O3

Zagadnienia techniki plazmowej i laserowej

Problems of plasma and laser engineering

In 2004 in the frame of statute activity realised have been 5 research topics encompassing production, investigation of properties and practical application of ionised media and laser radiation for technical and ecological purposes. Apart from statute activity realised have been other research activities regarding same topics and financed by KBN and FNP. Part of investigations has been realised in the frame of international cooperation.

In three Departments (Z1-Z3) realised have been following statute topics:
Z-1/T1 Generation and modelling of plasma in micowave discharge (Coordinator: Professor Z. Zakrzewski),
Z-2/T1 Application characteristics of technological intense laser beams (Coordinator: Professor G. Śliwiński)
Z-3/T2 Experimental investigations of energy exchange and emissions in solid matrices (Coordinator: Professor G. Śliwiński)
Z-3/T1 Application of laser technology for flow visualisation and material microprocessing, (Coordinator: Professor J. Mizeraczyk)
Z-3/T2 Application of plasma technology for purification of flue gases (Coordinator: Professor J. Mizeraczyk).

O3/Z1/T1. Generation and modelling of plasma in microwave discharge

The objective of works, continued for several years in the frame of that topic, are investigations and modification of microwave plasma generators. All works conducted in 2004 regarded discharges and plasma generators under atmospheric pressure.

In the reporting year continued has been a fundamental extension and modernisation of experimental facilities at the Department. That was possible thanks to, amongst the others, financing and direct supplies of equipment from the Air Liquide concern (France). In effect we have at our disposal several independent research rigs for investigations and usage of microwave plasma generators operating at, industrially recommended, microwave frequencies of 2.45 GHz and 915 MHz, equipped with supply systems, control and measurement of microwave output power, working gases and cooling fluid. With respect to experimental base two experimental rigs, assembled in 2004 and equipped with a newly acquired equipment, lay out a qualitative change of our research capabilities. A new rig for investigations of impulse discharges at frequency of 2.45 GHz enables operation in the power range from 0.6 kW to 6 kW (up till now 0.1-1 kW). For the first time we have at our disposal a rig for investigation of discharges sustained in the microwave field of frequency of 915 MHz and noticeably in the continuous power range from 2 kW to 20 kW (up till now only 2.45 GHz with maximum power of 6 kW).

In 2004 we have introduced in our laboratory new diagnostic techniques as well as we have commissioned and started to use adequate experimental equipment. These are: 1. spectroscopic me-

thod of electron concentration measurement and gas temperature (with a perspective of electron temperature measurement); 2. method of spatial and time investigation of development of long impulse discharges sustained by electromagnetic waves.

The principal research effort of the Department has been put into carrying out works related to development and optimisation of microwave plasma sources. This, carried out for several years scope of topics, is presently realised in the frame of statute activity and a contract with Air Liquide (AL). The works regard plasma generation in gaseous mixtures under atmospheric pressure. Their objective is optimisation of existing and development of new, more refined microwave plasma generators used in industrial technologies of purification of noble gases as well as industrial reactors for destruction of harmful waste gases. The scope of long-term activities encompasses the following topics:

- *Diagnostics and physical modelling of produced plasma,*
- *Electrodynamical investigations of generators' characteristics,*
- *Analysis of effectiveness of power transfer of microwaves to plasma and stability of generator operation,*
- *Analysis of influence of discharge conditions and geometrical factors on action time of staying in the discharge of gaseous mixture components and the distribution of chemical processes.*

As a result of the mentioned above works there are developed novel plasma generator designs with required electrodynamical parameters, which are conveyed to the contractor, who, after developing of prototype, implements them in practice.

In 2004 continued have been works on two types of generators with waveguide-based design (RW TIAGO and RW surfaguide). AL is underway with activities regarding the patent procedure. In relation to that all important information have been contained in confidential IFFM PAS reports and can only be published in future.

With respect to plasma sources of RW TIAGO type, we have performed works into investigations of their electrodynamical characteristics [E2-9, F-16]. Works have commenced on new kinds of such sources, which will be destined for operation at frequency of 915 MHz. The main objective of these works will be reduction of size with respect to wavelength (321 mm at 915 MHz in comparison to 123 mm at 2.45 GHz). Conducted have been modelling investigations [F-6], developed have been preliminary designs of applicators for 915 MHz [F-21, F-57, F-58] as well as activities started on realisation of such plasma sources.

