THE SZEWALSKI INSTITUTE OF FLUID-FLOW MACHINERY
POLISH ACADEMY OF SCIENCES

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

119

WYDAWNICTWO IMP PAN

GDAŃSK 2007

EDITORIAL AND PUBLISHING OFFICE

IFFM Publishers (Wydawnictwo IMP), The Szewalski Institute of Fluid Flow Machinery, Fiszera 14, 80-952 Gdańsk, Poland, Tel.: +48(58)6995141, Fax: +48(58)3416144, E-mail: esli@imp.gda.pl; now@imp.gda.pl http://www.imp.gda.pl/

Terms of subscription

Subscription order and payment should be directly sent to the Publishing Office

Warunki prenumeraty w Polsce

Wydawnictwo ukazuje się przeciętnie dwa lub trzy razy w roku. Cena numeru wynosi 25,- zł. Zamówienia z określeniem okresu prenumeraty, nazwiskiem i adresem odbiorcy należy kierować bezpośrednio do Wydawcy (Wydawnictwo IMP, Instytut Maszyn Przepływowych PAN, ul. Gen. Fiszera 14, 80-952 Gdańsk; e-mail: now@imp.gda.pl). Osiągalne są również wydania poprzednie.
Prenumerata jest również realizowana przez jednostki kolportażowe RUCH S.A. właściwe dla miejsca zamieszkania lub siedziby prenumeratora.

Articles in *Transactions of the Institute of Fluid-Flow Machinery* are abstracted and indexed within:

INSPEC Database;
Energy Citations Database;
Applied Mechanics Reviews;
Abstract Journal of the All-Russian Inst. of Sci. and Tech. Inf. VINITI.

ISSN 0079-3205

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

Appears since 1960

Aims and Scope

Transactions of the Institute of Fluid-Flow Machinery have primarily been established to publish papers from four disciplines represented at the Institute of Fluid-Flow Machinery of Polish Academy of Sciences, such as:

- Liquid flows in hydraulic machinery including exploitation problems,
- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
- Solid mechanics, machine mechanics including exploitation problems.

The periodical, where originally were published papers describing the research conducted at the Institute, has now appeared to be the place for publication of works by authors both from Poland and abroad. A traditional scope of topics has been preserved.

Only original and written in English works are published, which represent both theoretical and applied sciences. All papers are reviewed by two independent referees.

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 119, 2007, 65-78

EMILIA METEL*, JANUSZ PODLIŃSKI, MIROSŁAW DORS and JERZY MIZERACZYK

Laser visualization of the flow of bubbles in a pulsed streamer discharge in water

Centre for Plasma and Laser Engineering, The Szewalski Institute of Fluid Flow Machinery, Fiszera 14, 80-952 Gdańsk, Poland

Abstract

The pulsed corona discharge in water produces radicals and reactive species, such as O, OH and H_2O_2, which can oxidize organic compounds to H_2O and CO_2. However, the pulsed corona discharge in water generates also shock waves and numerous bubbles, which contains water vapor, oxygen, hydrogen and active species. In this work results of the laser visualization of the gas bubbles flow in a needle-to-cylinder pulsed corona discharge reactor filled with distilled water are presented.

Keywords: Pulsed discharge; Visualisation; Bubbles

1 Introduction

High voltage pulsed discharges in water have been investigated for many years due to its application [1-4]. The pulsed discharge in water is efficient in formation of chemically active species such as OH, H, O, H_2O_2 and O_3 (with or without air or oxygen bubbling), which cause degradation of organic compounds contained in water. Besides the chemically active species, the discharge generates ultraviolet radiation and shock waves, which also contribute to the organic compound degradation. The streamer discharge is accompanied with the bubbles formation. The size and the velocity of the bubbles [5-6], and also rebounds of the bubbles as a function of hydrostatic pressure, electrical energy and nature of the liquid [7] can be measured. Bubbles are filled with the gas, which presumably contains the gaseous hydrogen, water vapour and oxygen.

