



International Plasma Technology Center

**PLASMA ASSISTED
COMBUSTION,
GASIFICATION, AND
POLLUTION CONTROL**

**Volume II. Combustion and
Gasification**

Chief Editor
Igor B. Matveev

**Outskirts Press, Inc.
Denver, Colorado**

PREFACE

Dear Reader,

As promised, we published Volume 2 of the Plasma Assisted Combustion book, as we call it PAC book, and appreciate your interest in this new, fast growing and exciting field.

You may know that Volume 1 provided a description of different plasma sources especially designed for PAC. Here we collected the most valuable contributions to the field from different research groups all over the globe starting from 1970s. They cover all three types of fuels – gases, liquids, and solids and describe PAC processes that are under development or used industrially.

The first practical applications of different plasma sources for ignition and combustion enhancement date back to the 1960s and 1970s. The first PAC conference was organized by the Editor in 1989 in the former Soviet Union. At this time, the PAC community is relatively well organized with an annual International Workshop and Exhibition on Plasma Assisted Combustion (IWEPEC), now converted into the International Conference on Plasma Assisted Technologies or ICPAT starting in 2012, and special issues in the IEEE Transactions on Plasma Science on the topic of Plasma Assisted Technologies.

This two-volume work is one of the first projects of the newly established International Plasma Technology Center (IPTC). If successful, we plan to publish new editions every three-five years depending on progress in the field.

This book is intended to be used as a textbook at the senior or first-year graduate level by students from all engineering and physical science disciplines, by PhD students, researchers, and as a reference source by in-service engineers and other researchers.

Basic information on plasma physics and the accompanying physical processes important in PAC are contained in Volume 1. Devices, technologies, current state, and future works are placed in Volume 2.

This book does not contain derivations from first principles of some of the more advanced material from plasma physics, electrical engineering, or materials science. Such material can be found in graduate texts. This is also not an encyclopedia.

I would like to express my appreciation to all contributing authors (over 10 from 5 countries), whose support, suggestions, and hard work have contributed to the book in its present form.

Many thanks to the reviewers, whose valuable comments helped significantly improve the quality of the book.

I especially would like to thank Dr. Louis Rosocha for his helpful scientific editing of chapters 1-4, Mr. Michael Rosenberg for very thorough editing of chapters 4 and 8, and my wife Svetlana for technical editing and formatting of the book.

Finally, I am especially desirous of establishing contact with the university professors who teach or plan to develop courses on PAC, students, PAC researches, in-service professionals, and potential investors who use this book, in order to improve it, correct it, and answer any questions. Please feel free to contact me with any corrections or comments at (703) 340-5545 voice, (703) 849-8417 fax or by e-mail at ibmatveev@gmail.com.

*Best regards,
The Editor*

*Igor Matveev, Ph.D.
McLean, Virginia, USA
November 20, 2015*

AUTHORS

NIKOLAY V. ARDELYAN
Lomonosov Moscow State University
Moscow, Russia

VLADIMIR L. BYCHKOV
Lomonosov Moscow State University
Moscow, Russia

IGOR I. ESAKOV
Moscow Radiotechnical Institute
Moscow, Russia

LEV P. GRACHEV
Moscow Radiotechnical Institute
Moscow, Russia

MILAN HRABOVSKY
Institute of Plasma Physics ASCR
Prague, Czech Republic

KONSTANTIN V. KOSMACHEVSKII
Lomonosov Moscow State University
Moscow, Russia

IGOR B. MATVEEV
Applied Plasma Technologies, LLC
McLean, USA

VLADIMIR E. MESSERLE
Al-Farabi Kazakh National University
Almaty, Kazakhstan

ALEXANDER A. RAVAEV
Moscow Radiotechnical Institute
Moscow, Russia

SERHIY I. SERBIN
National University of Shipbuilding
Nikolaev, Ukraine

ALBINA A. TROPINA
Kharkov National Automobile and
Highway University
Kharkov, Ukraine

BORIS G. TRUSOV
Bauman Moscow State Technical
University
Moscow, Russia

ALEXANDER B. USTIMENKO
Al-Farabi Kazakh National University
Almaty, Kazakhstan

SERGEI G. ZVEREV
Peter the Great St.-Petersburg
Polytechnic University
St.-Petersburg, Russia

