thermal diffusivity of air at a pressure of 114 Torr and room temperature.

$$\mathbf{V}_{\mathbf{fr}}(\alpha) = \sqrt{\frac{\chi}{\tau_c(\mathbf{T}(\alpha), \mathbf{p}_c)}},$$

where χ - thermal diffusivity, τ_c (T, p) – approximation of calculations for propane-air mixture.

[3] Estimated values together with the flow velocity value give magnitudes of the flame cone angle, which agree very well with measured values (see Fig.5).

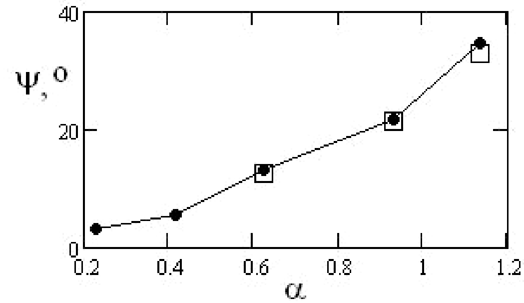

Fig. 5. Flame cone angle. Circles represent estimated values, boxes the measured values

Experiments show that the attached under critical discharge surely ignites the propane-air mixture flow, passing through the discharge domain at any value of air excess coefficient α. At α ~1, the flame front velocity achieves the value up to 9 m/s comparable with regular flow velocity value of 13.2 m/s. In this case, the combustion covers all the cross section of the mixture stream.

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Plasma-Assisted Combustion and Flameholding in High-Speed Flow

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Several fundamental problems related to high-speed combustion are under consideration, including fuel ignition under low temperature, induction time reduction, air-fuel mixing intensification, flame-front stabilization, completeness of combustion enhancement, etc. [1-6]. At least four mechanisms of the effect of plasma on ignition and combustion processes might be listed: ohmic heating (1), active radicals and particles deposition (2), plasma/MHD mixing (3), and plasma-induced flow structure steering (4). In some important situations, the active radicals' generation by plasma has a synergetic effect on the ignition [4-5], i.e. the required power occurs much less than for a thermal initiation of the reactions. The result of plasma-chemical modeling is presented as a motivation of experimental activity.

Application of plasma in the field on aerospace science defined the conditions of discharge generation: pressure P=0.1-1Bar and velocity of the flow V=100-1000m/s. Under such conditions the plasma of electrical discharges appears in filamentary form due to specific instability, like a superheating one. The properties of the filamentary plasma under so specific conditions are not known perfectly. This experimental work is aimed also in demonstration of filamentary plasma behavior at high-speed flow, in magnetic field and at an extended range of gas temperature. The instability of the filamentary plasma channel inflow is described as a source of extra mixing of components in a heterogeneous media.

A newly upgraded experimental facility, PWT-50H, is described for the test of ethylene and hydrogen ignition by electrical discharge in cavity and behind wallstep of high-speed duct. The geometry of the test is shown in Fig. 1. The photograph of discharge operation is presented in Fig. 2. These experiments are characterized by the following parameters: Mach number of undisturbed flow M=2, static pressure P_{st}=100-250Torr, typical discharge power W_{pl}=1-10kW, equivalence ratio through separation zone ER=0.15-3 (ER=1 at G_{C2H4}=0.8g/s approximately), and test duration t<0.5s. The facility is equipped with pressure transducers, schlieren system, optical and spectroscopic observations, etc.

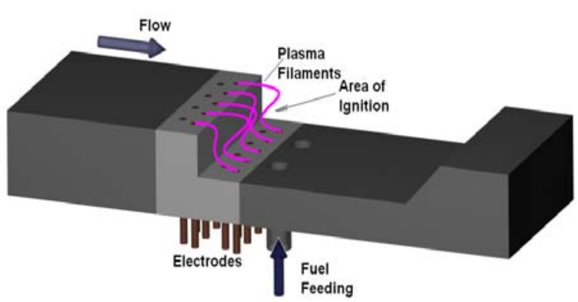

Fig. 1. Scheme of experimental arrangement

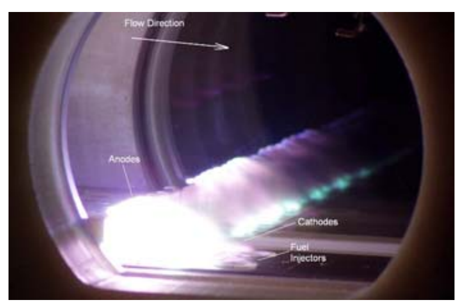

Fig. 2. Photo of the discharge operation behind wallstep

A main criterion for the detection of an effect by the discharge is a rise of the static pressure within the separation zone. Fig. 3 presents a typical graph of the discharge voltage and pressure record correlation. The experimental graph of pressure rise vs. fuel mass flowrate is shown in Fig. 4. The fuel injection was started prior the discharge and was switched off after it. The comparison of these data with the computed dependence of pressure rise on power release gives the estimation of the plasma-assisted combustion thermal effect, i.e. completeness. As it seen in Fig. 4 the combustion of a rich composition is more difficult to promoted by the electrical discharge than is a lean mixture. The physical reason is in instabilities development.

In refs. 7 and 8, the method of supersonic combustors' improvement has been proposed, which is based on generation of plasma-induced local unsteady separation. The artificial plasma-induced zones of the flow separation can be applied instead of mechanical arrangements, especially under non-optimal operation mode of the combustor. The experimental data on the flameholding over plane wall are presented as well. The flame stabilization mode could occur at a relatively low level of extra energy deposition.

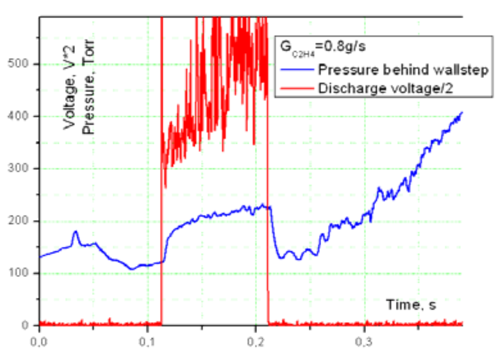

Fig. 3. Discharge and combustion correlation

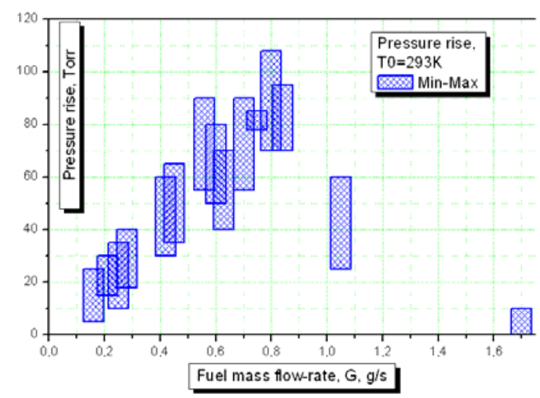

Fig. 4. Pressure increase vs fuel injection at T_0=300K.

The energetic threshold of the ignition and flameholding in a shear layer has been measured and is shown in the table below.

	H2 (T_0=300K)	C2H4 (T_0=300K)	C2H4 (T_0=500K)
Threshold of ignition in separated zone	1kW	2.5kW	4kW
Threshold of flameholding in shear layer	3kW	>4kW	>5kW
Threshold of flameholding over plane wall	4kW	6kW	-

The ignition effect of the gas discharge was compared for different levels of the E/N parameter. As it can be considered, the effectiveness of the flameholding is determined mostly by the level of power deposition, and secondarily by the power density. In frames of described experiments, the effect of reduced electrical field was negligible. A completeness of the combustion is estimated as η>0.7 with both hydrogen and ethylene fuels under optimal conditions. The data of computational analysis are presented as well.

Hopefully the results of this work are useful at design of practical devices for ignition, mixing, and flow structure modification. Advantages of plasma technology for high-speed combustion enhancement are discussed.

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First Test Results of the Transient Arc Plasma Igniter in a Supersonic Flow

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This paper considers the idea and the first test results of a combined cycle plasma torch (CCPT) application for flame holding in high-speed combustors. The CCPT was developed by Applied Plasma Technologies (APT) and is based on a low-power transient discharge plasma pilot [1] with fuel or air-fuel mixture feeding into the arc chamber, so that the main thermal effect is provided by chemical reactions in a plasma-activated medium.

The physical mechanisms of an air-fuel composition processing by electrical discharge for the combustion enhancement are well described during the last few years [2-7]. Two areas are the most important: Molecular kinetics modification (heating, plasma-chemical excitation, active particles generation); and the flow structure control to create local zones of intensive mixing and extended time of the mixture residence. Fig.1 below presents several schemes of the PAC (Plasma-Assisted Combustion) concept's realization in lab-scale tests.