Conducted have been investigation of plasma sources of RW surfaguide type aimed at 1. optimisation of electrodynamical characteristics, 2 increase of

output of processed gases by simultaneous sustaining of two discharges in one source.

In 2004 commissioned have been spectroscopic measurements of electron concentration in plasma based on a new method, not used earlier at the Centre. The method is based on determination of Stark extension of the atomic line H_β, emitted by plasma. The method has been used for measurement of electron concentration in microwave discharge of the "torch" type as well as in the discharge sustained by the surface wave. Obtained results have been presented at international conference [E2-24] as well as submitted for publication ins a prestigious journal [D1-5]. Method and obtained results have been described in IFFM PAS internal reports [F-19, F-23].

Developed has been a mathematical model of discharge sustained by the surface wave in capillary vessels. Successfully conducted has been experimental verification of such model. Results have been presented in a cyclic conference ESCAMPIG [E2-46] and IMP-PAN internal reports [F-32, F-37].

Experimental works in the area of investigations of physical mechanisms of discharges have been concentrated on investigations of impulse discharge. Investigated has been a development in time and in space of discharges sustained by electromagnetic surface waves, induced by the applicator of the surfaguide type. The Power impulse parameters were as follows: frequency of operation 2.45 GHz, time of presence of impulses in the range of μs and ms, peak power up to 6 kW (extended range of power with respect to investigations in 2003 r). Amongst the other obtained have been new experimental results enabling explanation of time and spatial development of discharge under atmospheric pressure. These results have been presented at international conference [E2-10, E2-11] as well as IFFM PAS internal reports [F-7, F-8] and will be published in future.

Part of works completed in the frame of that topic regarded implementation of microwave discharges in environmental protection. These works, coordinated by Prof. Mizeraczyk, were carried out principally as problems of the topic O3/Z3/T2 and were discussed in details in the appropriate part of the report. In the reporting year our participation in realisation of that topics were as follows:

Published have been the results of implementation of a continuous microwave discharge of the „torch" type for decomposition of volatile organic compounds and nitrogen oxides. The results have been published in a prestigious journal [E1-10].

Additionally commissioned have been investigations of decomposition of harmful substances (on the example of N_2O) during impulse microwave discharge of the "torch" type. Implementation of impulse mode of operation enabled reduction of energy consumption without impairment of decomposition effectiveness. The results have been published at conferences [E2-22, E2-

23, E2-25] as well as have been published in the international journal [E1-9]. Obtained results were also put together in IFFM PAS internal reports [F-18, F-21].

Continued have been modelling investigations of decomposition of harmful substances in continuous discharge (on the case of refrigerant CFC-11) and the impulse one (on the case of N_2O). The results have been presented in IFFM PAS internal report [F-13] as well as presented have been at international conference [E2-23].

In the reporting year continued have been works on numerical modelling of plasma microwave discharge, continuous and impulse ones, "torch" type ones and discharges sustained by surface wave. In the case of discharges in nitrogen performed have been calculations focused on recognition of impact processes which have most important influence on plasma characteristics. The results have been presented in reports [F-34, F-36, F-48]. In the frame of these works analysed has also been a set of active cross-section to the electron dispersion in the case of CO_2 and N_2O, which are used in determination of transport coefficients. It has been shown that in the case of CO_2 the increase of cross-section size in vibration excitation leads to a better consistency between results of calculations and experiments. The results have been presented at international conference and published in the paper [E1-32].

Part of calculations for plasma microwave discharges were performed using a PLASMAKIN library in a modified version II, developed at Technological and Nuclear Institute in Portugal, in cooperation with our Department. The results have been published at international conference [E2-48].

Developed has been a method of determination of electromagnetic field distribution in axisymmetrical system corresponding to RW TIAGO, which utilises a commercial code FlexPDE, devised for solving of systems of partial differential equations. The results have been published in reports [F-33, F-35].

Developed has been a data base [F22] for designing of comb waveguides based on square waveguides WR 340, WR 430 and WR 975. Such data base will be used in design of new waveguide-based applicators of electromagnetic field for microwave plasma generators operating at frequencies of 2.45 GHz and 915 MHz.

