

INSTITUTE OF PHYSICS

SERIES IN PLASMA PHYSICS

SERIES EDITORS:

S COWLEY, P STOTT AND H WILHELMSSON

The Series in Plasma Physics is an international series that meets the need for up-to-date texts in this rapidly developing field. Books in the series range in level from introductory monographs and practical handbooks to more advanced expositions of current research. Spanning both laboratory and astrophysical plasmas, topics covered include: magnetohydrodynamics and kinetic theory, waves and instabilities, magnetic and inertial confinement fusion, electron, ion and photon acceleration and heating, transport, turbulence, nonlinear plasma physics, dusty plasma physics, diagnostics, plasma processing and plasma simulation.

Atmospheric-pressure plasmas continue to attract considerable research interest due to their diverse applications including high power lasers, opening switches, novel plasma processing applications and sputtering, EM absorbers and reflectors, remediation of gaseous pollutants, and excimer lamps and other non-coherent light sources. Atmospheric-pressure plasmas in air are of particular importance as they can be generated and maintained without vacuum enclosure and without any additional feed gases.

This book reviews recent advances and applications in the generation and maintenance of atmospheric-pressure air plasmas. With contributions from leading international researchers the coverage includes advances in atmospheric-pressure plasma source development, diagnostics and characterization, air plasma chemistry, modeling and computational techniques, and an assessment of the status and prospects of atmospheric-pressure air plasma applications. The extensive sections on applications makes this book attractive for practitioners in many fields of application where technologies based on atmospheric-pressure air plasmas are emerging.

ISBN 978-0-367-86417-0



9 780367 864170



CRC Press

Taylor & Francis Group
an informa business

www.crcpress.com



1	Introduction and Overview	1
1.1	Motivation	2
1.2	Parameter Space of Interest	4
1.3	Naturally-occurring Air Plasmas	7
1.4	Sources of Additional Information	9
1.5	Organization of this Book	12
2	History of Non-Equilibrium Air Discharges	17
2.1	Introduction	17
2.2	Historical Roots of Electrical Gas Discharges	17
2.3	Historical Progression of Generating Techniques for Hot and Cold Plasmas	19
2.3.1	Generation of hot plasmas	19
2.3.2	Generation of cold plasmas	21
2.3.3	Properties of non-equilibrium air plasmas	24
2.4	Electrical Breakdown in Dense Gases	29
2.4.1	Discharge classification and Townsend breakdown	29
2.4.2	Streamer breakdown	35
2.4.3	Pulsed air breakdown and runaway electrons	38
2.5	Corona Discharges	41
2.5.1	Phenomenology of corona discharges	41
2.5.2	Negative dc corona discharges	47
2.5.3	Positive dc corona discharges	54
2.5.4	AC corona discharges	60
2.5.5	Pulsed streamer corona discharges	63
2.6	Fundamentals of Dielectric-Barrier Discharges	68
2.6.1	Early investigations	68
2.6.2	Electrode configurations and discharge properties	70
2.6.3	Overall discharge parameters	70

3	Kinetic Description of Plasmas	76
3.1	Particles and Distributions	76
3.2	Forces, Collisions, and Reactions	90
3.3	The Kinetic Equation	105
3.4	Evaluation and Simplification of the Kinetic Equation	117
4	Air Plasma Chemistry	124
4.1	Introduction	124
4.2	Air Plasma Chemistry Involving Neutral Species	127
4.2.1	Introduction	127
4.2.2	Neutral chemistry in atmospheric-pressure air plasmas	128
4.2.3	Summary of the important reactions for the neutral air plasma chemistry	130
4.3	Ion-Molecule Reactions in Air Plasmas at Elevated Temperatures	136
4.3.1	Introduction	136
4.3.2	Internal energy definitions	138
4.3.3	Ion-molecule reactions	140
4.3.4	Summary	153
4.4	Non-Equilibrium Air Plasma Chemistry	154
4.4.1	Introduction	154
4.4.2	Translational and vibrational energy dependence of the rates of chemical processes	156
4.4.3	Advances in elucidating chemical reactivity at very high vibrational excitation	161
4.5	Recombination in Atmospheric-Pressure Air Plasmas	168
4.5.1	Theory	169
4.5.2	$O_2^+ + e^-$	170
4.5.3	$NO^+ + e^-$	171
4.5.4	$N_2^+ + e^-$	173
4.5.5	$H_3O^+(H_2O)_n$	174
4.5.6	High pressure recombination	175
5	Modeling	183
5.1	Introduction	183
5.2	Computational Methods for Multi-dimensional Nonequilibrium Air Plasmas	185
5.2.1	Introduction	185
5.2.2	Basic assumptions	186
5.2.3	The conservation equations	186
5.2.4	Equations of state	189
5.2.5	Electrodynamic equations	189
5.2.6	Transport properties	190