*Corresponding author. E-mail: metel@imp.gda.pl

The aim of our investigation was to show streamers and gas bubbles formatio as well as motion of bubbles under the influence of electric field formed in th streamer discharge (point-to-cylinder electrode system) in the reactor with 1 an 3 needles in distilled water. The gas bubbles were used as tracers for the lase visualization of their flow.

2 Experimental setup

The experimental setup consisted of a reactor, DC power supply with a rotatin spark gap switch, CuBr laser, optics for the laser beam formation, a CCD vide camera for laser visualization of the bubbles and their flow and a photo-camer for visualization of the streamers (Fig. 1).

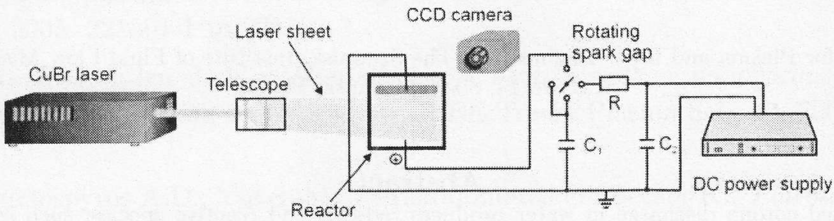

Figure 1. Experimental setup.

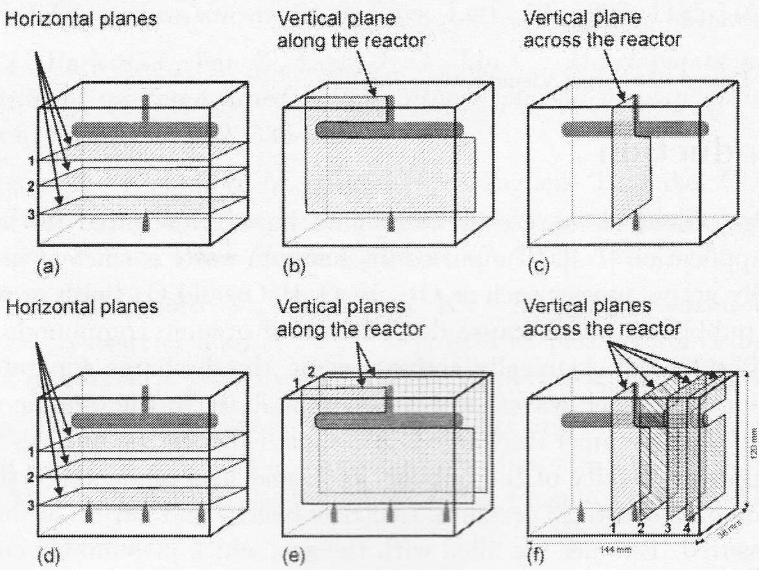

Figure 2. Observation planes in the reactors (36 mm wide, 144 mm long and 120 mm high) wit 1 or 3 needles.

The pulsed positive discharge was generated between a stressed stainless steel needle electrode(s) and a grounded brass cylinder electrode (Figs. 1 and 2). Two kind of needle arrangements were used: the first was equipped with one needle electrode, and the second – with three needle electrodes. The non-active part of the needle was covered with an insulator. The needle-cylinder spacing was 45 mm. The electrodes were placed in a glass parallel piped reactor (36 mm wide, 144 mm long and 120 mm high), which was filled with distilled water. The conductivity of water was 4 μS/cm.

Positive high voltage pulses were applied to the needle electrode(s) from a discharge capacitor C_1(2 nF) – Fig. 1. The capacitor was charged from a DC power supply through a resistor R (10 kΩ) and a capacitor C_2 (22 nF). The amplitudes of voltage and current pulse were up to 31 kV and 3 A respectively, with a pulse width up to 800 μs. Typical waveforms of voltage and current pulses recorded during the experiment are shown in Figs. 3 and 4. The pulse repetition rate of 50 Hz was determined by the rotation velocity of a rotating spark gap switch.