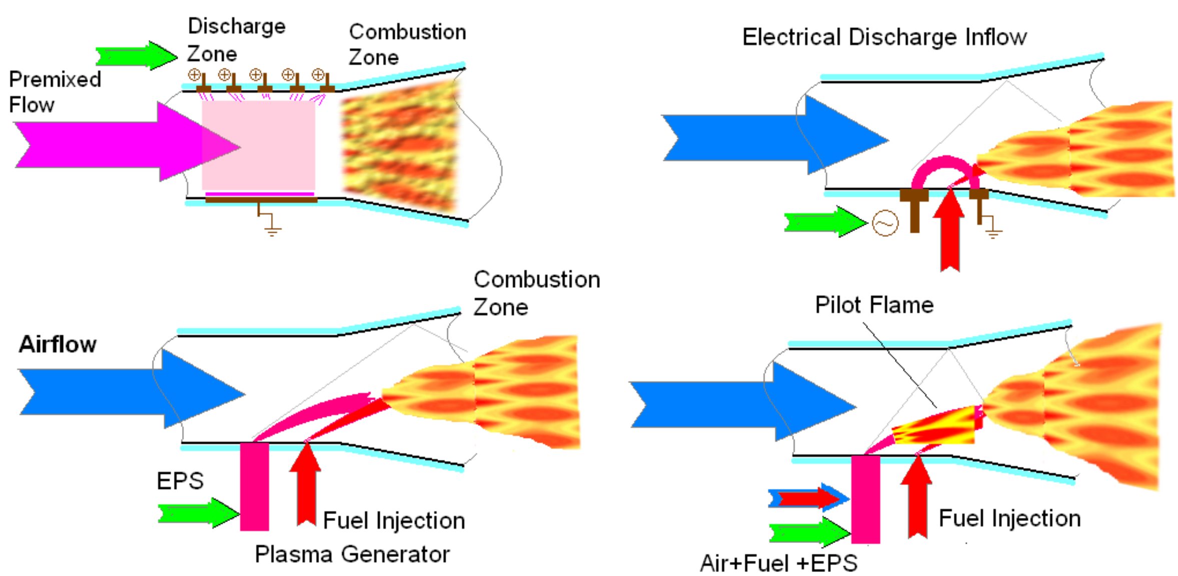

Fig. 1. Experimental schemes of the plasma assistance in high-speed combustion. Red color represents fuel injection, blue – air flow, green – electrical power supply

Two schemes in the first column are quite typical. The first scheme of premixed composition ignition is used in model tests and at theoretical analysis of non-equilibrium plasma effect on the flame propagation [8-9, for example]. The second scheme presents so called "plasma torch" generation for the fuel ignition [5, 10-11]. Torch location can be different: Torch upward, downward, in a cavity, and so on. We consider such a scheme as ineffective due to high power losses and too long a path of excited molecular gas to the zone of interaction for completion of a relaxation. It has to be noted that not only these schemes were tested but others as well. Numbers of interesting works were published, especially with RF and MW types of the plasma excitation.

Two schemes were supposed to avoid the heat loss: (1) the electrical discharge generation just in place of interaction with fuel, and (2) using a small amount of extra fuel as an additive to feedstock gas to increase thermal power of a plasma torch in place of interaction with fuel (active pilot flame). The first approach was tested in [12, 13] and shows exciting results. The forth scheme was tested in the present work.

The experiments were conducted in a short-duration blowdown wind tunnel with closed test section at Mach number M = 1.99 and static pressure P_{st} = 100 - 400 Torr, duration of steady-stage operation 0.4-0.8sec, and typical air mass flow through the duct about $G \approx 0.2\text{-}1.0$ kg/sec. Test section dimensions were 72*60mm or 50*20mm. The experimental set up has been equipped with a Schlieren system with short time exposure, high-speed video camera, a set of fast-response pressure transducers, a spectroscopic system, photo-sensors, current-voltage sensors, thermo-sensors, etc. The air mass flow rate through the plasma generator was $G1_{air}$ = 0.3-3 g/s, the fuel mass flow rate $G1_{fue\ l}$= 0.1-1 g/s. The operation modes permit regimes with combustion or partial fuel conversion [14]. The CCPT, engineered and manufactured by APT is shown in Fig.2.

Fig.2. CCPT with fuel feeding into the arc chamber in operation.

Preliminary test results in the explored configuration can be summarized as follows: (1) The main fuel injected directly to M = 2 airflow can't be ignited by only an electrically powered plasma generator (W_{pl} = 1 kW); (2) small addition of HC fuel into the plasma igniter (W_{pl} + $W_{comb} \approx$ 5kW) sufficiently increases efficiency of flame holding. In some regimes an extra power release was detected due to the main fuel combustion in the high-speed flow. Based on obtained results we can consider such a scheme as very promising for high-speed combustion enhancement.

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Triple Vortex Plasma Assisted Combustor

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Applied Plasma Technologies (APT) demonstrates a comprehensive approach to a new combustion technology development. Named a Triple Vortex Plasma Assisted Combustor it combines innovative and a recently patented reverse vortex combustor [1-4] with a non-thermal multi-mode plasma pilot burner[5] or spatial arc for ignition and flame control. At the same time we recognize that the reverse vortex technology is already known and was applied for combustion purposes in the turbine combustors and rocket engines by Alfa Romeo Avio S.A.p.A. (Italy) and ORBITEC, Inc. (USA.) [6-10], and Dr. Gutsol et al for high temperature streams insulation [11] .

Aerodynamic schemes of the combustor prototypes are shown in Fig. 1. Scheme I presents the simplest double-vortex combustor with the top air inlet, plasma pilot and fuel nozzles placed at the bottom. Scheme II shows a triple vortex combustor with top feeding of the main air supply and bottom feeding of fuel or fuel/air mixture. Scheme III shows the most advanced triple vortex combustor with spatial arc. In this case fuel is injected through the circular gap between the bottom swirler and a flat cathode. Burning in this gap and orbiting high voltage and low current arc provides reliable ignition and optionally continuous flame control.

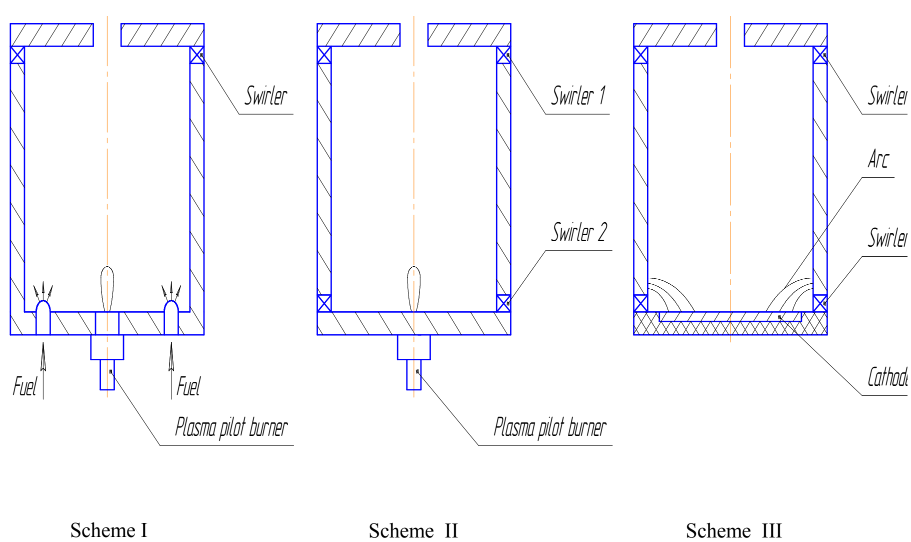


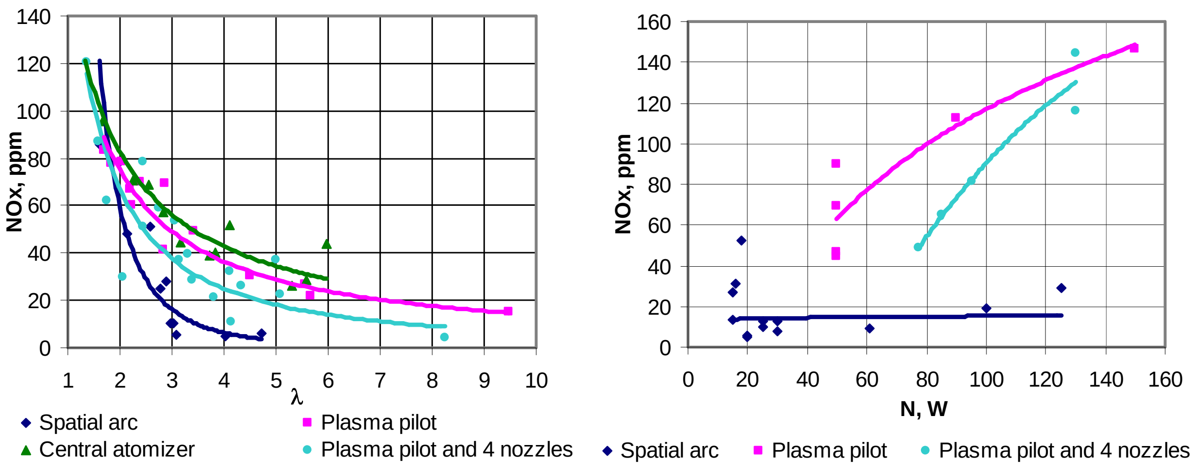
Fig. 1. Plasma Assisted Combustor schemes

All of these schemes have been realized in the atmospheric pressure prototypes shown in Fig. 2a and 2b. Fig. 2a presents a general view of scheme I combustor with ID = 145 mm named PATC-1. Fig. 2b represents the scheme II combustor with ID = 73 mm named PATC-2. In contrast to these schemes [11] the proposed triple vortex combustor has a third vortex which forms a higher concentration of fuel (gaseous, liquid or coal) and oxidizer in a mixing region adjacent to the fuel inlet which serves as a means to create a high level of turbulence in the mixing area to improve the combustor's performance. In addition, possibilities for the triple vortex combustor regulation are significantly increased as a consequence of the ability to adjust the location of the direct and reverse vortex contact zone by the changing the flow rates.

a) *b)*

Fig. 2. Plasma Assisted Combustor prototypes: a) PATC-1, b) PATC-2

Prior full-scale atmospheric pressure PATC tests proved the concept's advantages as follows [2]. High efficient internal mixing of fuel and oxidizer, stable combustion with dramatically extended flammability limits, simple air swirler and fuel injectors, no heating of the combustor walls, simple combustor design, cheaper materials for combustor fabrication, and simple conversion into the multi-fuel and multi-zone combustor. A laser Doppler velocimetry system was used to measure the mean axial and swirl velocity components and their respective fluctuations in the "Tornado" combustor under cold, non-reacting, isothermal conditions [3].



a) b)

Fig 3. Dependences of NO_x emissions

Fig. 3 shows generalized dependences of the nitrogen oxide emission on the combustor operation modes characterized by the air excess coefficient l for four basic fuel injection methods without electric discharge initiation (Fig. 3a), and with plasma device operation (Fig. 3b). NO_x emission did not exceed 150 ppm for l varying from 1.5 to 9.5 and the tendency for its increase occurs with discharge power growth.