Links with other research topics

Investigations in the frame of the topic O3/Z1/T1 were carried out in collaboration with activities carried out in the frame of O3/Z3/T2 statute topics, KBN 1124 research project Development and refinement of microwave techniques of environmentally harmful gases elimination *(led by Prof. Z. Zakrzewski) and KBN 1179 project* Development of a numerical model of plasma impulse discharge model *(led by Dr J. Stańco), external contract with Air Liquide (France)* Design and optimization of microwave sources of atmo-

spheric pressure plasmas *(led by prof. Z. Zakrzewski) as well as cooperation with institutions in Canada, Germany, France and Portugal.*

O3/Z2/T1. Application characteristics of intense technological laser beams

Experimentally as well as using a calculation model investigated have been characteristics of a multi-segment adaptive mirror for implementation, in the control system, of phase characteristics radiation from technological laser cw CO_2. Carried out have been interference measurements and determined have been characteristics of bimorfic mirror deformation in function of supplied voltages and different combination of active segments. Voltage. At control voltage from the range from -150V to +250V, recorded have been axisymmetrical spherical deformations of the mirror in the range from h=+4,041 μm (concave surfaces) to $h = -6,037\mu m$ (convex surfaces). The changes corresponded to changes of curvature radius from $R \approx +24$ m to $R \approx -16$ m. Hysteresis of recorded level of deformation with respect to applied sequences of voltages did not exceed 14%.

Subsequently investigated were conditions of radiation generation of MLT 2.5 laser, equipped with adaptive mirror, introduced into the laser resonator. The objective was to determine possibilities of dynamic control of radiation characteristics by substitution with a mirror featuring a controllable shape – AO, one of the multi-transfer mirrors of stable resonator. Measured have been radiation characteristics in function of mirror surface shape control parameters for two locations of the mirror AO in the system; (1) – AO replaces only the rear spherical mirror of the resonator and (2) – AO replaces one of the flat mirrors deflecting the beam trajectory in the resonator.

The results and conclusions from investigations are as follows;

1. *In both investigated cases recorded is maximum of output power, corresponding to a complex multi-mode field structure, for a maximum attainable value of concave surface of the mirror AO.*
2. *Resonator of type (2) is definitely more sensitive to the changes of AO mirror curvature than the type (1) resonator. With changes of curvature radius rendered by changes of the controlled voltage ($-150V$; $+250V$), in the system with resonator (1) the output power decreases gradually and a complete damping out of generation is recorded at voltage $U = +250V$, whereas in the case (2) the power abruptly decreases and damping out of generation takes place already at value of $U = +120V$.*
3. *With respect to AO mirror curvature radius recorded are significant changes of the beam modal structure. With increasing changes of the mirror curvature to-*

wards convex profiles the content of higher modes decreases. Adequately to the changes of the level of power as well as mode composition recorded are values of the beam quality parameter M^2, which in the case of resonator (1) varies from 3 to 1.5 whereas in the case (2) from 4 to 1.8.

4. *Changes of radiation characteristics in the near field, resulting from changes of DM mirror changes, translate to the changes of parameters of focused beam. In the case (1) together with change of AO mirror curvature recorded is even a twofold increase of power density in the focal plane, whereas in the case (2) almost a threefold, at the same values of pressure of working fluid and discharge current.*

For the sake of interpretation of results developed has been a numerical code simulating propagation of radiation beam in the laser system with configuration corresponding exactly to the experimental one. The algorithm has been developed based on a geometrical model of radiation transformation in multi-element optical system (matrices ABCD). The results of calculation analysis of propagation characteristics (divergence, beam dimensions and its quality) as well as sensitivity of systems on the changes of AO shape are consistent with the results obtained in experimental manner.

Commenced has been a cycle of investigations of the influence of adaptive system in external optical trajectory of the machine tool MLT2.5 on the conditions of radiation focusing in the region of interaction with material. Investigated have been changes of parameters of laser beam in focusing zone in function of changes of AO mirror curvature radius for two extreme locations of the mirror in the trajectory, corresponding to minimum and maximum distance of AO mirror from the plane of contraction of source laser beam. It has been concluded that the range and character of changes of the beam parameters in the focal zone depend significantly of the total length of trajectory (head – source), characteristics of output beam determined by configuration of resonator as well as position of AO mirror with respect to focusing system. Calculations in that part of work have been performed using numerical algorithms and have also been confirmed experimentally, and the work is continued. The results have been presented in the MSc dissertation [B-3], discussed at conferences [E1-28, E1-29 D1-13, D1-14, E2-5, E2-52÷55] as well as summarised in elaborations and internal reports [F-43, F-46, F-47].