CONTENTS

Preface	3
Authors	4
CHAPTER 1. Mathematical Modeling and Theoretical Investigations of Plasma-Chemical Combustion Processes (Serhiy I. Serbin)	10
1.1. Introduction.....	11
1.2. Trends of plasma-chemical-based combustion intensification applications in power plants	14
1.3. Modeling of gaseous flows	18
1.4. Modeling of liquid fuel combustion	25
1.5. Kinetic scheme of high-temperature hydrocarbon oxidation in the plasma flow.....	33
1.6. Reactor model of plasma-chemical conversion	35
1.7. Mechanism of pollutant formation in plasma-chemical combustion devices.....	38
1.8. Thermal influence of low-temperature plasma on liquid fuel burning	50
1.9. Characteristics of liquid fuel gasification	56
1.10. Investigations of plasma-chemical intensification in gas turbine combustors.....	60
1.11. Investigations of plasma-chemical intensification in internal combustion engines	78
References	84
CHAPTER 2. Numerical Modeling of Hot Jets Utilized by DC Plasma Generators for PAC (Nikolay V. Ardelyan, Vladimir L. Bychkov, Konstantin V. Kosmachevskii)	90
2.1. Introduction.....	91
2.2. Modeling of plasma jet generation	91
2.2.1. Plasma generators and properties of the generated plasma	91
2.2.2. Physical model	95
2.2.3. Mathematical model	100

2.2.4. Applied numerical method	102
2.2.5. Plasma jet formation and its impact on the counterflow	108
2.3. Plasma jet ignition of propane-air stoichiometric mixture.....	125
2.3.1. Ignition of propane-air stoichiometric mixture counterflow by the plasma jet.....	125
2.3.2. Modeling of the flat plasma jet in a stoichiometric propane-air supersonic crossflow	131
2.4. Conclusions.....	134
References	136
CHAPTER 3. Ignition (<i>Igor B. Matveev, Serhiy I. Serbin, Albina A. Tropina, Igor I. Esakov, Lev P. Grachev, Alexander A. Ravaev</i>).....	140
3.1. Introduction (<i>Igor B. Matveev</i>)	141
3.2. Ignition by low-current thermal plasma igniters (<i>Igor B. Matveev, Serhiy I. Serbin</i>).....	141
3.3. Ignition and pilots based on quasi-steady discharges (<i>Igor B. Matveev</i>).....	153
3.3.1. Atmospheric pressure igniters	153
3.3.2. High pressure pilots.....	156
3.3.3. Supersonic igniters	158
3.3.4. Power Supply Development	160
References to 3.1–3.3	164
3.4. Nanosecond pulsed discharge as an ignition source (<i>Albina A. Tropina</i>).....	166
3.4.1. Introduction	166
3.4.2. Mathematical model.....	169
3.4.3. Numerical results.....	174
3.4.4. The nanosecond pulsed igniter for internal combustion engines	180
3.4.5. Experimental results, step 1: breakdown ignition system based on the nanosecond pulsed discharge.....	182
3.4.6. Experimental results, step 2: ignition system based on a nanosecond pulsed discharge	190
References to 3.4	193
Attachments	197
3.5 Microwave ignition in high speed flows (<i>Igor I. Esakov, Lev P. Grachev, Alexander A. Ravaev</i>)	202
References to 3.5	211
3.6 RF ignition (<i>Igor B. Matveev</i>).....	212
References to 3.6	214

CHAPTER 4. Flame Control – Combustion Sustaining (<i>Igor B. Matveev, Serhiy I. Serbin</i>).....	215
4.1. Plasma fuel nozzles (PFNs)	216
4.2. Combustors with plasma assistance.....	225
4.2.1. Cold flow structure in a reverse vortex combustor	225
4.2.2. Hot flow structure in a reverse vortex combustor with plasma assistance.....	238
4.2.3. Investigations of a triple vortex combustor with spatial arc.....	249
4.2.4. Numerical optimization of reverse vortex combustor aerodynamic parameters.....	257
4.3. A hybrid type plasma assisted combustion and reformation system	264
4.4. High power combined plasma chemical gasification and combustion system for contaminated liquid hydrocarbon destruction.....	274
4.5. Synthesis gas afterburner based on injector type plasma assisted combustion system.....	280
References	289
CHAPTER 5. Plasma Gasification (<i>Vladimir E. Messerle, Boris G. Trusov, Alexander B. Ustimenko, Igor B. Matveev</i>)	294
List of symbols	295
Indices.....	297
5.1. Introduction.....	298
5.2. Plasma thermal and chemical treatment of fuel.....	299
5.2.1. Thermodynamic modeling	299
5.2.2. Experimental installations	302
5.2.3. Experiments and discussion	304
5.3. Complete gasification of coal	310
5.3.1. Description of the bench scale setup	310
5.3.2. Experimental procedure	312
5.3.3. Experimental results	314
5.4. Thermodynamic modeling of coal gasification (<i>Vladimir E. Messerle, Boris G. Trusov, Alexander B. Ustimenko</i>).....	316
5.4.1. Thermodynamic model TERRA.....	316
5.4.2. Calculations of the equilibrium state parameters for complicated systems.....	321
5.5. One-dimensional kinetic model of a plasma gasifier (<i>Vladimir E. Messerle, Alexander E. Ustimenko</i>).....	323