The PATC-2 preliminary tests confirmed the idea of the spatial electrical arc integration into the reverse vortex combustor for direct ignition and flame control with minimal power consumption. Several power sources for the arc feeding were tested, including a conventional automotive ignition coil, a nano-second pulse power generator and a high voltage DC power supply. For all cases no visible electrode erosion was observed after tens of hours of operation. The combustor with sustained arc had no lean flame-outs. This provides a simple and economically affordable alternative for high altitude engine re-starts, flame control of super lean and low Btu air/fuel mixtures.

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CONCLUSIONS

Several modifications of the plasma assisted triple vortex combustors have been engineered, manufactured and tested by Applied Plasma Technologies. The test results proved that the triple vortex combustor concept with plasma assistance selected for further development and marketing of the can provide: (1) cold walls operation, which leads to higher turbine efficiency due to the elimination of a need in the combustor cooling, simpler design, lower cost materials, lower manufacturing costs, lighter weight combustor; (2) higher performance due to better fuel and oxidizer mixing, much wider turn down ratios – no lean flame outs with plasma on; (3) simple, reliable, highly effective and economically affordable ignition and continuous flame control by different non-thermal plasma sources, including spatial arc with power from 10 W to 1 kW to ensure the engine's operation at any environment conditions, including low temperature and pressure; (3) fuel flexibility and possible multi-fuel operation; (4) simple combustor integration into existing engines, including tubular and annular configurations; (5) possibility to employ swirling input flows; (6) possible operation as a fuel reformer; (7) satisfactory gravimetric and volumetric parameters.

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Plasmatron with Regenerative Carbon Nano-Structured Electrodes

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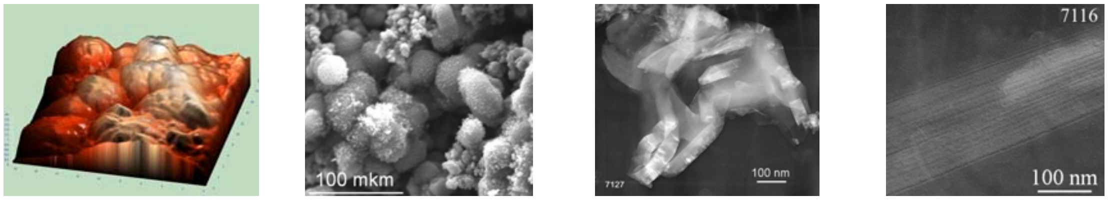
Simplicity and reliability of the arc plasma generators (plasmatrons) using cylindrical copper cathode and air as plasma forming gas predestine their application at heat and power engineering for plasma aided coal combustion. Life time of these plasmatrons electrodes is critical and usually limited to 500 hours [1, 2]. Considered in this paper the long life direct current arc plasmatron (Fig.1) has the cathode life significantly exceeded 500 hours. To ensure the electrodes long life the process of hydrocarbon gas dissociation in the electric arc discharge is used. In accordance to this method atoms and ions of carbon from near-electrode plasma deposit on the active surface of the electrodes and form electrode carbon condensate which operates as "actual" electrode. To realize aforesaid the construction of electro arc generator of air plasma has been developed and tested. Using special orifices propane/butane mixture is supplied to the zone of the arc conjunction to the copper water-cooled electrodes (cathode and anode). As a result inside the cathode cavity and internal surface of the anode medium of carbonic gas is formed. Linked with the arc in series, the magnetic coils guaranty stabilization of the discharge on the electrodes.

Fig. 1. Long life DC arc plasmatron

The arc is initiated using oscillator and starting electrode. The processes of propane/butane molecules dissociation and carbon atoms ionization start with the rise in temperature. Arisen from ionization positive carbon ions deposit onto the electrodes surface under the influence of near-cathode decline in potential and form coating of the electrode condensate regenerated continuously. This coating is "actual" cathode, deterioration of which is compensated by the flow of carbon ions and atoms. The coating thickness depends mainly on ratio of the flows propane/butane and air and the arc current and it does not exceed 500 μm. During experiments power of the plasmatron was varied from 76 to 132 kW and propane/butane flow in range of 0.4 – 0.7 l/m, thermal efficiency of the plasmatron reached 90%. At that mass averaged temperature on the exit of the plasmatron increased to 6000 K. The electrode condensate was examined using scanning electron microscopy, transmission electron microscopy and Raman spectroscopy. It is found that the electrode condensate is composite carbonic stuff made of carbon nano-clusters which consist mainly of single and multi-wall carbon nanotubes (Fig.2) and other carbonic forms including some quantity of the copper atoms intercalated to the carbonic matrix. Specific electrical resistance of the electrode condensate is less than 10^{-8} Ω m.



a) b) c) d)

Fig.2. Image of a sample of the cathode condensate through atomic power microscope (a), scanning electron microscope (b) and transmission electron microscope (c, d)

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Investigation of a Non-Steady State Discharge in a Pilot for Ignition and Flame Control

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Subject of the paper is investigations of non-steady state behavior for high-pressure gas discharge in the air-hydrocarbon mixtures as applied to the problem of ignition and flame stabilization. The device, used in the experiments (Fig. 1), is based on design of classical arc plasmatron [1, 2]. However, the distinctive feature of the plasmatron operation in our experimental conditions is that an average current is limited by the ballast resistor R_b at a level of about 0.1 A. Average power dissipated in plasmatron does not exceed 100 W. In spite of extremely low average power, plasmatron demonstrates reliable ignition and flame stabilization for air-propane mixtures in a wide range of equivalence ratios.

A key point in understanding physical mechanism of flame ignition and control is elucidation of non-steady state discharge behavior. An important role in the non-steady state discharge processes belongs to capacitance C of connecting cable. If the current from the power supply were high enough, then the discharge would be able to burn as a steady state thermal arc with distinctively expressed cathode spot. However, in the conditions of low current, the cathode

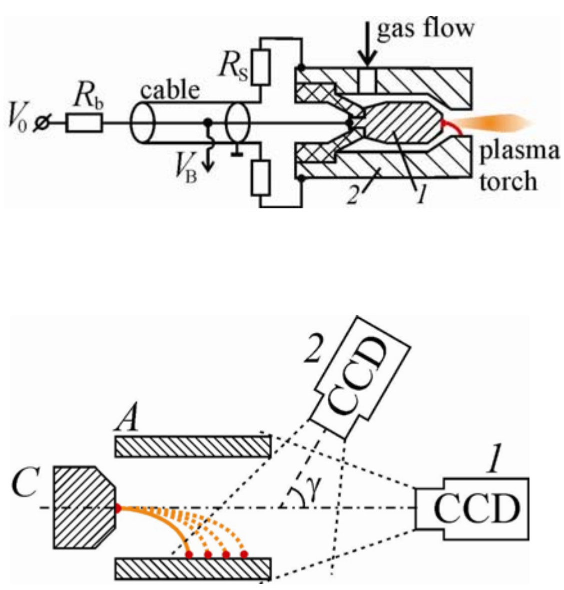

Fig. 1. Experimental arrangement of plasmatron and schematic of the optical observation by means of CCD camera.
R_b – ballast charging resistor; R_S –shunt for current recording; V_B - discharge voltage

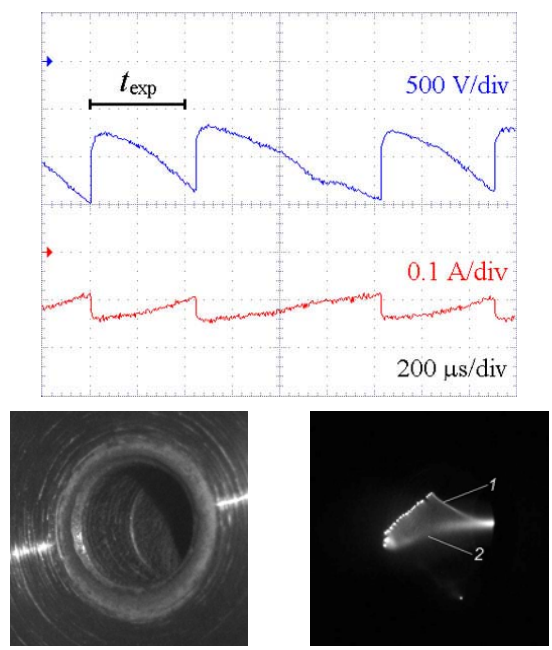

Fig. 2. Voltage and current waveforms and CCD photographs of the discharge image.
(γ = 45°). R_b = 13.6 kW, C = 300 pF, V_0 = 3.0 kV.
Gas flow G(air) = 0.1 g/s (v_{gas} = 4 m/s)

spot is extinguished, and during some time, the discharge is sustained in a low-current glow mode. The characteristic feature of a high-pressure glow discharge is so-called glow-to-spark transitions that occur randomly. When such a transition occurs, the capacitor *C* is discharged via the gap and a high-current pulse with duration of about 100 ns forms on background of glow discharge. The short duration spark channel is able to give origin to the ignition process. The temporal development of the ignition goes efficiently because of the surrounding medium does not represent a "cold gas", but a low-density non-equilibrium glow discharge plasma where the chemically active particles are already available. In such conditions, even small energy dissipation in the spark channel seems to be sufficient to start the burning process [1, 2].

