Dariusz CZYLKOWSKI, Bartosz HRYCAK, Mariusz JASIŃSKI

Institute of Fluid Flow Machinery, Polish Academy of Sciences, Fiszera 14, 80-231 Gdańsk, Poland

doi:10.15199/48.2018.07.07

Compact microwave plasma device for surface treatment

***Abstract**. Currently, plasma systems for plastic, metal, glass and composite surface modifications are of high interest from industry point of view. In addition, attention is paid to the reduction of investment as well as operating costs of the process. According to this, to meet industry expectations a novel compact microwave plasma device for surface treatment was designed, built and tested. The major advantage of the device is a unique shape of the generated plasma having a form of a plasma sheet suitable for surface treatment.*

***Streszczenie.** Wychodząc naprzeciw oczekiwaniom przemysłu zainteresowanego tanim urządzeniem do modyfikacji powierzchni tworzyw sztucznych, metali, szkła i kompozytów zaprojektowano, zbudowano i przeprowadzono testy nowego kompaktowego mikrofalowego źródła plazmy do obróbki powierzchni. Główną zaletą urządzenia jest unikalny kształt generowanej plazmy tzw. płaszczyzny plazmowej dogodny w obróbce powierzchni. (**Kompaktowe mikrofalowe urządzenie plazmowe do obróbki powierzchni**).*

Keywords: microwave plasma, plasma sheet, surface treatment.
Słowa kluczowe: plazma mikrofalowa, płaszczyzna plazmowa, obróbka powierzchni.

Introduction

Plasma (ionised gas) is an object of interest of research centres and commercial companies. Nowadays, from industry point of view, there is a growing interest in not expensive plasma sources for plastic, metal, glass and composite surface modifications. The plasma treated material changes its surfaces properties. For example, as a result of plasma treatment an increase of surface's adhesion potential can be obtained. Due to plasma modification hydrophobic and hydrophilic surface properties can be established. Using plasma it is also possible to coat material surface with protecting layer or layer of specific characteristics. So, plasma surface treatment can be used in surface cleaning, activating and coating and can be applied for example in cosmetic packaging, medical implants or cars parts [1-9]. In addition to the above, recently, attention is paid to the reduction of investment as well as operating costs of the surface treatment process. The importance of small devices, with low energy consumption, are increasing. Thus the so called "downsizing" is also a recent trend in a plasma science and engineering. Recently existing flame conventional devices dedicated to surface treatment on one hand are not environmentally friendly, on other hand can cause treated surface overheating leading to treated surface deformation. Meanwhile the plasma of moderate temperature is preferable. Against, applied radio frequency (RF) based methods of plasma surface modification are of high cost which further increases investment and operating costs. In this case one of the way is to use a microwave (2.45 GHz) frequency plasma at atmospheric pressure. Operating at atmospheric pressure eliminates an expensive vacuum apparatus. Using standard microwave frequency of 2.45 GHz allows to use cheap commercial magnetron such as that installed in microwave oven.

Therefore, to fulfill industry expectations of low cost source of non-thermal plasma (of required temperature) for surface treatment a novel microwave plasma source was invented in the Centre for Plasma and Laser Engineering of the Szewalski Institute of Fluid Flow Machinery Polish Academy of Sciences. The idea was inscribed on the list of intellectual property protected by Polish law under patent no PL 215139 B1 [7] . Based on the novel plasma source the compact microwave plasma device for surface treatment was designed, built and tested. The major advantage of the device is a unique shape of the generated plasma having a form of a plasma sheet suitable for surface treatment [11, 12]. The device delivers plasma of moderate temperature depending on the kind of working gas, gas flow rate and absorbed microwave power [11].

Idea of the microwave plasma sheet

The idea of the microwave plasma sheet originates from the atmospheric pressure surface-wave discharge [13-16]. In such a type of discharge the plasma sustained by surface wave in a gas at atmospheric pressure has the form of a plasma column generated inside a dielectric capillary tube (Fig. 1a). Therefore, its main advantage is electrodeless operation. Sustaining the plasma in dielectric tube prevents contaminations from metallic electrode. That is why in that a way generated plasma is used in a gas processing like gas purification and abatement of gaseous pollutants. Applying suitable high gas flow rate passing through the dielectric tube results in plasma going out of the tube permitting the processing of the material's surface. In such a way narrow cylindrical plasma column leaves a circular trace on the treated surface. To obtain plasma surface modification over large area time-consuming scanning of the modified surface is needed to cover its full area. The better solution, from surface treatment point of view, seems to be applying a set of dielectric tubes (Fig. 1b) with plasma columns.