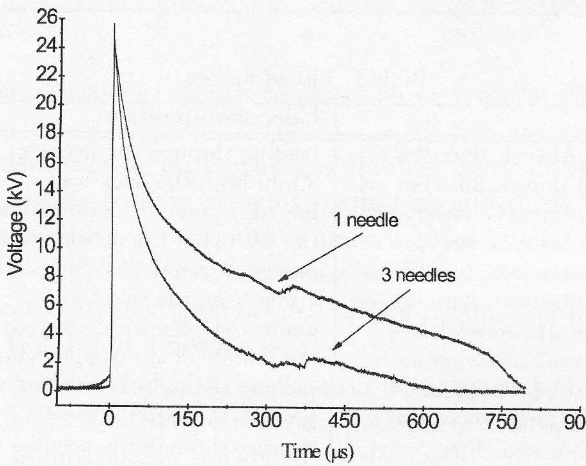

Figure 3. Typical waveforms of pulse voltage for pulsed streamer discharge at discharge voltage of 25 kV.

A CuBr laser with yellow (578.2 nm) and green (511.6 nm) lines of an average power 1.5 W and repetition rate of 18 kHz was used for visualization of the flow in the reactor. The laser beam emitted by the CuBr laser was transferred into a laser sheet by a cylindrical telescope. Images of the bubbles moving in the water were recorded by a CCD camera in the form of movies (Tab. 1). Visualization of the bubbles flow in the water was performed in a few horizontal and vertical positions of the laser sheet, crossing the reactor as shown in Fig. 2. For visualization of

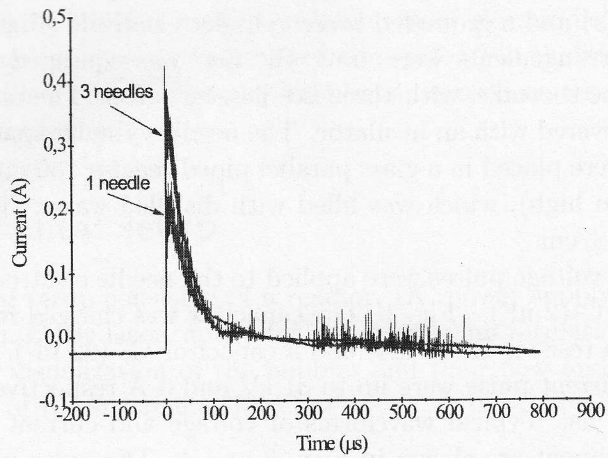

Figure 4. Typical waveforms of discharge current for pulsed streamer discharge at discharge voltage of 25 kV.

Table 1. List of movies.

Lp.	Movie	Laser sheet position
1.	VerticalAlong1_3needles.avi	passing through the needles
2.	VerticalAlong2_3needles.avi	3 mm from the back wall
3.	VerticalAcross1_3needles.avi	passing through the central needle
4.	VerticalAcross2_3needles.avi	the middle of the needle-needle spacing
5.	VerticalAcross3_3needles.avi	passing through the side needle
6.	VerticalAcross4_3needles.avi	7 mm from the side wall
7.	Horizontal1_3needels.avi	under the cylindrical electrode
8.	Horizontal2_3needels.avi	the middle of the needle-cylinder spacing
9.	Horizontal3_3needels.avi	passing through the needles
10.	VerticalAlong_1needle.avi	passing through the needle
11.	VerticalAcross_1needle.avi	passing through the needle
12.	Horizontal1_1needle.avi	under the cylindrical electrode
13.	Horizontal2_1needle.avi	the middle of the needle-cylinder spacing
14.	Horizontal3_1needle.avi	passing through the needle

the streamers a CMOS photo-camera (Canon EOS 20D) with an aperture value of 5.6 and a different exposure times was used.