Investigations of the discharge had been carried out with a use of oscilloscope measurements with nanosecond time resolution and by means of recording the discharge image with CCD camera. An example of voltage and current waveforms is shown in Fig. 2. Here we can see the bright channel (*1*) that originated at the instant of glow-to-spark transition. The breakdown occurred from central part of the cathode end to inner surface of the anode nozzle over a short distance. The spark discharge transforms in a glow mode with distinctively expressed anode current attachment (anode spot). At the glow stage, the gas flow essentially affects to the discharge behavior. It results in displacement of the anode spot over the anode surface in direction of plasmatron exit and increasing the plasma column length. The anode spot does not migrate smoothly, but its migration resembles a consequence of jumps (see dotted structure of the anode trace in Fig. 2).

At the end of exposition time, the plasma channel is already attached to the edge of plasmatron exit aperture (position *2* in Fig. 2). After that, new glow-to-spark transition occurs and the described cycle is repeated.

As a whole, the discharge burning regime can be referred to as a kind of glow discharge with random transitions from glow to spark. Two types of transitions have been observed: completed and non-completed transitions. For the case of completed transition a high-conductivity spark channel appears in the gap, and for non-completed transitions the diffuse channels with a moderate conductivity arise. Both types of the channels serve as efficient starting mechanism for initiation of the burning process.

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Three-Temperature Model of Nonequilibrium Air Plasma

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The purpose of the work is to construct the physical and mathematical model of the direct current air discharge in a transverse gas flow. For the theoretical modeling of the non-equilibrium air plasma the two-temperature model is commonly used. At the same time it is known that for air discharges non-equilibrium processes are connected with an additional energy transfer channel from the electromagnetic field to the plasma which is realized through the vibration of molecules and then through the vibrational–translational relaxation processes. To obtain the adequate discharge model in this study the equation for the vibrational temperature of the nitrogen molecules in addition to the equations for the neutral particles temperature and electron temperature was introduced. It was assumed that the vibrational temperature of oxygen and nitride oxide molecules due to a fast vibrational-translational relaxation of these species is close to the translational gas temperature. The model also includes the equation for the electric potential, the balance equations for the electron, ion and excited molecules density, Ohm's law and the system of Navier-Stokes and two parametric RNG $\kappa-\varepsilon$ turbulence model equations. It has been assumed that the energy distribution of electrons is Maxwellian with corresponding temperature of electrons T_e as a function of electric field strength. The discharge plasma is assumed to be quasi- neutral and the deviations from quasi-neutrality in the near electrode regions were accounted for by appropriate boundary conditions.

The radiation losses were neglected. Rate constants of the reactions with electron participation were assumed to be functions of electron temperature. As the ratio of average electric field strength in the discharge gap to the gas number density is equal $\theta = E/N = 0.45\ Td$ the electron losses due to attachment and electron-ion recombination can be higher than the electron-impact ionization rate.

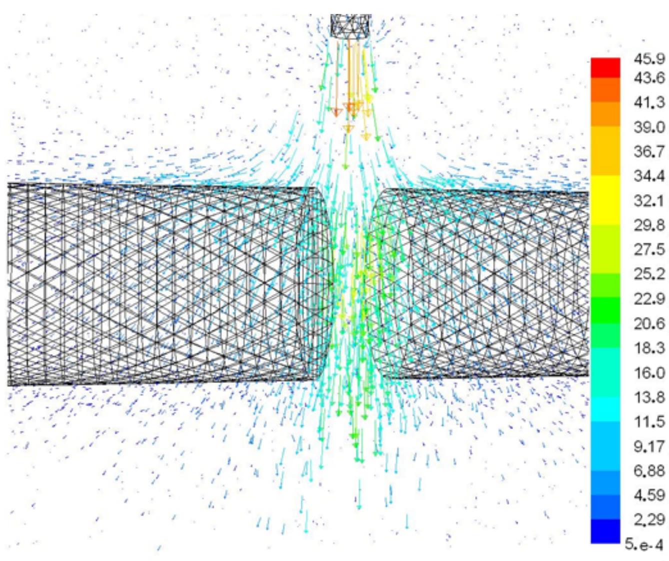

Fig.1. Sketch of the problem and calculated velocity vectors

The processes that can compensate the electron losses are the electron detachment (three body and dissociative detachment), photodetachment (for atmospheric pressure this process can be neglected) and processes of ionization rate enhancing due to vibrational excitation. It is known that the last process is very important for steady-state discharges. In the equation for the gas temperature the additional heat sources are connected with a vibrational-translational relaxation of molecules, ion-ion and electron-ion recombination and dissociative attachment. The calculations have been carried out for the case of the transverse dc arc discharge. The calculation area in three-dimensional geometry includes the system of two horizontal opposite electrodes (solids), the vertical nozzle for air supply and the arc and surrounding air region (Fig.1). The system of equations was solved numerically by an iteration method using low relaxation and procedure SIMPLE. Effective values of the transfer coefficients were determined as the sum of laminar and turbulent components. The special approach based on the conjugate problem solution has been used. The discharge current value and inlet gas velocity were varied in limits 0.1A-0.5A and 10m/s-100m/s. It has been determined that for all air flow rates and total current values the electron temperature exceeds the vibrational temperature and the vibrational temperature exceeds the gas temperature. In the arc column the electron temperature T_e and the vibrational temperature T_V were varied in limits $0.5 \leq T_e \leq 1.8$, $0.3 \leq T_V \leq 0.8$. It should be noted that the maximum value of T_e is reached in the inter-electrode gap and it is decreased downstream and with increasing air flow rate. At the same time the maximum value of the vibrational temperature T_V and gas temperature is reached downstream where the concentration of excited molecules is maximum ($\approx 10^{24}$ $1/m^3$). With the gas flow rate decreasing the region occupied by the excited molecules is moved upstream.

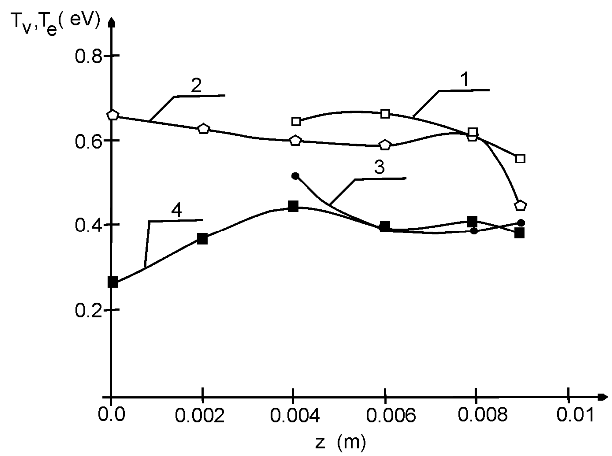

Fig.2. The axial profiles of the electron (1,2) and vibration temperature (3,4): 1,3 — the experimental data [5], 2,4 — calculated one (I = 200 mA)

The calculated results have shown good agreement with the experimental data (Fig.2) except in the downstream area where some differences in T_e values are observed. In experiments the electron temperature was increased downstream but the calculations had shown the opposite result. In our opinion it can be connected with the differences between the calculated electron temperature as a parameter of the Maxwell distribution and the measured temperature of the atomic and molecular states excitation as a parameter of the Boltzmann plot. It is known that in definite non-equilibrium conditions these temperatures and their behavior

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CFD Calculations of Reverse Vortex Reactive Flows

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The development of a new generation of combustion chambers with plasma torch and spatial arc should be based on better understanding of the physical and chemical processes of turbulent combustion in highly swirled flows and the modeling of such combustors taking into account the complexity of their 3D geometry and variety of operation modes.

Theoretical investigations of the operating processes in triple vortex (or "Tornado") combustors [1] with highly turbulent flows of air, fuel, and products of their reactions are not simple [2]. Due to intensive development and achieved progress in numerical solutions of the fluid dynamics and chemical kinetics equations it is now possible to model the main physical and chemical processes inside combustors that are difficult to study experimentally. This can dramatically reduce costs for research and development of prospective devices.

For modeling of physical and chemical processes inside a triple vortex combustor with plasma torch and spatial arc a generalized method based on numerical solution of the combined conservation and transport equations for a multi-component chemically reactive turbulent system was employed [3, 4]. This method provides a procedure for the sequential numerical integration of the differential equations, which describe reacting viscous gas flows. A 3D model of stationary and non-stationary reacting flows has been utilized which permits prediction of the plasma-chemical influence and optimization of parameters of the combustors taking into consideration mixing, turbulence, radiation and combustion.