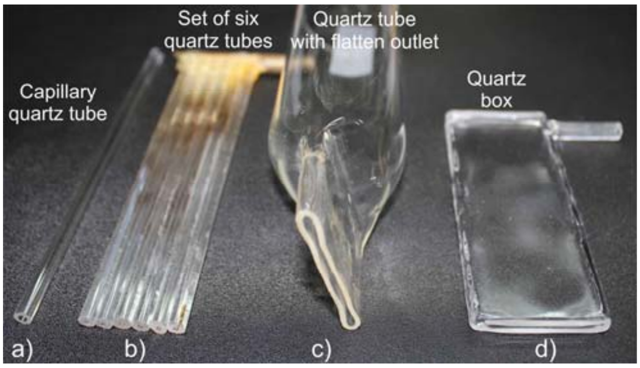

Fig.1. Quartz capillary tube (a), set of capillary quartz tubes (b), quartz tube with flatten outlet (c) and quartz box (d)

As it was described in [17] it is possible to accommodate a few dielectric tubes within one coupling gap of the microwave plasma source supplied from one microwave power generator. However, surface scanning using such multitube plasma source leaves not modified space between plasma modified tracks. To overcome this inconvenience resulting from the thickness of the walls of dielectric tubes it was proposed to use large diameter dielectric tube with flatten outlet (Fig. 1c). Due to the problems with accommodating large diameter tube in plasma source and with working gas supply and filamentation phenomena [18-21] the experiments with using it in plasma surface treatment ended unsuccessfully. Instead of it, the idea of flat cuboid dielectric box appeared (Fig. 1d). It is made of two parallel rectangular tiles spaced to each other at a distance of about 1 mm. Space between tiles is closed on three sides. A dielectric pipe for working gas supply is introduced into one of the sides. The narrower open side at the top of the dielectric box forms the output slit of the plasma. As a result of energy transfer from the electromagnetic field of microwaves into the plasma forming gas, the plasma is generated inside the flat quartz box and because of the gas flow protrudes outside the box. Plasma generated is of regular shape which dimensions depends on the dielectric box dimensions. Figure 1 shows exemplary photo of the microwave plasma sheet supplied from a waveguide wedge.

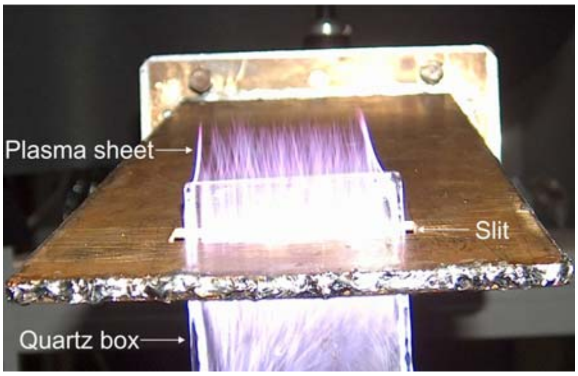

Fig.2. Photo of the microwave plasma sheet supplied from a waveguide wedge

Compact microwave plasma device for surface treatment

As it was shown in [10-12, 22] the dielectric box enabling plasma sheet formation can be supplied from different kind of microwave structures. The plasma sheet source can be stripline structure based (Fig. 3) or waveguide based (Figs. 4-5). In the second case the standard rectangular waveguide (Fig. 4) or a wedge waveguide (Fig.5) can be used. As it can be seen from figure 4 different ways of dielectric box placement within rectangular waveguide are possible. Dielectric box can be placed perpendicularly to the waveguide narrow walls (Fig. 4a), parallelly to the waveguide narrow walls (Fig. 4b) or within waveguide narrows walls (Fig. 4c).

In the case of plasma sheet source based on a stripline structure as a result of the microwave power limitations only operation with microwave power lower than 500 W is possible. In the second case the problems arising from the unwieldy rectangular waveguide, mostly often terminated with movable plunger, and from technical problems in constructing waveguide wedge restrict practical application them in the plasma surface treatment.