3 Results

Typical images of the streamer discharge in water for 1 and 3 needle electrodes are presented in Figs. 6a–6c and Fig. 7, respectively. Figures 6a–6c show images taken with the photo-camera at the same voltage (28 kV) but with different exposure times. One can observe that the length of the streamers is similar in all cases. The number of pulses registered by photo-camera (Figs. 6a–6c) depends on the exposure time (Fig. 5): at the exposure time of 8 ms – one pulse (Fig. 6a) is registered, at the exposure time of 25 ms – one or two pulses (Fig. 6b) and at the exposure time of 67 ms – three or four pulses (Fig. 6c) are registered. The diameter of the streamer channel is about 0.5 mm (Figs. 6–7). Similar diameter (0.4–0.7 mm) values on the images of the pulsed streamer discharge in water obtained with the OH bandpass filter were recorded by Sun et al. [8].

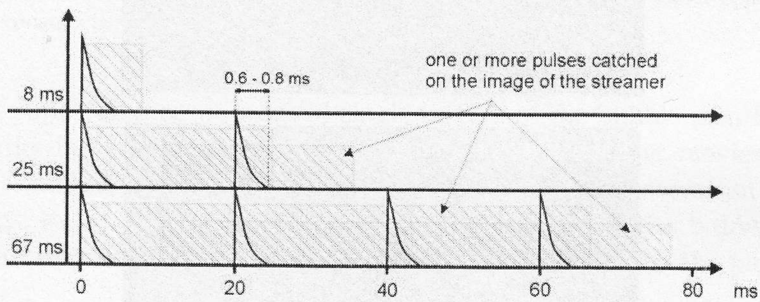

Figure 5. The number of discharge pulses registered by photo-camera at different exposure times.

During the discharge in water the gas bubbles were formed. According to our results the bubbles contain gaseous hydrogen, and presumably oxygen and water vapor. The bubbles were produced near the needle electrode(s) and due to buoyant and electrohydrodynamic forces the bubbles were moved upward towards the cylindrical electrode. Initiation of the bubbles production was observed at the voltage of 18 kV (for 1 and 3 needles).

The movement of the bubbles, easily seen with the naked eye, was recorded with the video camera. The movies showing the bubble flow in the water are listed in Tab. 1. It was found that in the streamer discharge with either 1 or 3 needles the increase in the current causes higher production of the bubbles upwards the cylindrical electrode (VerticalAlong2_3needles.avi movie recorded for the plane 2 shown in Fig. 2e; VerticalAlong_1needle.avi movie recorded for the plane shown in Fig. 2b) and a widening discharge region. When the current was decreased a lower bubble production was observed. After turning the applied voltage off the bubble production stopped.

The movies VerticalAlong1_3needles.avi and Horizontal3_3needels.avi (recorded for the planes 1 and 3 shown in Figs. 2e and 2d, respectively) show that the discharge inception in the reactor with 3 needles is not simultaneous. It can be caused by a non-uniform charge distribution on the plate connecting all needles and a breakdown through the covered insulator.