In the part of topic related to plasma discharges for gaseous lasers investigated was a theoretical new way of CO_2 laser excitation at barrier discharge using the nanosecond impulse generator. The method seems to be perspective for excitation of high-pressure lasers, for example excimer ones. Investigated also was the problem of imple-

mentation of barrier discharge for the case of large power CO_2 laser with selective nitrogen excitation and electron cooling effect and ion heating in the boundary layer (plasma-sheath) of discharge in Ar.

The works within the scope of statute activity were supported with 2 KBN research grants. For example, in the frame of the KBN research project "Diagnostics of hydrocarbons combustion process" carried out have been the following activities:

- *Investigated were laminar and turbulent combustion velocities using the Langmuir probes and Schlieren photography;*
- *Measured was temperature of the flame, level of ionisation and other characteristics of signals in mixture of propane and air;*
- *Measured were I-V characteristics of Langmuir probes;*
- *Developed were numerical codes for calculation of chemical and plasmochemical processes in the combustion front;*
- *Investigated has been gasdynamics of the combustion front in the closed chamber;*
- *Spectroscopically recorded were spectra of combustion process of hydrocarbon flame in air.*

The results of that part of the topic were collected in papers [E1-1, E1-37], post-conference proceedings [E1-11, E1-25, D1-1] as well as discussed were at conferences [E2-2÷4, E2-39, E2-56].

Links with other research topics

The works regarding realisation of the topic O3/Z-2/T1 were supported with KBN research project „Systems of adaptive optics for large power lasers" *(led by Dr G. Rabczuk) and a KBN research project* „Diagnostics of hydrocarbon combustion process" *(led by Dr A. Cenian).*

O3/Z2/T2. Experimental investigations of energy exchange and emissions in solid matrices

Continued have been investigations of laser remelting protection layers and, for the needs of laser stereolitography, in the frame of research project 0809/T08/02/22, of a statute activity together with bilateral cooperation with National Centre for Metallurgical Research in Madrid.

Metalographic investigations of laser coatings consisting of 2-3 layers of stellite SF6 (inspection using the optical microscope and SEM, investigations of chemical composition, corrosion and abrasion resistance) have been conduced at CENIM laboratories. The samples featured a small-grain structure. Concluded has been a lack of cracks in coated samples on the base heated to temperature T_p beyond 600^oC, where for the same value of T_p better results were obtained for the lack of time lapse between coating of subsequent layers.

Measurements carried out using energy-dispersive spectroscopy method (XEDS) proved that the chemical com-

position in the entire coating is practically homogeneous and the zones of biggest changes in chemical composition correspond to zones of combination of coating with the base and coupling of respective paths and coating layers.

Corrosion investigations carried out in the NaCl solution of 3.56% concentration (conditions corresponding to sea water) proved that the corrosion potential measured for coated layers is always greater from the measured value for the base without coating. In doing so there are differences in the results obtained for coated layers under different experimental conditions. Best results have been obtained for a coating put on a base heated to higher temperature $T_p = 690^oC$ *and at longer time lapse between putting of subsequent coating layers. Similar behaviour was proved by a coated sample where the base was heated to* $T_p = 630^oC$*, and there was no time lapse between coating of subsequent layers. The worst results were obtained for* $T_p = 690^oC$ *and a lack of breaks between layer coating, hence biggest mean temperature of the entire coating. Such behaviour is rendered by a temperature dependent coating iron enrichment, which migrates from the steel base (confirmed by investigations of chemical composition).*

Series of abrasion resistance investigations were carried out on the MicroTest equipment using the „pin-on-disc" method. Obtained results of averaged abrasion velocity for investigated coatings are of the order of $1.6 \cdot 10^{-5}$ mm^3/Nm *whereas for the base without protective layer measured have been values of the order* $1.1 \cdot 10^{-3}$ mm^3/Nm*. However, in the case of other material of the base, with the increase of base temperature it has been concluded that the abrasion resistance decreases in the case of laser coated protective layers. It has been concluded that the requirements regarding conditions of coating necessary for obtaining coatings without cracks as well as conditions for which layers are obtained with highest corrosion and abrasive resistance seem to be excluding each other. Therefore necessary is a precise control of process conditions and such determination of* T_p *and* Δt *values, for which cracks will not be present and at the same time such that reduction of strength properties was the smallest.*