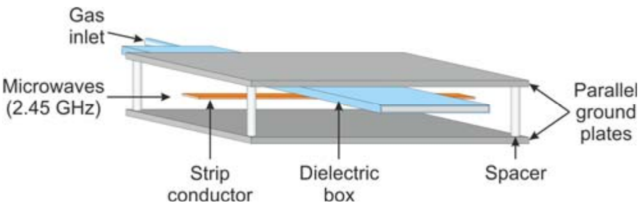

Fig.3. Microwave plasma sheet source based on a stripline structure

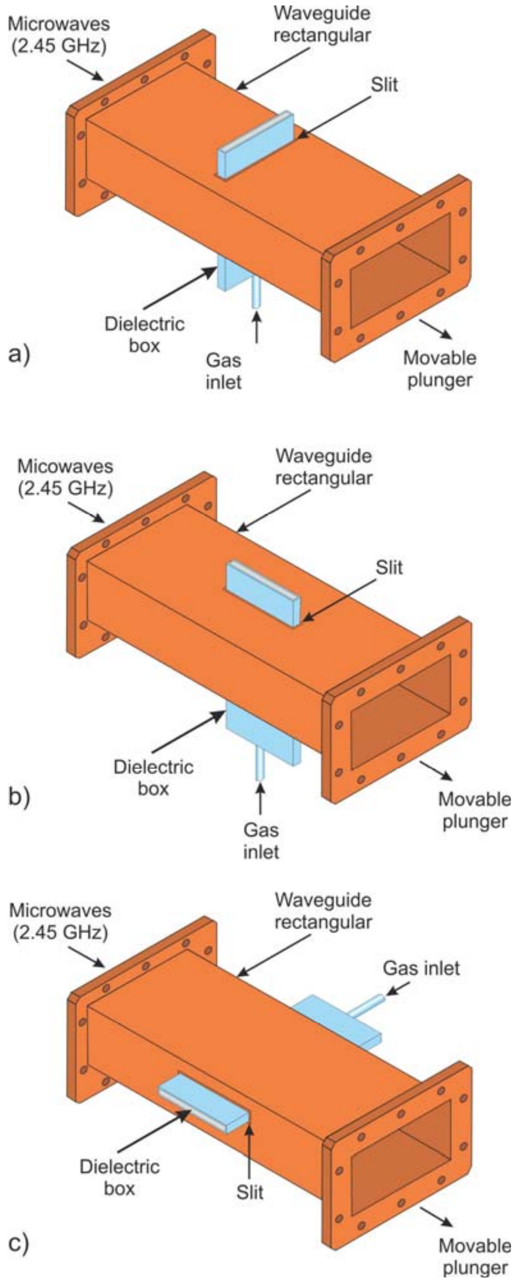

Fig.4. Different microwave plasma sheet sources based on a rectangular waveguide: (a) dielectric box perpendicular to the waveguide narrow walls, (b) dielectric box parallel to the waveguide narrow walls, (c) dielectric box within waveguide narrows walls

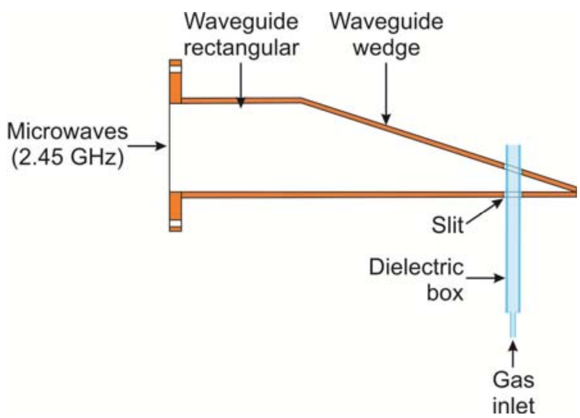

Fig.5. Microwave plasma sheet source supplied from a waveguide wedge

In figure 6 the schematic view of the novel compact microwave plasma device for surface treatment is shown.

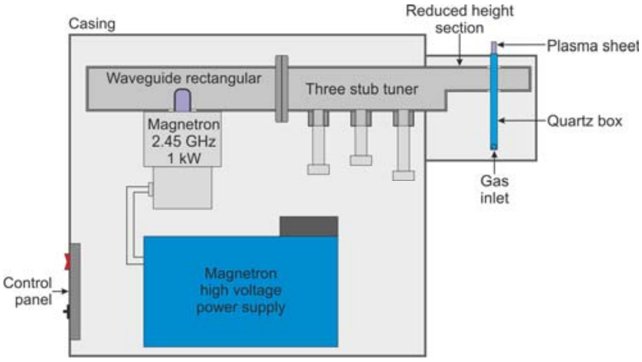

Fig.6. The schematic view of the novel compact microwave plasma device for surface treatment

As it can be seen, in the device the rectangular waveguide of the reduced height section preceded by built-in three stub tuner is used (Fig. 7). Using the reduced height section, higher electric field intensity in the plasma forming region can be ensured. The reduced height section is terminated with short circuit enabling more accessible plasma sheet surface treatment. Photos of the novel compact microwave plasma device for surface treatment are shown in figure 8.