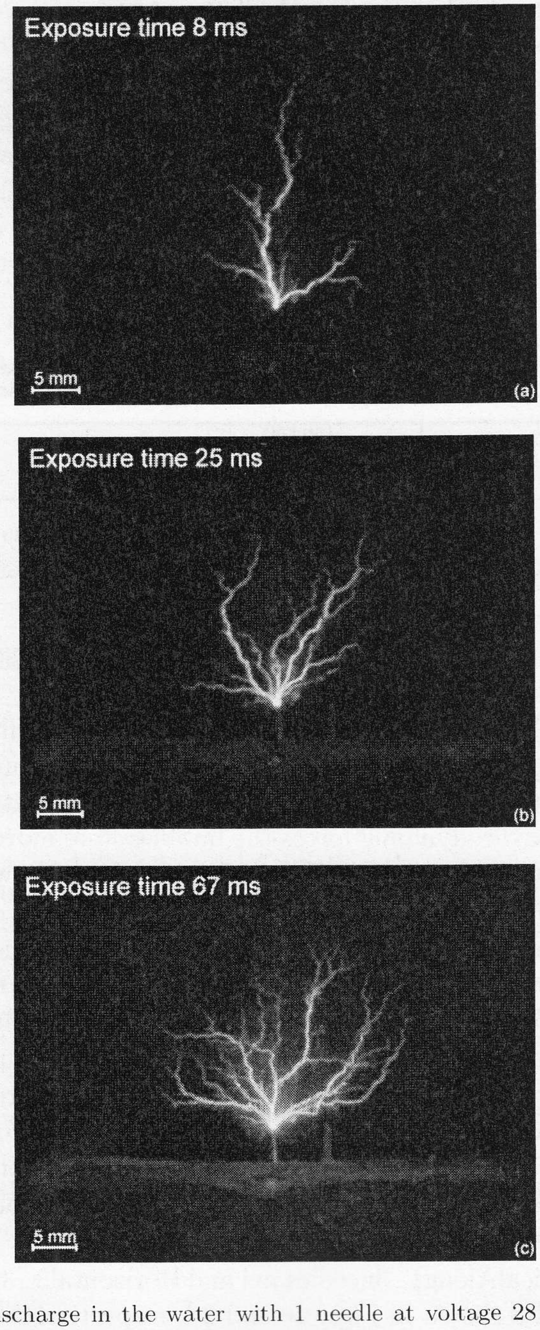

Figure 6. Streamer discharge in the water with 1 needle at voltage 28 kV with the discharge current up to 3 A. Needle-cylinder spacing 45 mm: (a) the exposure time 8 ms; (b) the exposure time 25 ms; (c) the exposure time 67 ms.

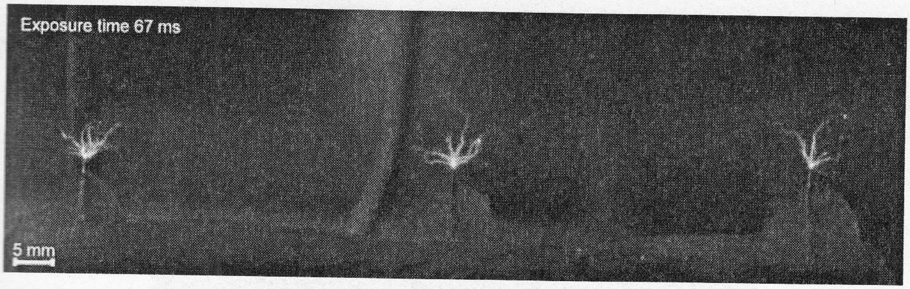

Figure 7. Streamer discharge in water with 3 needles at voltage 30 kV with the discharge current up to 3 A. Distance between the needles: 49 mm. Needle-cylinder spacing 45 mm. Exposure time: 67 ms.

In this paper we present selected single images of the bubble positions during the discharge in the water, extracted from the corresponding movies, with the sketches of the bubble flow trajectories deduced from the observation of the full movie (Figs. 8–15). Each arrow represents the direction of the bubbles motion. Movies were recorded at the discharge voltage up to 31 kV, with the pulse current up to 3 A.

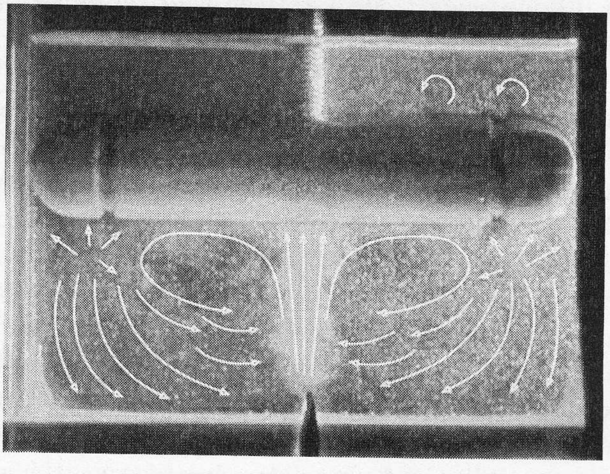

Figure 8. Trajectories of the flow of bubbles in vertical plane along the reactor with 1 needle deduced from the video movie VerticalAlong_1needle.avi. The laser sheet passing through the needle (Fig. 2b). The discharge voltage up to 31 kV, the discharge current up to 3 A.