Developed have been results of calculations (carried out by Proffessors Ostachowicz and Krawczuk) of numerical temperature fields and stressed in laser coated two-layer stellite layers [E1-13, D1-7]. These indicate, that from the point of view of stresses disadvantageous is application of two or more layer coatings, and the negative effect is enhanced at extending the time lapse between coating of subsequent layers. That confirms the described above results of experimental investigations, where for the same value of the base temperature better results (i.e. no cracks) were obtained for the lack of time lapses between coating of subsequent layers. The works have been summarised in papers [E1-11, E1-12], post-conference proceeding [D1-6], whereas

unpublished results were collected in the report [F-25].

Commenced have been experimental investigations on AlN cermetal for the semi-conductor materials industry, ablation tests proved a strong temperature effect on the surface, which reveals through change of colour and electric conduction in a large region around the crater. Explanation to the observed phenomenon can bring about expected understanding to the results of carried out already material investigations [E1-23, D1-11].

Continuing investigations in the range of application techniques utilising lasers in conservation of monumental objects conducted have been experimental investigations of laser ablation of historical contaminations of paper documents and stone objects. Selected have also been effective methods of process diagnostics – LIF, LIBS, SEM techniques and colorimetry. In experimental investigations, using the laser cleaning of paper obtained has been a series of original results, which have been summarised in doctoral dissertation and a paper. Performed has been analysis of contamination composition. Diagnostics of laser induced plasma has been successful in the conservatory project of one of the first volumes of the Bible from 1596, printed in Poland (Leopolita's Bible). Systematic measurements of fluorescence spectra of paper samples proved that the LIF technique is an efficient tool of non-destructive analysis. In particular, obtained have been repeatable results of identification and ablative removal of pigments. Consistency of experimental results has been concluded for different historical samples from the period of XVI-XVIII century with the results for modelling samples, prepared by the Institute of Cellulose and Paper in Łódź. Experimental investigations have been conducted in a close cooperation with a group of analysts from Copenhagen School of Conservation, Institute of Chemical Physics from Madrid and RCBS Gdańsk.

Prepared have been technically and disclosed to international forum a set of information to supplement the COST code database and established has been a consultation point for new techniques for conservators.

Developed has been educational material encompassing problems of laser technique for conservators and museum wardens as well as organised has been international seminar/workshop titled „Lasers and optical techniques in conservation of monumental objects".

The result of works in 2004 is, amongst the others, development of international scientific cooperation. That is also demonstrated by the increase of activity of domestic researchers. The research project Cost-G7 attracted, amongst the others, groups from Gdańsk University of Technology, Toruń University and conservators from National Museum and private laboratories. In the light of increasing interest, also from the conservators, with the results of hitherto conducted investigations continuation of the topics seems to be justified.

The results of that part of the topic, supported by two KBN research grants have been collected in the doctoral dissertation [B-4], publications [E1-14], volumes and post-conference proceedings [E1-15, E1-24, D1-3, D1-4], whereas unpublished results were presented in report [F-35].

Links with other research topics

The works related to realisation of topic O3/Z2/T2 have been carried out in combination with activities performed in the frame: research project No. PB 1129/T08/98/15„Multilayer stellite structures for laser stereolitography and regeneration" *(led by Prof. G. Śliwiński), KBN research project SPUBM/COST* „Laser technique in conservation of material culture wealth" *(led by Prof. G. Śliwiński), KBN research project* „Investigations of changes in paper structure due to laser purification for restoration/conservation of bibliographical monuments" *(led by Prof. G. Śliwiński).*

O3/Z3/T1. Application of laser technique for flow visualisation and material microprocessing

Both problems of the topic O3/Z-3/T1, i.e. application of laser technique for flow visualisation and laser material microprocessing are linked by a common laser source (an impulse CyBr laser or impulse Nd:YAG laser with a double frequency conversion), which can be applied both in flow visualisation and material microprocessing.

