M U N I

COMMENTARY TO HABILITATION THESIS

Name of the habilitation thesis

Development of Non-thermal Plasma Sources for Fast Plasma Treatment of Materials: Diagnostics and Applications

Name and surname of the applicant

Mgr. Jan Čech, Ph.D.

The thesis is designed as a commentary on annotated scientific papers. It addresses two technologically significant plasma sources for fast and efficient treatment of solid surfaces (DCSBD, Diffuse Coplanar Surface Barrier Discharge) and liquids (CaviPlasma). The selection of annotated papers summarises the author's contribution to the targeted development of these industrially applicable plasma sources at the Department of Physics and Technology at Masaryk University (DPPT).

The physical phenomena in coplanar barrier discharge (CDBD) and electric discharge in hydrodynamic cavitation were studied using various diagnostic techniques. The author was specialised in plasma diagnostics using optical emission of the discharge. He utilised the newly acquired diagnostics equipment, namely the intensified gated CCD cameras (the author was responsible for the ICCD camera selection process), for the space and phase-resolved optical emission spectroscopy and imaging, respectively. The correlated electric and optical measurements were designed to study, e.g. the statistical behaviour of microdischarges in CDBD or the development of spark/glow discharges in cavitation. The single photon counting spectroscopy was utilised for ultra-low light events, aka the newly discovered charge relaxation event in CDBD. The dynamics of microdischarges and 2D electric field development were studied using intensified CCD camera imaging. But not only were the diagnostics performed. The application potential of DCSBD and CaviPlasma discharges was also investigated, and the author was involved in numerous application tests.

In the first part of the thesis, a detailed investigation of DCSBD/CDBD was summarised in the selection of ten annotated papers. The DCSBD is a special implementation of coplanar dielectric barrier discharge, which was developed into an industrially applicable, robust and reliable plasma source at DPPT under the leadership of Prof. Mirko Černák, master's and doctoral theses supervisor of the author. The author collaborates on this progress through research on DCSBD and a dedicated CDBD setup. The author's key findings include investigating the influence of electrode arrangement and temperature on the discharge properties, and the study on microdischarges dynamics in the multi-filamentary regime of CDBD. Further research identified the residual heat influence on the memory effect of DBD and the author's discovery and characterisation of the Charge Relaxation Event (CRE), a previously undocumented pre-breakdown ultra-low intensity phenomenon of CDBD. The discovery of conditions leading to diffuse/homogeneous CDBD on microdischarge level enabled the utilisation of the helium emission lines ratio method for mapping the development of 2D-resolved electric field in helium CDBD. The author was also involved in a broad portfolio of DCSBD applications from which the application studies in a hydrogen atmosphere were selected for presentation.

The second part of the thesis deals with the discovery and utilisation of the CaviPlasma®, the technology for efficient large-volume liquid treatment. This novel and internationally patent-protected technology combines hydrodynamic cavitation with electric discharge generated at the specific axial electrode geometry. The author is a co-inventor of this technology. The commentary to the five annotated papers summarises the development of CaviPlasma from the very first steps focused on cyanobacteria-contaminated water remediation up to the current generation of the technology that was presented by the licensee at EXPO 2025 in Osaka in the form of the commercial treater prototype unit.

The annotated papers demonstrate the high-throughput water treatment with excellent treatment efficiency, e.g. hydrogen peroxide yield up to 12.4 g/kWh and production rate more than 17 g/h using the lab-scale 1.5 m^3/h CaviPlasma unit. The presented diagnostics were performed using electrical, optical, and spectral methods, as well as chemical analyses of the treated water. The parametric studies of discharge regimes of operation in unbridged and bridged electrode configurations were published. The phase-resolved imaging and electrical measurements enabled spark/glow discharge regime identification. The dedicated spectrometric study in a broad research collaboration enabled the identification of some of the generated reactive oxygen species (ROS), revealing the presence of long-living products – the hydrogen peroxide and ozone, and also short-lived products – the OH radical, or singlet oxygen. The dynamics of the OH radicals were investigated by a luminol chemiluminescence, which enabled the identification of space and time-resolved OH dynamics in the cavitation-plasma system. The mapping of OH radicals reveals the enhanced interaction zone in the cavitation cloud collapsing end and the extended interaction zones beyond the active discharge region in the after-cavitation wake stream. The author believes the CaviPlasma® technology represents a promising breakthrough in plasma-liquid treatment. It has strong potential for environmental and bio applications owing to its engineering simplicity and unprecedented volumetric rating.

The author's principal contribution to annotated papers is estimated in terms of content (quantity), summarised in the respective tables, and in terms of quality, as shown in the list below the tables.

[1] CECH, Jan*(corresponding author)*, Pavel STAHEL, Zdenek NAVRATIL and Mirko CERNAK, 2008. Space and Time Resolved Optical Emission Spectroscopy of Diffuse Coplanar Barrier Discharge in Nitrogen. *Chemicke Listy*. **102**(S4), S1348-S1351. ISSN 1213-7103.