Turbulent flows in a triple vortex combustor are characterized by eddies with a wide range of length and time scales. The largest eddies are typically comparable in size to the characteristic length of the mean flow. The smallest scales are responsible for the dissipation of the kinetic energy of turbulence. Therefore, in some cases, for the definition of instantaneous velocities inside the combustor the large eddy simulation (LES) model has been used [5].

CFD methods have been used for modeling of the following processes:

- swirl flows in a "Tornado" combustor under cold, non-reacting, isothermal conditions;
- reactive flows inside reverse vortex combustor with internal diameters (ID) of 145 and 73 mm;
- gaseous fuel burning inside a triple vortex combustor with spatial arc and ID of 73 mm;
- coal burning and gasification processes in a 1 MW hybrid plasma torch;
- liquid fuel gasification processes in a hybrid plasma reformer with ID of 73 mm.

Contours of static temperature in a reverse vortex combustor with ID 145 mm working on gaseous propane are shown in Fig. 1. Operation conditions are: air mass flow rate through tangential swirler 15.53 g/s, air inlet temperature 318.5 K, air mass flow rate through the plasma torch 0.666 g/s, temperature of plasma feedstock air 294.1 K, propane mass flow rate through the plasma torch 0.155 g/s, propane inlet temperature 294.1 K. In calculations a RNG *k*-e turbulence model with swirl dominated flow, 3D pressure based solver, steady formulation, SIMPLE pressure-velocity coupling, eddy-dissipation combustion model of propane (C_3H_8) are used. Note, that a special exhaust tube with 600 mm length has been added to the exit combustor nozzle to avoid air injection from the atmosphere and combustion products dilution.

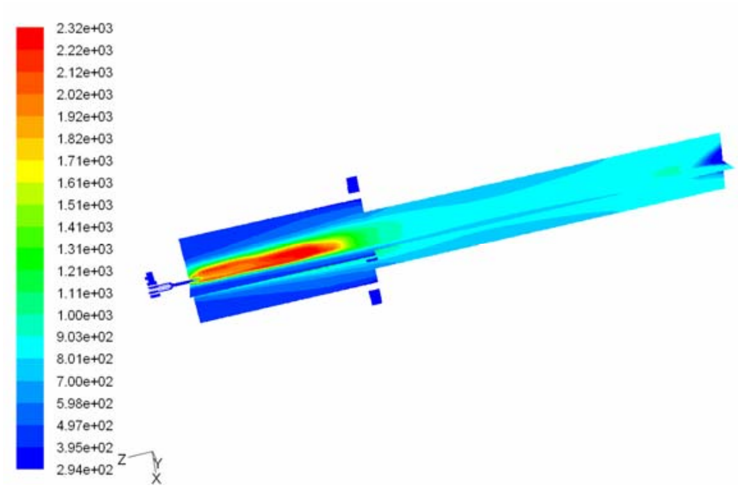

Fig. 1. Contours of temperature

Contours of H_2 mole fraction in hybrid plasma reformer working on liquid diesel fuel $C_{10}H_{22}$ are shown in Fig. 2. Operation conditions are: air mass flow rate through tangential swirler 5 g/s, air mass flow rate through the plasma torch 0.6 g/s, temperature of plasma air 1000 K, water steam mass flow rate through the plasma torch 0.1 g/s, liquid fuel mass flow rate through the plasma torch 1.4 g/s, fuel inlet temperature 300K. Rosin-Rammler diameter distribution for injection of fuel drops is assumed. Minimum, maximum, and mean diameters 10, 30, and 70 micrometers correspondingly, spread parameter 3.5, injection velocity 5 m/s. For turbulent dispersion the discrete random walk model with number of tries 10 has been utilized.

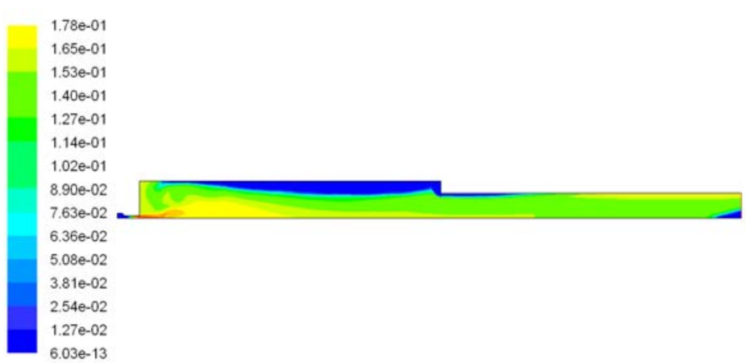

Fig. 2. Contours of H_2 mole fraction

For calculations RNG $\kappa - \varepsilon$ turbulence model with swirl dominated flow, 2D axi-symmetric pressure based solver, steady formulation, SIMPLE pressure-velocity coupling, Eddy Dissipation Concept (EDC) combustion model of $C_{10}H_{22}$ which combine turbulence-chemistry interaction with simple chemical mechanism (5 main reactions) are used. On the exit reformer cross-section calculated values of main mixture components mole fractions are the following: $CO = 0.1409$, $H_2 = 0.1501$, $C_{10}H_{22} = 0.019$, $CO_2 = 0.0468$, $H_2O = 0.0782$, $O_2 = 0.0037$.

The performed theoretical investigations have demonstrated the modeling capability for the complex aerodynamic flows with chemical reactions inside reverse and triple vortex combustors and plasma reformers using coal and liquid organic materials. This work revealed deficiencies of the existing turbulence and combustion models for the prediction of parameters and have indicated major directions for the improvement of computational models.

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Mathematical Modeling of Argon Plasma in ICP Torch by Non-Equilibrium Model

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The features of plasma in RF ICP torches such as a high purity due to the absence of electrode and large volumes of plasma have resulted in a wide range of applications [1]. One of the most widespread applications of ICP torches is a spectrum source for spectrochemical analysis.

The numerical modeling of plasma parameters in RF ICP torches is widely used to analyze the plasma processes and to select the optimal operating conditions of the torch.

The non-equilibrium model of plasma involves the following equations:

- equation of energy balance for electrons:

$$\mathrm{div}\left(\left(\frac{5}{2}kT_e+E_i\right)n_e\vec{v}\right)=\mathrm{div}\left(\lambda_e \mathrm{grad}T_e\right)+\sigma_e E_\varphi^2-u_{rad}-b_{eh}\cdot\left(T_e-T_h\right) \quad , \qquad (1)$$

- equation of energy balance for heavy species:

$$\mathrm{div}\left(\frac{5}{2}kT_h\left(n_i+n_a\right)\vec{v}\right)=\mathrm{div}\left(\lambda_h \mathrm{grad}T_h\right)+b_{eh}\cdot\left(T_e-T_h\right) \quad , \qquad (2)$$

- equation of electromagnetic problem:

$$\frac{\partial^2\dot{E}_\varphi}{\partial z^2}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\dot{E}_\varphi}{\partial r}\right)-\left(\frac{1}{r^2}+j\mu_0\omega\sigma_e\right)\dot{E}_\varphi=0 \quad , \qquad (3)$$

- continuity equation and momentum transfer equations for axial and radial components of velocity in usual notations.

This system of non-linear differential equations was solved using the SIMPLER algorithm [2].To calculate non-equilibrium plasma parameters in RF ICP torch, it is necessary to use data for thermodynamic and transport properties of non-equilibrium argon plasma. The calculation of non-equilibrium plasma composition is the basis of thermodynamic and transport properties calculations.

The following system of equations was used for the calculation of plasma composition:

- quasi-neutrality equation:

$$n_e=n_{Ar+} \quad , \qquad (4)$$

- Dalton's law of partial pressures:

$$p=n_e kT_e+\left(n_{Ar}+n_{Ar+}\right)kT_h \quad , \qquad (5)$$

- Potapov equation:

$$n_e \left(\frac{n_{Ar+}}{n_{Ar}} \right)^{T_h / T_e} = g_e \frac{Z_{Ar+}(T_e)}{Z_{Ar}(T_e)} \left(\frac{2\pi\ m_e k T_e}{h^2} \right)^{3/2} \exp\left(-\frac{E_i}{kT_e} \right) \quad , \qquad (6a)$$

or non-equilibrium Saha equation:

$$n_e \frac{n_{Ar+}}{n_{Ar}} = g_e \frac{Z_{Ar+}(T_e)}{Z_{Ar}(T_e)} \left(\frac{2\pi\ m_e k T_e}{h^2} \right)^{3/2} \exp\left(-\frac{E_i}{kT_e} \right) \quad , \qquad (6b)$$

At the present time, in most of works, non-equilibrium plasma composition is calculated using either non-equilibrium the Saha equation [3, 4] or the Potapov equation [5, 6]. The present work is devoted to the calculation of non-equilibrium Ar plasma parameters in an ICP torch for spectrochemical analysis and the comparison of the results obtained using Saha and Potapov equations.

The calculated ICP torch for spectrochemical analysis works at a frequency of 27.12 MHz, plasma power is 1-2 kW, inner diameter of the torch is 24 mm and the plasma gas is argon. The plasma torch has three axial gas flows: transport gas flow is G1=3 l/min, plasma gas flow is G2=2.5 l/min, sheath gas flow is G3=20 l/min.

Two cases were calculated: without (2 gas flows) and with transport gas flow (3 gas flows). Results calculated using Saha equation and Potapov equation were compared. Results of calculation by equilibrium (LTE) model are also given for comparison.