Figure 8 (based on VerticalAlong_1needle.avi movie) shows the bubble flow trajectories in the vertical plane along the reactor passing through 1 needle (Fig. 2b). It is seen that the bubbles flow stream was flowing from the needle vicinity to the grounded electrode, and then at the left and the right side it started to circulate, forming bubble flow vortices. The vortices cause the water mixing in the reactor volume and transport the bubbles back towards the discharge region. Above the cylindrical electrode small vortices were observed.

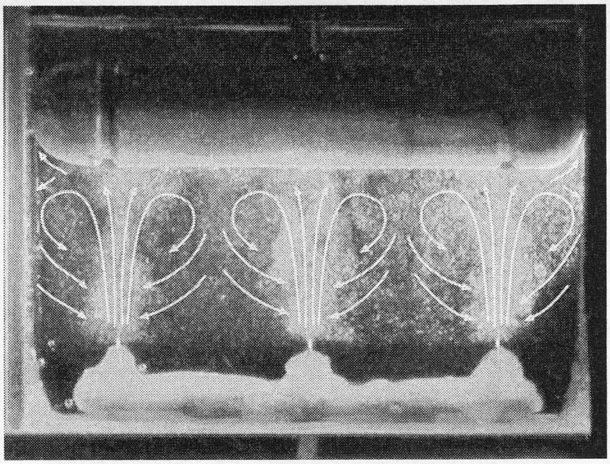

Figure 9. The bubbles flow trajectories in the vertical plane 1 along the reactor with 3 needles deduced from the video movie VerticalAlong1_3needles.avi. The laser sheet passing through the needles (Fig. 2e). The discharge voltage up to 31 kV, the discharge current up to 3 A.

Trajectories of the flow of bubbles in the reactor with 3 needles in vertical plane along the reactor passing through the needles (plane 1 in Fig. 2e) are shown in Fig. 9 (based on VerticalAlong1_3needles.avi movie). It is seen that flow patterns of three bubble streams corresponding to each needle electrode were formed. The streams of bubbles moving from the needle electrode to the cylindrical electrode were relatively strong. After coming to the cylindrical electrode the bubble stream turned downwards, forming vortices on both sides of each discharge. The downward bubble streams were weaker compared to the upward bubble stream. The vortices were smaller than in the reactor with 1 needle. It could be caused by different currents (the discharge current of 0.2 and 0.4 A for 1 and 3 needles at voltage of 25 kV, respectively) and a small spacing between the needle electrodes. They cause a relatively strong mixing of the water in the whole reactor volume.

In vertical plane along the reactor behind the needles (plane 2 in Fig. 2e), motion of the bubbles in the discharge direction was slow (Fig. 10, based on VerticalAlong2_3needles.avi movie). It is worth noting that the bubbles motion between the streams directed downward was stronger than in the plane passing through the needles (plane 1 in Fig. 2e).