Experimental work (%)	Supervision[1] (%)	Manuscript (%)	Research direction (%)
30	--	30	25

[2] CECH, J.*(corresponding author)*, P. STAHEL and Z. NAVRATIL, 2009. The influence of electrode gap width on plasma properties of diffuse coplanar surface barrier discharge in nitrogen. *European Physical Journal D* [online]. **54**(2), 259–264. ISSN 1434-6079. Available at: doi:10.1140/epjd/e2009-00013-1

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
60	--	50	35

[1] The category ‚Supervision' represents the supervision of students and is enumerated, where applicable.

[3] CECH, Jan*(corresponding author)*, Jana HANUSOVA, Pavel ST'AHEL and Mirko CERNAK, 2015. Diffuse Coplanar Surface Barrier Discharge in Artificial Air: Statistical Behaviour of Microdischarges. *Open Chemistry* [online]. **13**(1), 528–540. ISSN 2391-5420. Available at: doi:10.1515/chem-2015-0062

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
60	75	75	70

[4] RAHEL, Jozef, Zsolt SZALAY, **Jan CECH** and Tomas MORAVEK, 2016. On spatial stabilization of dielectric barrier discharge microfilaments by residual heat build-up in air. *European Physical Journal D* [online]. **70**(4, Article 92). ISSN 1434-6079. Available at: doi:10.1140/epjd/e2016-70061-5

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
25	--	15	15

[5] MORAVEK, Tomas, **Jan CECH**, Zdenek NAVRATIL and Jozef RAHEL, 2016. Pre-breakdown phase of coplanar dielectric barrier discharge in helium. *European Physical Journal-Applied Physics* [online]. **75**(2, Article 24706). ISSN 1286-0050. Available at: doi:10.1051/epjap/2016150538

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
30	25	25	30

[6] NAVRATIL, Zdenek, Tomas MORAVEK, Jozef RAHEL, **Jan CECH**, Ondrej LALINSKY and David TRUNEC, 2017. Diagnostics of pre-breakdown light emission in a helium coplanar barrier discharge: the presence of neutral bremsstrahlung. *Plasma Sources Science & Technology* [online]. **26**(5, Article 055025). ISSN 1361-6595. Available at: doi:10.1088/1361-6595/aa66b5

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
15	15	15	15

[7] CECH, Jan*(corresponding author)*, Zdenek NAVRATIL, Michal STIPL, Tomas MORAVEK and Jozef RAHEL, 2018. 2D-resolved electric field development in helium coplanar DBD: spectrally filtered ICCD camera approach. *Plasma Sources Science & Technology* [online]. **27**(10, Article 105002). ISSN 1361-6595. Available at: doi:10.1088/1361-6595/aade41

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
50	75	50	50

[8] PRYSIAZHNYI, V., A. BRABLEC, **J. CECH**, M. STUPAVSKA and M. CERNAK, 2014. Generation of Large-Area Highly-Nonequlibrium Plasma in Pure Hydrogen at Atmospheric Pressure. *Contributions to Plasma Physics* [online]. **54**(2), 138–144. ISSN 1521-3986. Available at: doi:10.1002/ctpp.201310060

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
15	--	20	15

[9] KROMKA, Alexander, **Jan CECH**, Halyna KOZAK, Anna ARTEMENKO, Tibor IZAK, Jan CERMAK, Bohuslav REZEK and Mirko CERNAK, 2015. Low-temperature hydrogenation of diamond nanoparticles using diffuse coplanar surface barrier discharge at atmospheric pressure. *Physica Status Solidi B-Basic Solid State Physics* [online]. **252**(11), 2602–2607. ISSN 1521-3951. Available at: doi:10.1002/pssb.201552232

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
15	--	20	15

[10] CECH, J.*(corresponding author)*, Z. BONAVENTURA, P. STAHEL, M. ZEMANEK, H. DVORAKOVA and M. CERNAK, 2017. Wide-pressure-range coplanar dielectric barrier discharge: Operational characterisation of a versatile plasma source. *Physics of Plasmas* [online]. **24**(1, Article 013504). ISSN 1089-7674. Available at: doi:10.1063/1.4973442

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
50	40	50	30

[11] MARSALEK, Blahoslav, Eliska MARSALKOVA, Klara ODEHNALOVA, Frantisek POCHYLY, Pavel RUDOLF, Pavel STAHEL, Jozef RAHEL, **Jan CECH**, Simona FIALOVA and Stepan ZEZULKA, 2020. Removal of Microcystis aeruginosa through the Combined Effect of Plasma Discharge and Hydrodynamic Cavitation. *Water* [online]. **12**(1, Article 8). ISSN 2073-4441. Available at: doi:10.3390/w12010008

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
10	--	10	10

[12] CECH, Jan*(corresponding author)*, Pavel STAHEL, Jozef RAHEL, Lubomir PROKES, Pavel RUDOLF, Eliska MARSALKOVA and Blahoslav MARSALEK, 2020. Mass Production of Plasma Activated Water: Case Studies of Its Biocidal Effect on Algae and Cyanobacteria. *Water* [online]. **12**(11, Article 3167). ISSN 2073-4441. Available at: doi:10.3390/w12113167