5.2.7	Chemical kinetics	193
5.2.8	Numerical method	193
5.2.9	Simulation results	195
5.2.10	Conclusions	198
5.3	DC Glow Discharges in Atmospheric Pressure Air	199
5.3.1	Introduction	199
5.3.2	Two-temperature kinetic simulations	200
5.3.3	Predicted electric discharge characteristics	211
5.3.4	Experimental dc glow discharges in atmospheric pressure air plasmas	218
5.3.5	Electrical characteristics and power requirements of dc discharges in air	228
5.3.6	Conclusions	231
5.4	Multidimensional Modeling of Trichel Pulses in Negative Pin-to-Plane Corona in Air	233
5.4.1	Introduction	233
5.4.2	Numerical model	235
5.4.3	Results of numerical simulations	238
5.4.4	Conclusions	244
5.5	Electrical Models of DBDs and Glow Discharges in Small Geometries	245
5.5.1	Introduction	245
5.5.2	Model of plasma initiation and evolution	246
5.5.3	Dielectric barrier discharges	251
5.5.4	Micro-discharges: discharges in small geometries	258
5.5.5	Conclusions	259
5.6	A Computational Model of Initial Breakdown in Geometrically Complicated Systems	262
5.6.1	Introduction	262
5.6.2	The numerical model	265
5.6.3	Simulation results	269
5.6.4	Discussion	274
6	DC and Low Frequency Air Plasma Sources	276
6.1	Introduction	276
6.2	Barrier Discharges	277
6.2.1	Multifilament barrier discharges	278
6.2.2	Modeling of barrier discharges	280
6.3	Atmospheric Pressure Glow Discharge Plasmas and Atmospheric Pressure Townsend-like Discharge Plasmas	286
6.3.1	Introduction	286
6.3.2	Realization of an APG discharge plasma	287
6.3.3	Applications of APG discharge and APT discharge plasmas	291

6.4	Homogeneous Barrier Discharges	293
6.4.1	DBD-based discharges at atmospheric pressure	294
6.4.2	The resistive barrier discharge (RBD)	299
6.4.3	Diffuse discharges by means of water electrodes	301
6.5	Discharges Generated and Maintained in Spatially Confined Geometries: Microhollow Cathode (MHC) and Capillary Plasma Electrode (CPE) Discharges	306
6.5.1	The microhollow cathode discharge	307
6.5.2	The cathode boundary layer discharge	319
6.5.3	The capillary plasma electrode discharge	321
6.5.4	Summary	324
6.6	Corona and Steady State Glow Discharges	328
6.6.1	Introduction	328
6.6.2	Methods to control negative corona parameters	329
6.6.3	DC glow discharge in air flow	334
6.6.4	Transitions between negative corona, glow and spark discharge forms	338
6.6.5	Pulsed diffuse glow discharges	348
6.7	Operational Characteristics of a Low Temperature AC Plasma Torch	350
6.7.1	Introduction	350
6.7.2	Torch plasma	351
6.7.3	Power consumption calculation	359
7	High Frequency Air Plasmas	362
7.1	Introduction	362
7.2	Laser Initiated or Sustained, Seeded High-Pressure Plasmas	364
7.2.1	Introduction	364
7.2.2	Laser-sustained plasmas with CO seedant	365
7.2.3	Ultraviolet Laser Produced TMAE Seed Plasma	379
7.3	Radiofrequency and Microwave Sustained High-Pressure Plasmas	395
7.3.1	Introduction	395
7.3.2	Review of rf plasma torch experiments	395
7.3.3	Conclusions	406
7.3.3	Laser initiated and rf sustained experiments	407
7.3.4	Methods for spatial localization of a microwave discharge	413
7.4	Repetitively Pulsed Discharges in Air	419
7.4.1	Introduction	419
7.4.2	Experiments with a single pulse	421
7.4.3	Experiments with 100 kHz repetitive discharge	423
7.4.4	Conclusions	427