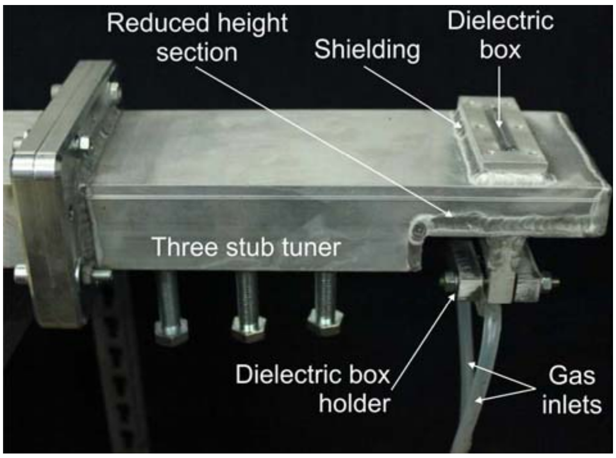

Fig.7. Three stub tuner and rectangular waveguide of the reduced height section of the novel compact microwave plasma device for surface treatment

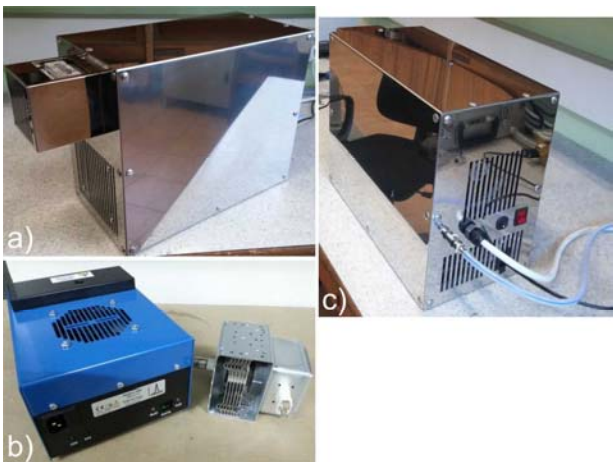

Fig.8. Photos of the novel compact microwave plasma device for surface treatment: (a) front view, (b) built-in high voltage power supply and magnetron, (c) rear view

Experiment

The experimental investigations of the novel compact microwave plasma device for surface treatment involved investigations of its electrodynamic characteristics, defined as dependence of the reflected microwave wave power as a function of incident microwave power for various gas flow rates; spectroscopic investigations of plasma parameters (plasma composition, gas temperatures); investigation of the plasma sheet influence on various surfaces (e.g. polyethylene, rubber) and investigations of microorganism decontamination by using microwave plasma sheet.

All experimental tests of the novel compact microwave plasma device were performed in argon at flow rate in the range of 5 - 25 NL/min, and absorbed microwave up to 850 W. The dielectric box made of quartz of external dimensions of length, width and thickness equal 100, 50 and 6.3 mm, respectively was applied.

In figure 9 a schematic representation of the experimental setup for spectroscopic diagnostics of the plasma sheet generated using compact microwave plasma device is shown. It consists of a compact microwave plasma device, gas supply and flow control and optical emission spectroscopy (OES) system. OES system includes a spectrometer equipped with sensitivity calibrated CCD camera, quartz lens and diaphragm. The spectrometer is controlled by a software installed in a PC.

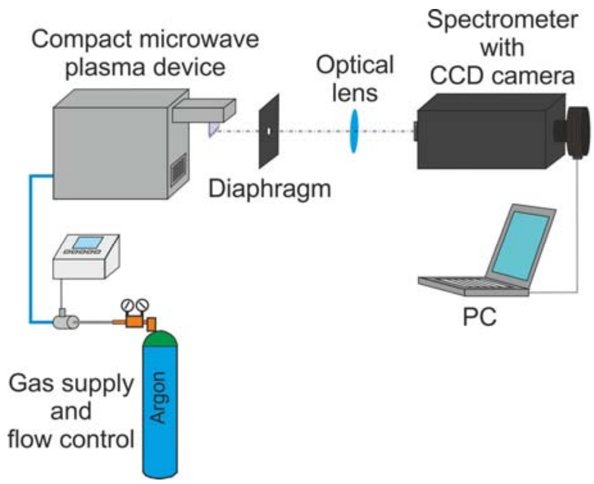

Fig.9. The schematic representation of the experimental setup for spectroscopic diagnostics of the plasma sheet generated using compact microwave plasma device.