The problem titled „Application of laser technique for flow visualisation" *regarded implementation of impulse lasers CuBr and Nd:YAG for visualisation of gas flow patterns and measurements of velocity fields by means of PIV method (Particle Image Velocimetry). In the frame of that topic conducted have been visualisations and investigations of velocity fields in flows, where electrical fields were present, i.e.:*

- *Models of electrofilters and real electrofilter,*
- *Several models of plasma reactors for purification of flue gases from harmful substances.*

The results regarding measurements of velocity fields in models of electrofilters were published in 1 article in Philadelphia list [E1-26], 2 articles in continuous editions journal [E1-17, E1-20], 4 conference papers [E2-36, E2-42, E2-49, E2-51] and IFFM PAS internal reports [F-1, F-10, F-31].

The results regarding measurements of velocity fields in models of plasma reactors were published in 2 articles from Philadelphia list [E1-5, E1-19], 5 conference papers [E2-6, E2-7, E2-12, E2-40, E2-44] and 2 IFFM PAS internal reports [F-28, F-30].

The activities were also carried out in cooperation with following foreign centers: Oita University, Department of Electrical and Electronic Engineering, Oita, Japan, Prof. T. Ohkubo

and McMaster University, Department of Engineering Physcics, Faculty of Engineering, Hamilton, Ontario, Canada, Prof. J.-S. Chang.

Obtained results confirmed the applicability of PIV method for investigations of flows in flow systems in presence of electric field (electrofilters and plasma reactors). Obtained results are useful for assessment of the effectiveness of electrofilter operation, including also the assessment of removal capability of dust particles. That is the actual trend in the area of electrofilters.

Flow investigations in models of non-thermal plasma reactors for purification of flue gases from harmful substances confirmed the results of investigations, which started in recent years, from which it results that in the process of purification there takes place not only the region where plasma is present but also regions without it, where due to secondary electrohydrodynamical flow the chemically active particles are attracted, and which were produced in the plasma region.

The topic named „application of laser technique for material microprocessing" *regarded development of a MOPA laser system (Master Oscillator – Power Amplifier) CuBr and its implementation in precision material processing as well as for investigations of thermal semi-conductor elements.*

The results regarding that topic were published in 2 conference papers [E2-19, E2-35] and 3 IFFM PAS internal reports [F-1, F-2, F-31].

The most prominent results of that topic form a further modification of MOPA CuBr laser system for precision material processing. Presently, the MOPA CuBr laser system consists of two laser tubes (MO – master oscillator and PA – power amplifier) as well as MTS system for synchronization of discharge impulses in both tubes. Thanks to such a construction the generation capabilities of CuBr laser are extended significantly. Selection of repeating frequency becomes possible as well as of a number of impulses generated by the laser. Apart from that the MOPA CuBr laser system can operate as a fast optical diaphragm for blocking of the laser beam (reaction time of the order of as few μs). Thanks to that a full potential of traversing the laser beam on a surface of material by means of laser scanner is utilized, which was not possible before due to implemented too slow mechanical diaphragm. Presently, the developed and manufactured MOPA CuBr laser system incorporating the optical scanner is one of the most advanced devices of such kind in Europe.

Links with other research topics

Works regarding realisation of the topic O3/Z3/T1 were carried out in combination with activities conducted in the frame of KBN research project 1756/T10/01/21 "Investigations of exhaust gases velocity fields in models of electrofilters with the aid of laser methods with the view of optimisation of purification process" *(led by Prof. J. Mizeraczyk), KBN research*

project 1498/T11/02/22 "Applications of CuBr laser of new generation for investigations of transitional characteristics of thermal semi-conductor elements" *(led by Dr M. Kocik) and Foundation for Polish Science (subsidy 8/2001)*„Theoretical and experimental investigations of combustion gases in models of electrofilters with the view of optimization of dedusting process".

O3/Z3/T2. Application of plasma technique for purification of flue gases

A long term objective of investigations carried out at the Department of Plasma and Laser Techniques Applications is development of new, effective and pro-ecological plasma methods of purification of different kinds of flue gases from harmful gaseous components.

The scope of activities in the current year regarded application of plasma techniques for purification of flue gases encompassed:

- *elimination of nitrogen oxides from flue gas simulators in non-thermal plasma reactors with catalysers or molecular sieve (a reactor with a positive constant-voltage corona discharge),*
- *decomposition of freons and nitrogen suboxides by means of microwave discharge of the "torch" type,*
- *electrohydrodynamical effect in non-thermal plasma reactors (that is linked to one of the problems in the topic O3/Z-3/T1),*
- *application of Laser Induced Spectroscopy for measurements of time and space distributions of active particles in non-thermal plasma used for decomposition of nitrogen oxides,*
- *investigations of properties of different modes of corona discharge.*

Investigations of nitrogen oxides eliminations from flue gases in a positive constant-voltage reactor corona discharge borne benefits in explanation of mechanisms of removal of nitrogen oxides in the presence of catalyser or a molecular sieve. Particular results have been published in 1 MSc thesis [B-2], 4 articles from Philadelphia list [E1-6÷8], E1-22] and 8 conference papers [E2-13÷17, E2-41÷43].