7.5	Electron-Beam Experiment with Laser Excitation	427
7.5.1	Introduction	427
7.5.2	Electron loss reduction	428
7.5.3	Experimental discharge; electron beam ionizer	429
7.5.4	Results and analysis of discharge operation	431
7.5.5	Summary; appraisal of the technique	440
7.6	Research Challenges and Opportunities	443
8	Plasma Diagnostics	446
8.1	Introduction	446
8.2	Elastic and Inelastic Laser Scattering in Air Plasmas	450
8.2.1	Background and basic theory	450
8.2.2	Practical considerations	462
8.2.3	Measurements of vibrational distribution function	465
8.2.4	Filtered scattering	469
8.2.5	Conclusions	480
8.3	Electron Density Measurements by Millimeter Wave Interferometry	482
8.3.1	Introduction	482
8.3.2	Electromagnetic wave propagation in plasma	483
8.3.3	Plasma density determination	486
8.4	Electron Density Measurement by Infrared Heterodyne Interferometry	488
8.4.1	Introduction	488
8.4.2	Index of refraction	490
8.4.3	The infrared heterodyne interferometer	492
8.4.4	Application to atmospheric pressure air microplasmas	493
8.4.5	Measurement of the electron density in dc plasmas	494
8.4.5	Measurement of the electron density in pulsed operation	498
8.4.6	Conclusions	500
8.5	Plasma Emission Spectroscopy in Atmospheric Pressure Air Plasmas	501
8.5.1	Temperature measurement	501
8.5.2	NO A-X and N ₂ C-B rotational temperature measurements	506
8.5.3	N ₂ ⁺ B-X rotational temperature measurements	508
8.5.4	Measurements of electron number density by optical emission spectroscopy	508
8.6	Ion Concentration Measurements by Cavity Ring-Down Spectroscopy	517
8.6.1	Introduction	517
8.6.2	Cavity ring-down spectroscopy	518

8.6.3	N_2^+ measurements	520
8.6.4	NO^+ measurements	531

9	Current Applications of Atmospheric Pressure Air Plasmas	537
9.1	Introduction	537
9.2	Electrostatic Precipitation	539
9.2.1	Historical development and current applications	539
9.2.2	Main physical processes involved in electrostatic precipitation	541
9.2.3	Large industrial electrostatic precipitators	546
9.2.4	Intermittent and pulsed energization	549
9.3	Ozone Generation	551
9.3.1	Introduction: Historical development	551
9.3.2	Ozone properties and ozone applications	553
9.3.3	Ozone formation in electrical discharges	554
9.3.4	Kinetics of ozone and nitrogen oxide formation	555
9.3.5	Technical aspects of large ozone generators	560
9.3.6	Future prospects of industrial ozone generation	563
9.4	Electromagnetic Reflection, Absorption, and Phase Shift	565
9.4.1	Introduction	565
9.4.2	Electromagnetic theory	566
9.4.3	Air plasma characteristics	569
9.4.4	Plasma power	571
9.4.5	Applications	572
9.5	Plasma Torch for Enhancing Hydrocarbon–Air Combustion in the Scramjet Engine	574
9.5.1	Introduction	574
9.5.2	Plasma for combustion enhancement	577
9.5.3	Plasma torch for the application	580
9.6	The Plasma Mitigation of the Shock Waves in Supersonic/Hypersonic Flights	587
9.6.1	Introduction	587
9.6.2	Methods for flow control	588
9.6.3	Plasma spikes for the mitigation of shock waves: experiments and results	589
9.7	Surface Treatment	597
9.7.1	Introduction	597
9.7.2	Experimental	599
9.7.3	Cleaning	601
9.7.4	Oxidation	605
9.7.5	Functionalization	607
9.7.6	Etching	613
9.7.7	Deposition	615
9.7.8	Conclusions	617

9.8	Chemical Decontamination	621
9.8.1	Introduction	621
9.8.2	de-NO _x process	622
9.8.3	Non-thermal plasmas for de-NO _x	625
9.8.4	Parametric investigation for de-NO _x	630
9.8.5	Pilot plant and on-site tests	632
9.8.6	Effects of gas mixtures	632
9.8.7	Environmentally harmful gas treatments	636
9.8.8	Conclusion	639
9.9	Biological Decontamination by Non-equilibrium Atmospheric Pressure Plasmas	643
9.9.1	Non-equilibrium, high pressure plasma generators	643
9.9.2	Inactivation kinetics	645
9.9.3	Analysis of the inactivation factors	648
9.9.4	Conclusions	653
9.10	Medical Applications of Atmospheric Plasmas	655
9.10.1	A bio-compatible plasma source	655
9.10.2	<i>In vivo</i> treatment using electric and plasma methods	657
9.10.3	Plasma needle and its properties	663
9.10.4	Plasma interactions with living objects	666
	Appendix	673
	Index	679

Note:

A summary of references to Air Plasmas compiled by R Vidmar is available on the Web at:

<http://bookmark.iop.org/bookpge.htm?&isbn=0750309628>