The movement of bubbles in the vertical plane across the reactor with 1 needle (Fig. 2c) is shown in Fig. 11 (based on VerticalAcross_1needle.avi). One may see

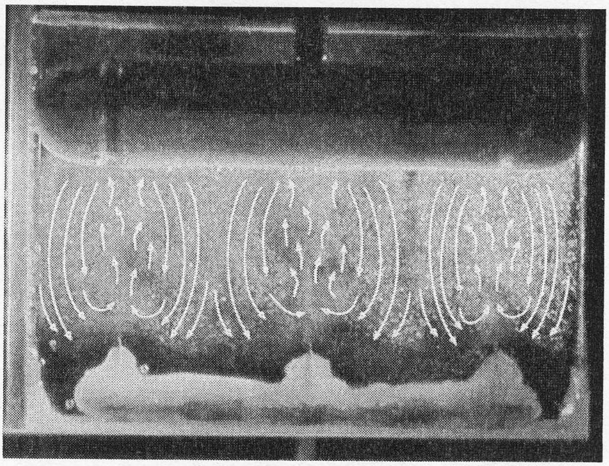

Figure 10. The trajectories of the flow of bubbles in vertical plane 2 along the reactor with 3 needles deduced from the video movie VerticalAlong2_3needles.avi. The laser sheet 3 mm from the back wall (Fig. 2e). The discharge voltage up to 31 kV, the discharge current up to 3 A.

that the bubbles moved in the relatively wide stream upward, then they passed through a narrow gap between the reactor wall and the cylindrical electrode, forming small vortices above it, and then they faded.

In the reactor with 3 needles the vertical observation plane across the reactor was located in four places (Fig. 2f). Two of the planes were passing through the needles, the middle (plane 1 in Fig. 2f) and the side one (plane 3 in Fig. 2f). The motion of the bubbles towards the cylindrical electrode (Fig. 12a, extracted from VerticalAcross1_3needles.avi movie; Fig. 12b, extracted from VerticalAcross3_3needles.avi movie) was similar to that in the reactor with 1 needle (Fig. 11), however there were vortices formed right next to the side walls under the cylindrical electrode. In the plane between the needles (plane 2 in Fig. 2f) the bubbles moved downward and from the regions near the side walls to the reactor center (Fig. 13a, based on VerticalAcross2_3needles.avi movie). In the plane placed near the side wall (plane 4 in Fig. 2f) the bubbles also flowed downward, however a higher velocity than in the plane 2 between the needles was obtained (Fig. 13b, based on VerticalAcross4_3needles.avi movie).

In the horizontal plane close the cylindrical electrode in the 1-needle reactor (plane 1 in Fig. 2a) the bubbles pushed up from the needle electrode were dispersed symmetrically to the reactor walls (Fig. 14a, based on Horizontal1_1needle.avi movie). In the corners of the reactor small horizontal vortices were observed. For 3-needle reactor the horizontal movement of the bubbles around each needle electrode in the plane 1 (Fig. 2d) looks similarly to that of 1-needle reactor (Fig. 15a,

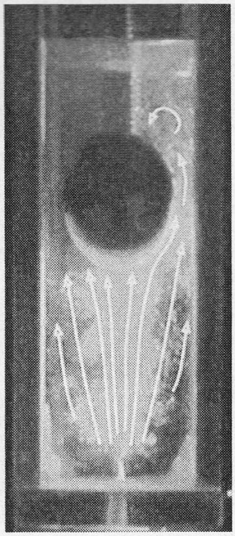

Figure 11. The trajectories of the flow of bubbles in vertical plane across of the reactor with 1 needle deduced from the video movie VerticalAcross_1needle.avi. The laser sheet passing through the needle (Fig. 2c). The discharge voltage up to 31 kV, the discharge current up to 3 A.