Distributions of the following values were obtained: temperatures of electrons (T_e) and heavy species (T_h), plasma velocity (v_z, v_r), gas flow (ψ) and electromagnetic values.

The results of the calculations have shown that the non-equilibrium model is closer to experimental data compared to the equilibrium one when mathematical modeling of the RF ICP torch for spectrochemical analysis.

The non-equilibrium models have shown that the greater part of the plasma in the ICP torch is far from LTE. In the case of two gas flows, the substantial deviation from LTE is observed near the wall and inlet of the torch but near the axis of the torch the plasma is close to LTE. Feeding of the transport gas flow leads to a substantial deviation from LTE on the axis.

Differences between the non-equilibrium model with Potapov equation and the one with Saha equation were shown. The final choice between these two models can be done only on the basis of experimental data.

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Chemical Reactions in Heat and Mass Transfer Between Small Particles and Plasma

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A number of plasma technologies involve the treatment of small particles. Generally the numerical modeling of the small particle behavior in a plasma flow can help in the selection of optimal treatment conditions. A model of small particle motion, heat and mass transfer in plasma was described in a paper by J. Amouroux et al [1].

In this paper, the motion of the particle in a plasma jet will not be considered. The heating of a single particle with a diameter d_s moving with a constant velocity $\acute{V}_s$ in a plasma kept at constant temperature T_p and velocity $\acute{V}_p$ is considered.

The heating of one particle is supposed to follow four sequential steps: Heating of the solid particle up to the melting temperature T_{melt}; melting of the particle at constant temperature T_{melt}; heating of the liquid droplet up to the boiling temperature T_{boil}; boiling of the particle at constant temperature T_{boil}.

Neglecting the heat propagation phenomenon within the particle, the energy balance in the boundary layer surrounding the particle can be written:

$$m_s c_{ps} \frac{dT_s}{dt} = \sum_i P_i \quad , \qquad (1)$$

where $\sum_i P_i$ is the sum of the different heat fluxes corresponding to the steps presented in Fig. 2, each of them being expressed by a power P_i.

The model [1] describes processes taking place in chemically neutral plasma (for example, argon plasma) well. But if the particle is heated in reactive plasma, different chemical reactions can occur between the particle material vapor and plasma at the particle boundary layer or reactions between the molten particle and the plasma at the particle surface. Some reactions result in an energy release (exothermic reactions), others in an energy absorption (endothermic reactions). In any case, the heat transfer that goes along with chemical reactions has to be taken into account in the energy balance of the particle.

This will be illustrated through the example of a silicon particle in an air plasma.

During the third (heating of the liquid droplet up to its boiling temperature) and the fourth (boiling of the droplet) steps of heating, the silicon evaporates from the particle surface, resulting in a cloud of silicon vapor surrounding the particle. When the silicon vapor is oxidized in the air plasma with the formation of silicon oxide (SiO), energy is released through the reaction:

$$\text{Si (gas)} + \text{O (gas)} \leftrightarrow \text{SiO (gas)} - \Delta_1 H_{SiO}(T) \quad , \qquad (2)$$

where $\Delta_1 H_{SiO}(T)$ is the enthalpy of the chemical reaction.

The heat flux P_{chem} due to the chemical reaction can be calculated using the following equation:

$$P_{chem} = \Delta_r H_{SiO}\left(T_{b.l.}\right) \cdot \dot{m}_{Si_{react}} \quad , \tag{3}$$

This heat flux shall be subtracted from the right side of equation (1) when the third and fourth steps of particle heating are considered. The value of P_{chem} depends on various conditions (velocity of particle relative to plasma, plasma temperature etc).

Calculations have shown that the energy of the chemical reaction may play a very important role in the process of the particle heating under reactive plasma conditions. Under certain conditions, the heat flux P_{chem} due to the chemical reaction can be several times higher than the conductive-convective heat transfer from the plasma.

To evaluate the effect of the chemical reaction onto the energy balance to the particle, the parameter δ_{chem} (characterizing the part of the power of the chemical reaction in the energy balance to the particle) is proposed:

$$\delta_{chem} = \frac{E_{chem}}{E_{pl}} \quad , \tag{4}$$

where E_{chem} and E_{pl} represent energies gained by the particle due to the chemical reaction and due to the conductive-convective heat transfer from plasma:

$$E_{chem} = \int_0^{t_{total}} P_{chem} dt \quad , \qquad E_{pl} = \int_0^{t_{total}} P_{pl} dt \tag{5}$$

It was determined that the parameter δ_{chem} increases under the following conditions: increase of the relative particle velocity Δ_V, decrease of plasma temperature T_p, increase of the particle diameter d_s.

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Numerical Analysis of High-Speed Flows with Combustion of Fuel Ignited by a Plasma Torch

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There is a growing interest to applications of plasma not only externally as an effective way to modify and control flowfields around bodies at supersonic and hypersonic speeds [1], but also internally for ignition of fuel and flame-holding under supersonic conditions. [2-5] Particularly, this ignition method is very attractive for scramjets. Many authors investigated experimentally ignition and enhancement of supersonic combustion of hydrogen and hydrocarbon fuels using different designs [2-4] and combinations of plasma torches.[5] A very attractive design was proposed by Matveev *et* al, [4] which allows significant reduction of consumed average power by superimposing high-current nanosecond pulses on a glow plasma background and using a fuel-air mixture in a plasma torch. For optimization of developed designs and reducing costs of the experiments, it is necessary to understand better the details of the flowfield produced by cross-flow plasma jets. This can be accomplished by means of numerical simulations which have been used extensively to study cold flows resulting from cross-flow jets for the last fifty years. [6-8]

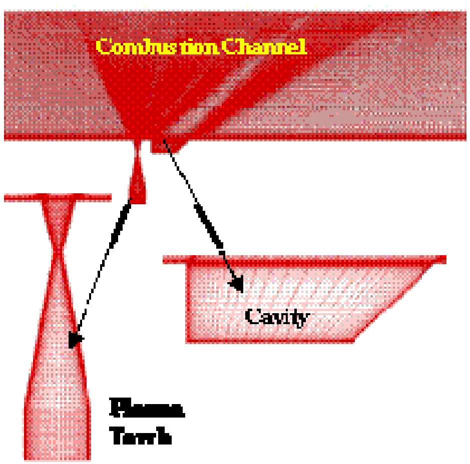

Fig. 1. Computational domain

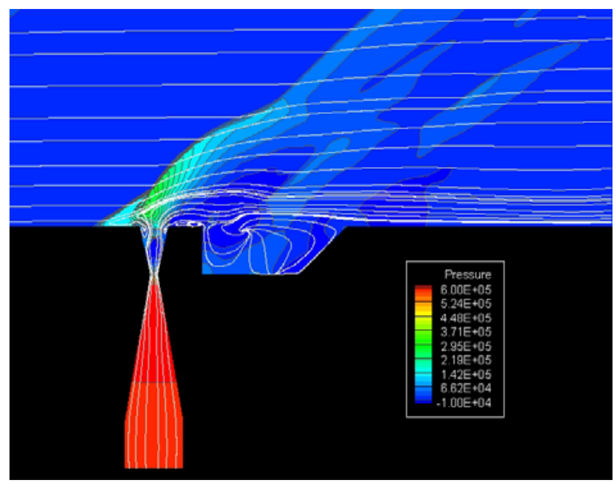

Fig. 2. Pressure contours near torch nozzle shown together with patterns of streamlines

In the present work, preliminary numerical simulations of plasma assisted combustion at high speed are carried out. The focus of the computational model is to provide details of the flowfield structure during mixing between a fuel-air mixture and a feedstock. The computational domain is shown in Figure 1. It is assembled of a rectangular combustion channel (35×10 mm^2), part of the plasma torch and a cavity (depth is 10 mm, floor is 20 mm, downstream face is inclined at 45 deg). A mixture of propane-air enters from the left upstream of the plasma jet at Mach number of two. As an initial step, products of propane-air combustion at the temperature of adiabatic flame are supplied through the plasma torch. Several simulations were carried out with different flow conditions (chemical reaction on and off, different mass flow rates of feedstock). Parameters such as a plasma jet height penetration, location of a shock developed as a result of interaction between incoming supersonic flow and jet, temperature distribution and recirculation in the cavity were examined. Figure 2 represents instantaneous static pressure contours near the torch nozzle together with patterns of streamlines.

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Application of Erosive Plasma Generator Over Flammable Liquids

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Nowadays a problem of effective ignition and combustion of fuels is facing a development of a new generation of aircraft. Active search of new effective and reliable ways of flammable substances ignition in the high-speed flows takes place in different laboratories, which provide for considerable improvement of combustor chambers and engine characteristics. By now a great number of experiments on ignition and combustion of gaseous hydrocarbon fuels were realized with a help of different gas discharges, but questions of combustion activation and ignition of liquid hydrocarbon fuels with a help of plasma are investigated much less, but they are closer to real conditions. Questions of discharge development over surfaces of liquid fuels and dielectric liquids are practically uninvestigated yet. In this work we consider preliminary experiments with erosive discharge over liquids – water and alcohol.

CAPILLARY LONG PLASMA GENERATOR.

Principle scheme of a long capillary plasma generator (LCD) is represented in Fig.1. Its connection scheme with a power block is represented in Fig. 2.