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
15	--	40	15

[13] CECH, J.*(corresponding author)*, P. STAHEL, L. PROKES, D. TRUNEC, R. HORNAK, P. RUDOLF, B. MARSALEK, E. MARSALKOVA, P. LUKES, A. LAVRIKOVA and Z. MACHALA, 2024. CaviPlasma: parametric study of discharge parameters of high-throughput water plasma treatment technology in glow-like discharge regime. *Plasma Sources Science & Technology* [online]. **33**(11, Article 115005). ISSN 1361-6595. Available at: doi:10.1088/1361-6595/ad7e4e

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
30	25	50	30

[14] CECH, J., P. STAHEL, L. PROKES, D. TRUNEC, R. HORNAK, P. RUDOLF, B. MARSALEK, E. MARSALKOVA and P. LUKES, 2025. Glow discharge in water cavitation cloud with improved efficiency for hydrogen peroxide production. *Plasma Sources Science & Technology* [online]. **34**(6, Article 065009). ISSN 1361-6595. Available at: doi:10.1088/1361-6595/addf79

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
30	75	50	40

[15] HORNAK, Radek, **Jan CECH*(corresponding author)***, Pavel ST'AHEL, Lubomir PROKES, David TRUNEC, Pavel RUDOLF and Blahoslav MARSALEK, 2025. Spatial Mapping of OH Radicals Produced by Electric Discharge in Hydrodynamic Cavitation Cloud. *Journal of Physical Chemistry Letters* [online]. **16**(25), 6279–6285. ISSN 1948-7185. Available at: doi:10.1021/acs.jpclett.5c00979

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
30	75	40	60

The author's qualitative contribution to the annotated papers (where appropriate (significant), the co-authors are indicated):

- [**1**] Design and construction of the "The Box" experimental apparatus (with P.S.), conduction of experiment – electrical measurements, optical emission spectroscopy (with Z.N.) and imaging, data analysis (with Z.N.), responsible for the writing of the manuscript
- [**2**] Design (with P.S. and Z.N.) and conduction of experiment – electrical measurements, optical emission spectroscopy and imaging, data analysis, responsible for the writing of the manuscript
- [3**]** Design (with P.S) and conduction (with J.H.) of experiment – electrical measurements, optical emission spectroscopy and imaging, data analysis, responsible for the writing of the manuscript
- **[4]** Numerical model and analysis of residual heat build-up, joint interpretation of results with J.R., comments on the manuscript
- **[5,6]** Discovery of investigated phenomenon, design and conduction (with T.M.) of ICCD-related measurements and analysis, preparation of the respective part of the manuscript, comments on the manuscript

- **[7]** Design (with Z.N.) and conduction of ICCD-related measurements (with Z.N., T.M. and M.S.) and analysis (with Z.N.), responsible for the writing of the manuscript
- **[8]** Design and conduction of ICCD-related measurements and analysis, optical emission spectroscopy (with A.B.), preparation of respective part of the manuscript, co-editing of the manuscript (with A.B. and M.C.)
- **[9]** Design and conduction of plasma treatment experiment, design and conduction of plasma diagnostics and data analysis; writing of respective parts of the manuscript, comments on the manuscript
- **[10]** Design (with P.S. and M.Z.) and conduction of experiment (with P.S., H.D.), (phase-resolved) imaging and electrical characterisation and analysis, responsible for the writing of the manuscript (Z.B. was responsible for the development and application of modified Paschen law part of the manuscript)
- **[11]** Co-inventor of the CaviPlasma technology, optical emission spectroscopy (with P.S. and J.R.) and related part of the manuscript, comments on the manuscript
- **[12]** Design and conduction of the diagnostics experiment (with P.S., J.R. and L.P.), electrical measurements (with P.S.), optical emission spectroscopy and imaging, data analysis, responsible for the writing of the manuscript
- **[13]** Design and conduction of the experiment (diagnostics – with P.S., parametric study – with L.P., R.H., E.M.), electrical measurements (with R.H.), optical emission spectroscopy and imaging, data analysis, responsible for the writing of the manuscript (co-editing with D.T.); phenol and colourimetric measurement of peroxide with P.L., OH analysis A.L. and Z.M.
- **[14]** Design and conduction of the experiment (diagnostics – with P.S. and R.H., parametric study – with P.L, P.S. and L.P.), electrical measurements and optical emission spectroscopy and imaging (with R.H.), data analysis (with R.H.), responsible for the writing of the manuscript (co-editing with D.T.)
- **[15]** Design and conduction of experiment (with L.P. and R.H.), electrical measurements (with L.P) and analysis, optical emission spectroscopy (with R.H.), (spectrally resolved) imaging and analysis, data analysis with numerical model (with D.T. and P.R.), responsible for the writing of the manuscript (co-editing with D.T. and R.H.)