Investigations of freon and nitrogen suboxides decomposition by means of impulse microwave discharge of the „torch" type were conducted together with the research group from the Department of Electrodynamics of Ionised Gases O3/Z-1, led by Prof. Z. Zakrzewski. The major results of that cooperation was development of a highly-efficient method of decomposition of freons and nitrogen suboxides by means of impulse microwave plasma under atmospheric pressure. Another important result is development of spectroscopic method of temperature measurement of the working fluid in microwave plasma. Investigations were carried out in cooperation with Oita University, Depart-

ment of Electrical and Electronic Engineering, Oita, Japan, Prof. T. Ohkubo and McMaster University, Department of Engineering Physics, Faculty of Engineering, Hamilton, Ontario, Canada, Prof. J.-S. Chang. Obtained results were published in 2 articles from Philadelphia list [E1-9, E1-10], 5 conference papers [E2-9, E2-22÷25] and 6 IFFM PAS internal reports [F-13, F-18, F-20, F-21, F-23, F-24].

In the frame of a contract with Air Liquide, France, carried out were, together with a research group of Prof. Z. Zakrzewski, investigations of velocity fields in flows in microwave plasma reactors (4 IFFM PAS internal reports [F-11, F-26, F-29, F-41].

Investigations of electrohydrodynamical effect in non-thermal plasma reactors regarded measurements of NO, O_3 i and H_4NO_3 transport om non-thermal plasma reactors by means of spectrophotometric method and PIV method. It has been experimentally shown that both O_3 and NH_4NO_3 are produced in the course of elimination process of nitrogen oxides NO_x in corona discharge, which are subsequently transported upstream the main flow of gas by the secondary flow (electrohydrodynamical flow) rendered by the discharge. Obtained results confirmed the positive influence of the electrohydrodynamical effect on the effectiveness of purification of flue gases in non-thermal plasma reactors. Investigations were carried out in cooperation with Oita University, Department of Electrical and Electronic Engineering, Oita, Japan, Prof. T. Ohkubo and McMaster University, Department of Engineering Physics, Faculty of Engineering, Prof. J.S. Chang. Obtained results were published in 1 MSc thesis [B-1], 1 article from Philadelphia list [E1-1], 1 article in a journal not on the latter list [E1-18] and 1 conference paper [E2-8].

In the frame of cooperation with Oita University, Department of Electrical and Electronic Engineering, Oita, Japan, Prof. T. Ohkubo, continued were activities on application of Laser Induced Spectroscopy in measurements of time and spatial distributions of active particles in non-equilibrium plasma used in decomposition of nitrogen oxides. Laser Induced Spectroscopy is a modern research tool in for example non-thermal plasma, which effectively supports experimental and numerical investigations of harmful gases decomposition by means of plasma catalysis. In 2004 the principal results of investigations regarding application of Laser Induced Spectroscopy for decomposition of nitrogen oxides was a spatial measurement of a rate of OH radicals production in the „corona radical shower" reactor type. Obtained results were published in 1 journal article [E1-21] and 1 conference paper [E2-34].

Investigations of properties of corona discharge were also conducted in cooperation with Oita University, Department of Electrical and Electronic Engineering, Oita, Japan, Prof. T. Ohkubo and McMaster University, Department of Engineering Physics, Faculty of Engineering, Prof. J.S. Chang. Investi-

gated were electrical characteristics of self-sustained corona discharge as well as induced by laser impulses. The results were published in 1 article from Philadelphia list [E1-16] and conference papers [E2-36, E2-37, E2-47].

Links with other research topics

The works regarding realisation of a topic O3/Z3/T2 were carried out in combination with activities conducted in the frame of IFFM PAS statute activity coordinated by Prof. Z. Zakrzewski: O3/Z1/T1 „Generation and modelling of plasma in microiwave discharge", and in the frame of a contract with Air Liquide, France (coordinated by Prof. Z. Zakrzewski).