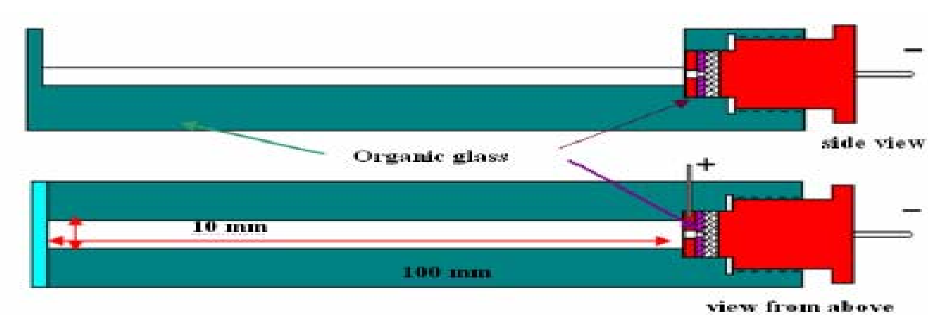

Fig. 1. Principle scheme of long capillary plasma generator (LCD)

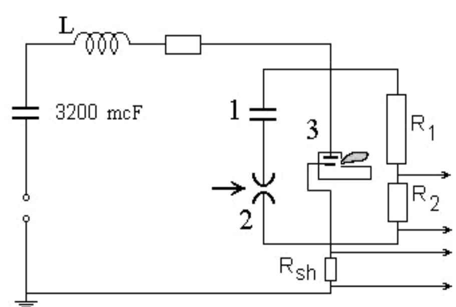

Fig. 2. Principle scheme of the circuit with capillary long plasma generator.
1 – initiating capacity; 2 –a commutator creating the initiating breakdown;
3 – a capillary, R_1, R_2 – resistances of the voltage divider.

LCD is made of organic glass (PMMA, which melting temperature is T~ 120-130°C), material of the electrodes is copper, graphite; the erosive insert is organic glass. A cuvette for location of working liquids has dimensions of 142´10´ 6 mm. The long dimension of a channel was chosen to observe the motion of a liquid and development of hydrodynamic processes.

Temporary dependencies of current and voltage in the discharge permitted the evaluation of maximum values of the voltage and the current: U_{max}=240 B, I_{max}=1,8×10^{3}A, and by integrating obtain energy stored in the discharge: E=390 J. These characteristics show that the discharge operation time is t_{dis}≈10 ms. Energy of the discharge is close to those realized in the work by Ershov A.P. et al Avramenko R.F. et al [1-2], so we can expect close plasma characteristics at the exit from the plasma generator channel. Their work shows realization of high gas and electronic temperatures ~6 kK and electron concentrations Ne~10^{17}-10^{18} cm^{-3} in the plasma generator's channel, which can thermally and chemically impact on hydrocarbon gases.

Investigations of erosive discharge stream over water surface were made with a help of a 9-frame camera K011. In Fig. 3 one can see the plasma stream propagation over water in a time period of 2,100 – 3,700 *ms* from the starting moment of plasma flow. One can see in these frames that water begins to intensively vaporize, characterized by appearance of a wider halo over the channel. In Fig.4. one can see ignition of vapors over the alcohol surface.

The experiments undertaken have shown that an erosive plasma can be an effective heater of water surface and igniter of vapors over flammable liquids (alcohol).

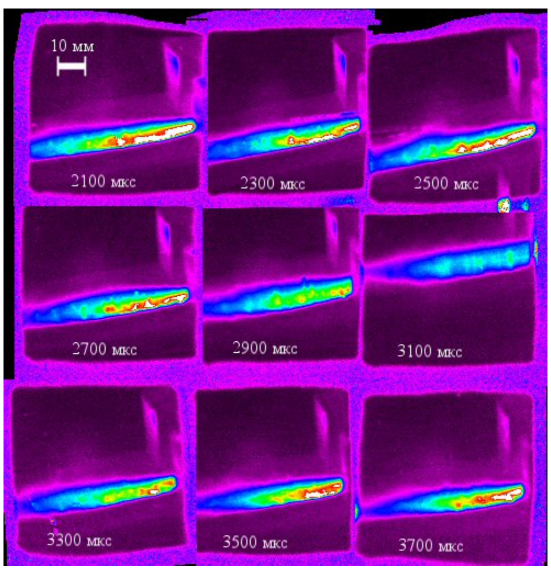

Fig. 3. Frames of plasma stream propagation over water surface (100,100,2000). Size in the frames is in mm, time moments are in ms

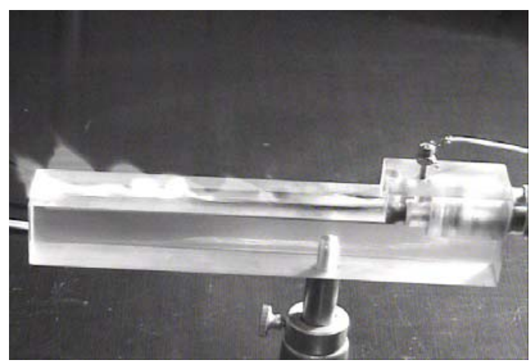

Fig. 4. Frames of plasma stream ignition of vapors over alcohol surface

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New Plasma Technologies for Fuels Utilization

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This paper presents new plasma technologies of fuel utilization, which were developed and advanced to a commercial or experimental-industrial scale [1-4]. They are plasma technology of oil (gas)-free boilers start-up and pulverized coal flame stabilization at coal fired thermal power plants; plasma technology of liquid slag stabilization for the boilers with liquid slag removal; plasma technology of power coals processing to carbonic sorbents; scheme for decentralized heat supply with use of plasma gasification of coal and thermo-chemical preparation of fuels for burning; plasma technology of pulverized coal ignition and the flame stabilization in rotary furnaces for alumina agglomeration in the aluminum industry and for oil-free clinker firing for cement production; plasma technology for oil refining residuum utilization; plasma-cyclone technology for bricks firing; plasma-coal technology for heating and annealing for the details for blacksmith's work. These technologies are realized with the aid of plasma-fuel systems (PFS) which were developed to improve efficiency of coal combustion for power production and to decrease harmful emission. PFS is pulverized coal burner equipped with an arc plasmatron. The base of the PFS technology is plasma thermo-chemical preparation of coal for burning. It consists of heating of the pulverized coal and air mixture by an arc plasma up to temperature for coal volatiles release and char carbon partial gasification. In PFS the coal-air mixture is deficient in oxygen and the carbon is oxidised mainly to carbon monoxide. As a result, at the exit from the PFS a highly reactive mixture of combustible gases and partially burned char particles, together with products of combustion, are formed, while the temperature of the gaseous mixture is around 1,300K. Further mixing with the air promotes intensive ignition and complete combustion of the prepared fuel. The main part of the PFS is the plasmatron. Its operational capability under industrial conditions depends on the life of its electrodes. A direct current air arc plasmatron with the cathode life significantly exceeding 500 hours has been developed. To ensure long life of the electrodes the process of hydrocarbon gas dissociation in the electric arc discharge is used.

To produce gas suitable for use in a power-plant a technology of plasma steam-air gasification of coal and a plasma gasifier was developed. This technology solves the problems of oil-free start-up of the boilers, pulverized flame stabilization, liquid slag stabilization at the boilers with liquid slag removal. It decreases nitrogen oxides formation and permits the broadening of the range of coal types incinerated at one and the same boiler's furnace, keeping technical, economical and ecological parameters of the boiler within design boundaries. One more technology is plasma-steam gasification and complex processing of coal to produce synthesis gas ($CO+H_2$), hydrogen (H_2) from organic mass of coal and valuable components from its mineral mass. This technology is directed to advance several branches of industry such as heat-and-power generation, chemical and industry, metallurgical industry. From the ecological point of view this technology is most promising. It consists of heating coal dust coal by with an arc plasma, which is an oxidant, up to the temperature of complete gasification. The organic mass of the coal is thereby converted into environmentally friendly fuel such as synthesis gas, which is free from ash particles, nitrogen oxides and sulphur oxides. Simultaneously reduction of the oxides of the mineral mass of coal is taking place and valuable components such as silicon, ferrosilicon, aluminum, carbo-silicon and microelements of rare metals (uranium, molybdenum, vanadium etc.) are recovered.

To incorporate a new technology it is necessary to demonstrate its advantages in comparison with conventional technologies. Here mathematical modeling and numerical analysis are indispensable. To numerically investigate the these technologies and to develop equipment for their realization the following developed and standard mathematical models and computer codes are used.

Automated software code TERRA for thermodynamic calculations of multi-component heterogeneous systems is used to determine the conditions for thermal equilibrium of fuel and oxidant mixture at high temperatures. Code TERRA has a database of thermodynamic properties for more than 3,500 chemical compounds over a temperature range of 300 to 6,000 K. The database includes thermodynamic properties of organic and mineral components of hydrocarbon fuels.

Computer code PLASMA-COAL is designed for computation of the processes of moving, heating and kinetics of thermo-chemical conversion of the coal-oxidant mixture in PFS or plasma reactor. The base of this code is a one-dimensional model which describes a two-phase chemically reacting flow with an internal plasma source. The model is distinguished by its detailed description of the kinetics of chemical reactions for 116 reactions. The kinetic scheme includes the stages of coal volatile matter evolution, char carbon, sulphur and nitrogen gasification and conversation of evolved volatile products in the gas phase.