The analysis of the experimental results allowed us to make the following conclusions:

- using inbuilt three stub tuner almost 100% of microwave power transfer from the microwave generator to the plasma sheet can be ensured,
- due to skin effect and argon thermal conductivity [18-21] plasma sheet contains many oscillating argon filaments,
- plasma sheet uniformity (number of argon filaments per unit of quartz box width) depends on the absorbed microwave power and argon flow rate,
- plasma sheet protruding length out of the quartz box depends on the argon gas flow rate, absorbed microwave power and method of quartz box placement in the reduced height section,
- depending on the absorbed microwave power and argon flow rate the spectroscopically measured gas temperature of the plasma sheet varied from about 500 to 1200°C,
- the results of the plasma sheet surface (polyethylene, synthetic rubber, acrylic glass) treatment from wettability modification point of view indicate the significant reduction

of the contact angle, lasting even up to 200 h after plasma treatment,
- preliminary tests on quality of selected spices (e.g. black pepper, wild berries) showed the possibility of microorganism colony reduction by a two order of magnitude of the initial number of colony forming units.

In figure 10 exemplary photo of the metal plate treatment using compact microwave plasma device for surface treatment is shown.

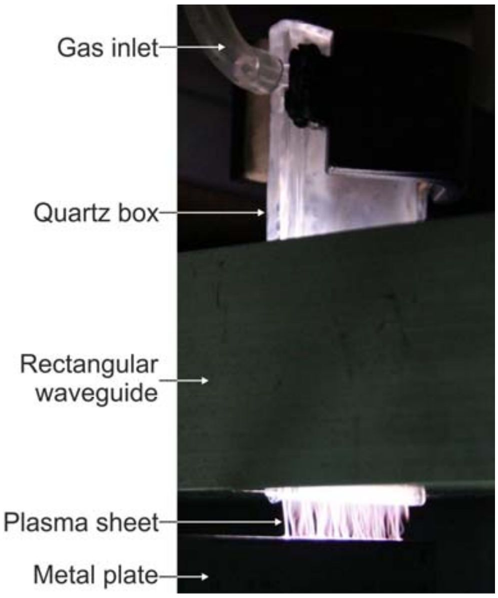

Fig.10. Photo of the metal plate treatment using compact microwave plasma device for surface treatment. Argon gas flow rate - 30 NL/min. Absorbed microwave power - 1000 W.

Conclusions

The undisputed advantages of the presented compact microwave plasma device for surface treatment are the unique form of a regular in shape plasma sheet, small dimensions and simple design resulted in low cost of production. Using the device the rapid and uniform plasma treatment of the three-dimensional large areas can be realised. Moderate plasma sheet temperature avoids treated surface overheating and thus its deformation and destruction. Argon operated plasma sheet device, in comparison with conventionally used flame method, is much more environmental friendly. Preliminary experimental tests indicate a high potential of the presented novel device for industrial implementation for production of materials with improved surface and coatings properties.

Acknowledgements

This research was supported by The National Science Centre, Poland, under the programme no. 2015/19/B/ST8/02123.

***Authors**: mgr inż. Dariusz Czylkowski, mgr inż. Bartosz Hrycak, dr hab. inż. Mariusz Jasiński, Institute of Fluid Flow Machinery, Polish Academy of Sciences, Fiszera 14, 80-231 Gdańsk, Poland, E-mail: dczylkowski@imp.gda.pl, bhrycak@imp.gda.pl, mj@imp.gda.pl*