5.5.1. Mathematical model Plasma-Coal and kinetic scheme	323
5.5.2. Numerical simulation results	333
5.5.3. Comparison of experimental and calculated data.....	335
5.6. Plasma gasification of coal of varied ranks	336
5.6.1. Numerical Simulation.....	336
5.6.2. Experimental	342
5.7. Thermodynamic and kinetic modeling of bituminous coal plasma gasification (Igor B. Matveev, Vladimir E. Messerle, Alexander E. Ustimenko)	347
5.7.1. Thermodynamic Simulation	348
5.7.2. Kinetic Simulation.....	350
5.8. Plasma gasification of coal with different oxidants	356
5.8.1. Numerical Experiments	356
References	362
CHAPTER 6. Plasma Support of Soal Ignition and Combustion (<i>Vladimir E. Messerle,</i> <i>Alexander E. Ustimenko</i>).....	366
6.1. Introduction.....	367
6.2. Plasma supported coal combustion.....	368
6.2.1. Basic principle of plasma technology of coal ignition	369
6.2.2. Measurement in and computation of the PFS.....	371
6.2.3. 3D modeling of pulverized coal combustion in a TPP furnace Practical set-up	379
6.2.4. Practical application of plasma-fuel systems in coal-fired TPPs	383
6.3. Efficiency of plasma ignition processes: experimental and numerical investigations of coal ignition and combustion	387
6.3.1. Plasma-Fuel System	388
6.3.2. PFSs Industrial Tests	389
6.3.3. Simulation of the Furnace Equipped with PFS: Method and the Comparison of Numerical and Experimental Data.....	391
6.3.4. Simulation of 75 t/h steam productivity industrial boiler's furnace equipped with PFS s	398
6.3.5. Simulation and a full-scale test for a boiler of 420 t/h steam productivity	402
6.4. Plasma ignition solutions for coal fired boilers	407
6.5. Conclusions.....	413
References	415

CHAPTER 7. Plasma Gasification of Organic Waste and Biomass (<i>Milan Hrabovsky</i>).....	418
7.1. Introduction.....	419
7.2. Processes in plasma gasification reactor.....	421
7.3. Energy balance of plasma gasification.....	425
7.4. Effect of kinetics of the process.....	428
7.5. Experimental investigation of plasma gasification in steam plasma	431
7.5.1. Plasma gasification reactor.....	431
7.5.2. Gasification of biomass and plastics	433
7.5.3. Gasification of pyrolytic oil	437
7.6. Conclusions.....	442
References	443
CHAPTER 8. Gasification Based on the Second Generation RF Plasma (<i>Igor B. Matveev, Serhiy I. Serbin</i>)	447
8.1. New generation RF plasma.....	449
8.1.1. Introduction	449
8.1.2. Progress in the second generation RF plasma development (<i>Igor B. Matveev, Sergei G. Zverev, Svetlana A. Matveyeva</i>).....	450
8.2. Alternatives for coal (<i>Igor B. Matveev</i>)	455
8.2.1. Introduction	455
8.2.2. Plasma coal treatment.....	455
8.2.3. Alternative power plant with plasma coal gasification	456
8.3. Integrated plasma coal gasification combined cycle power plant (<i>Igor B. Matveev, Serhiy I. Serbin</i>)	460
8.3.1. Introduction	460
8.3.2. IPGCC	461
8.4. Sewage sludge-to-power.....	470
8.4.1. Introduction	470
8.4.2. New approach.....	470
8.5. Gas-to-liquids.....	477
8.5.1. Introduction	477
8.5.2. Plasma assisted reforming of natural gas for GTL.....	478
8.5.3. Modeling of the methane-oxygen reformer.....	483
8.5.4. Gas turbine integrated GTL.....	489
References	495