Computer codes FLOREAN (Institut für Wärme- und Brennstofftechnik, Braunschweig, Germany), CINAR ICE (Imperial College London, UK) and PFS-CFD the base of which is KIVA-F (Rouen University, France) are used for three-dimensional computation for the furnaces employed to burn pulverized coal for boilers, including boilers equipped with PFS. These codes are based on numerical solution of the equations of energy and mass transfer taking into account the chemical reactions.

All the mentioned codes were validated comparing experiments in laboratory with full-scale operating conditions. These codes ensure competitiveness of the new technologies due to decrease in the cost for the research and experimental development and to reduce the duration of the latter and to accelerate the process of the realization of the technologies.

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Plasma Clean – a Non-Thermal Plasma Approach to Air Quality Improvement

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INTRODUCTION

Plasma Clean has developed an affordable low power non-thermal plasma system for the treatment of contaminated air. We have adopted a modular approach to plasma cassette design (see Figure 1) which is scaleable depending on the air processing requirements. The system has been designed to remove low levels (less than 50ppm) of organic contaminants from air and we have shown that efficiency, unlike conventional air cleaning techniques, increases with decreasing concentration of pollutant. This is of particular advantage for odour abatement where odours are generally sub-100ppb. The system remains at ambient temperature during normal operation and unlike many non-thermal plasma systems the NOx output is negligible.

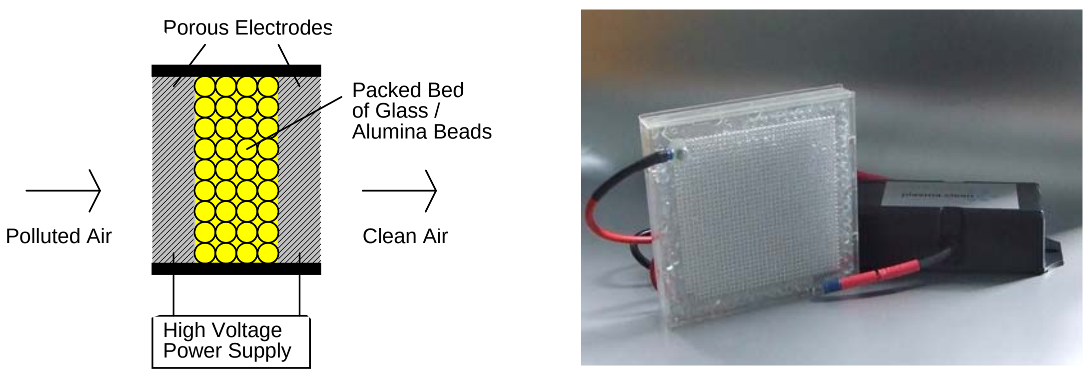

Fig. 1. Schematic diagram and image of a Plasma Clean cassette. A high voltage is applied across the electrodes which results in a plasma discharge at the interface between the beads in the pack bed. Each module is 140mm (5 1/2 inch) square.

VOC ABATEMENT AND ODOUR CONTROL

Volatile Organic Compounds (VOCs) are organic chemicals that form a gas at room temperature. They are used in a wide range of market sectors from semi-conductor manufacturing plants to chemical processing plants including paint, coatings and chemical manufacturing. VOCs which are allowed to escape into the atmosphere contribute significantly to photochemical smog production and many VOCs have detrimental affects on human health. As a result there is increasing legislation aimed at controlling the emission of VOCs.

Conventional technniques for VOC abatement include adsorption by activated carbon, thermal incineration and thermal catalysis. Adsorption methods using activated carbon are widely used to remove VOCs but the adsorption efficiency is often low and so large volumes of material are required. This increases the cost to push waste gas through the system. Changes in landfill legislation in the UK also means that disposal of contaminated carbon is becoming increasingly expensive. Thermal techniques can also have a high capital cost and tend to be economically viable only when large volumes of highly contaminated gas streams are to be treated.

Plasma Clean has developed an innovative system for improving environmental air quality by the removal of harmful Volatile Organic Compounds (VOCs), odours and microbes. Plasma Clean's patented non-equilibrium, or non-thermal, gas plasma technology is referred to as a dielectric barrier surface discharge reactor (DBSD). Inside the Plasma Clean cassette, the temperature of the energetic electrons range from 10,000 to 100,000K, whilst the actual gas temperature remains near ambient. Through electron-impact ionization, dissociation and excitation of the source gases, active radicals and ionic and excited atomic and molecular species are generated, which can initiate plasma-enabled chemical reactions (Figure 2).

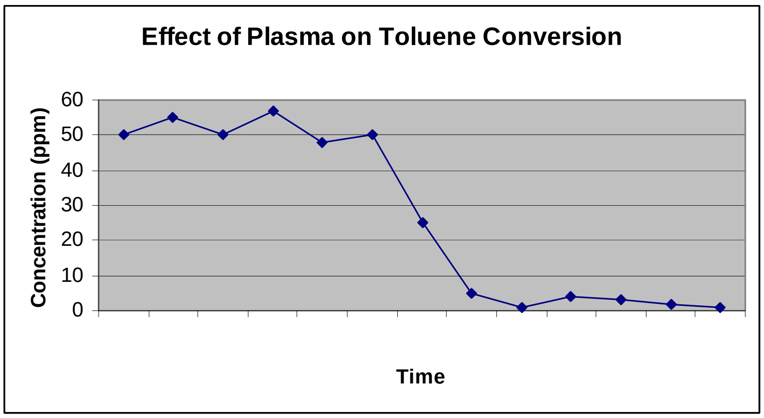

Fig. 2. Removal of 50ppm toluene by a Plasma Clean DBSD cassette. Contaminated air with a face velocity of 0.25m/s in ambient temperature and pressure conditions. Plug power: 160W.

SUMMARY

The Plasma Clean system requires low power levels to operate and has a low back pressure which means that running costs are significantly reduced compared to alternative technologies such as carbon. The Plasma Clean system is therefore less expensive both economically and in terms of environmental impact.

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***David Glover** is CEO of Plasma Clean Ltd, a UK-based start-up focussing on non-thermal plasma's for pollution control. David has worked in the technology sector for the past 15 years and has been involved in developing and financing a number of early stage technology businesses. David has a doctorate in environmental microbiology and started his career by studying the role of environmental micro-organisms in pollution control. Although the focus has now switched from microbes to plasma's the common theme has always been to help create a safer and better environment.*

New Solar Cell Manufacturing Processes and Equipment Using Atmospheric Plasma Technology

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The manufacture of solar cells for the purpose of the production of electric power requires many fabrication steps and processes similar to those used in the manufacture of integrated circuits in the semiconductor industry. Such as wafer fabrication, diffusion, contact formation etc.

The solar cell manufacturing process, however, is substantially more cost driven than that of semiconductor integrated circuit fabrication that is mainly driven by performance. The solar cell manufacturing industry has a track record of 35% CAGR

A typical solar cell fabrication process starting with sawn polycrystalline wafers involves the following process steps:

- Wafer etching for removal of surface damage and surface texturing*
- Diffusion in air for junction formation *
- Glass removal etching *
- Anti-reflection coating *
- Metallization
- Edge isolation
- Cell testing

The typical cost for a solar cell is 1.37 $/watt

The cost for each of the required process steps and the cost of the material, including wafer cost, are shown in Fig.1 in the form of a pie chart.

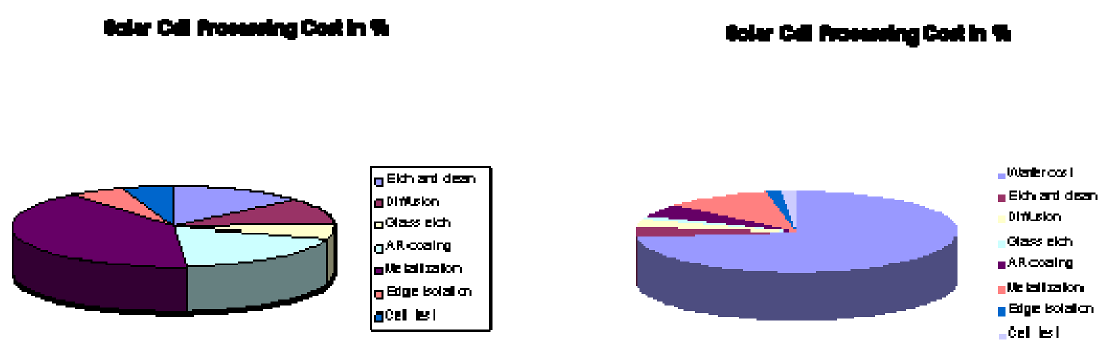

Fig.1: Cost per watt for poly-crystalline solar cells

Essentially all process steps involve relatively conventional technology frequently adopted from the semiconductor industry and adapted in the interest of cost. The process steps starred involve high temperature processing, thin film coating or chemical etching. These same processes are subject to innovation by atmospheric plasma technology and consequent substantial cost reduction.

Process steps using chemical etching are particularly troublesome due to the environmental impact and costs resulting from the necessity to dispose large quantities of spent acids.

In this presentation potential new and low cost plasma processes are suggested and discussed. The economic impact of these on the mainstream solar cell fabrication is described indicating a possible significant market for novel processes and equipment for the burgeoning photovoltaic industry.

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JOURNAL PUBLICATION

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Manuscript submission deadline **01-March-2008.**

Announcing a Special Issue of the IEEE Transactions on Plasma Science Plasma-Assisted Combustion (Scheduled for December 2008)

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 2008.

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 2006) 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, 2008** 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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