REFERENCES

[1] Conrad J.R., Radtke J. L., Dodd R. A., Worzala F.J., Tran N.C., Plasma source ion-implantation technique for surface modification of materials, *Journal of Applied Physics*, 62, (1987), 4591-4596
[2] Stoffels E., Flikweert A. J., Stoffels W.W., Kroesen G.M.W., Plasma needle: a non-destructive atmospheric plasma source for fine surface treatment of (bio)materials, *Plasma Sources Sci. Technol.*, 11 (2002), 383–388
[3] Desmet T., Morent R., De Geyter N., Leys C., Schacht E., Dubruel, P., Nonthermal plasma technology as a versatile strategy for polymeric biomaterials surface modification: A review, *Biomacromolecules*, 10 (2009), 2351-2378
[4] Mui T.S.M., Silva L.L.G., Prysiazhnyi V., Kostov K.G., Surface modification of aluminium alloys by atmospheric pressure plasma treatments for enhancement of their adhesion properties, *Surface and Coatings Technology,* 312 (2017), 32–36
[5] Bhanthumnavin W., Wanichapichart P., Taweepreeda W., Sirijarukula S., Paosawatyanyong B., Surface modification of bacterial cellulose membrane by oxygen plasma treatment, *Surface and Coatings Technology,* 306, Part A (2016), 272–278
[6] Rezaei F., Dickey M.D., Bourham M., Hauser P.J., Surface modification of PET film via a large area atmospheric pressure plasma: An optical analysis of the plasma and surface characterization of the polimer film, *Surface and Coatings Technology,* 309 (2017), 371–381
[7] Moraczewski K.,. Stepczyńska M.,. Malinowski R.,. Rytlewski P., Jagodziński B., Żenkiewicz M., Stability studies of plasma modification effects of polylactide and polycaprolactone surface layers, *Applied Surface Science*, 377 (2016), 228-237
[8] Şahina Ö., Kaya M., Plasma-surface modification on bentonite clay to improve the performance of adsorption of methylene blue, *Applied Clay Science*, 116–117 (2015), 46-53
[9] Zhu F., Plasma modification of starch, *Food Chemistry*, 232 (2017), 476-486
[10] Jasiński M., Goch M., Mizeraczyk M., Plasma device for treatment of material surfaces. *Patent RP* No. 215139
[11] Jasiński M., Goch M., Mizeraczyk J., Urządzenie mikrofalowe do generacji płaszczyzny plazmowej, *Przegląd Elektrotechniczny*, 86 (2010) 112-114
[12] Czylkowski D., Jasiński M., Mizeraczyk J., Novel low power microwave plasma sources at atmospheric pressure, *Przegląd Elektrotechniczny,* 88 (2012) 39-42
[13] Moisan M., Beaudry C., Bertrand L., Bloyet E., Gagne J.M., Leprince P., Marec J., Mitchell G., Ricard A., Zakrzewski Z., New RF plasma sources using surface wave propagation: characteristics and applications, *Ins. Elec. Eng. Conf. Publ.,* 143, (1976) 382
[14] Moisan M., Glaude V., Leprince P., Mitchel G., Zakrzewski Z., Surfaguide - waveguide plasma source using surface-waves, *Bulletin of the American Physical Society* 21 (1976) 812-812
[15] Moisan M., Beaudry C., Leprince P., A new device for the production of long plasma columns at a high electron density, *Phys. Lett.*, 50A (1974), 125-126
[16] Moisan M., Zakrzewski Z., Pantel R., Leprince P., A waveguide-based launcher to sustain long plasma columns through the propagation of an electromagnetic surface wave, *IEEE Trans. Plasma Sci.*, PS-12 (1984), 203-214
[17] Moisan M., Zakrzewski Z., Etemadi R., Rostaing J.C., Multitube surface-wave discharges for increased gas throughput at atmospheric pressure, *J. Appl. Phys*., 83 (1998), 5691-5701
[18] Kabouzi Y., Calzada M.D., Moisan M., Tran K.C., Trassy C., Radial contraction of microwave-sustained plasma columns at atmospheric pressure, *Journal of Applied Physics*, 91 (2002), 1008-1019
[19] Castaños-Martínez E., Moisan M., Expansion/homogenisation of contracted/filamentary microwave discharges at atmospheric pressure, *IEEE Transactions on Plasma Science*, 39 (2011), 2192 - 2193
[20] Castaños-Martínez E., Moisan M., Kabouzi Y., Achieving non-contracted and non-filamentary rare-gas tubular discharges at atmospheric pressure, *J Phys. D: Appl. Phys.,* 42 (2009), 012003 (5pp)
[21] Kabouzi Y., Moisan M., Pulsed microwave discharges sustained at atmospheric pressure: study of the contraction and filamentation phenomena, *IEEE Transactions on Plasma Science*, 33 (2005), 292-293
[22] Jasiński M., Mizeraczyk J., Plasma sheet generated by microwave discharge at atmospheric pressure, *IEEE Transactions on Plasma Science*, 3, (2011), 2136-2137