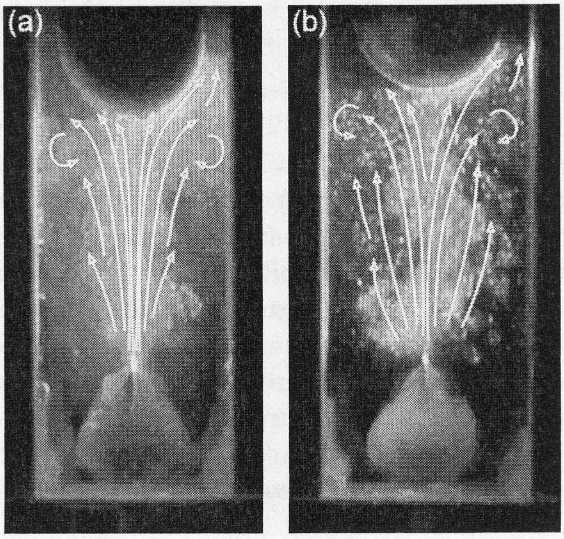

Figure 12. The trajectories of the flow of bubbles in vertical planes across the reactor with 3 needles (Fig. 2f): (a) the laser sheet passing through the central needle, plane 1 (extracted from the video movie VerticalAcross1_3needles.avi); (b) the laser sheet passing through the side needle, plane 3 (extracted from the video movie VerticalAcross3_3needles.avi);. The discharge voltage up to 31 kV, the discharge current up to 3 A.

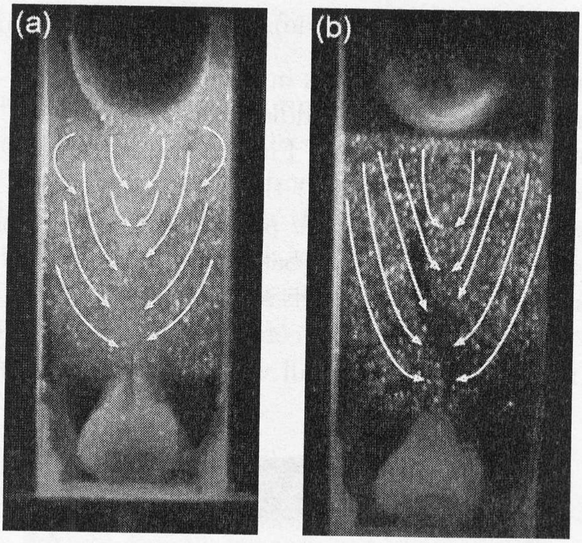

Figure 13. The trajectories of the flow of bubbles in vertical plane across the reactor with 3 needles (Fig. 2f): (a) the laser sheet between the needles, plane 2 (extracted from the video movie VerticalAcross2_3needles.avi); (b) the laser sheet 7 mm from the side wall, plane 4 (extracted from the video movie VerticalAcross4_3needles.avi). The discharge voltage up to 31 kV, the discharge current up to 3 A.

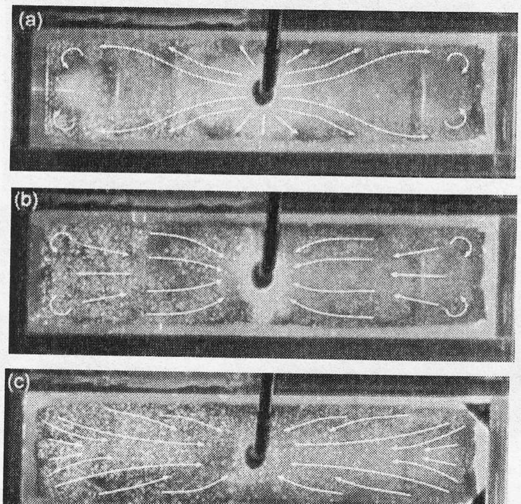

Figure 14. The trajectories of the flow of bubbles in horizontal plane of the reactor with 1 needle (Fig. 2a): (a) the laser sheet under the cylindrical electrode, plane 1 (extracted from the video movie Horizontal1_1needle.avi); (b) the laser sheet in the middle of the needle-cylinder spacing, plane 2 (extracted from the video movie Horizontal2_1needle.avi); (c) the laser sheet passing through the needle, plane 3 (extracted from the video movie Horizontal3_1needle.avi). The discharge voltage up to 31 kV, the discharge current up to 3 A.

based on Horizontal1_3needels.avi movie).

Regardless of the number of needles in the reactor, in both horizontal plane the apparent difference occurs in the middle between needle electrodes, i.e. place in the middle of the reactor (planes 2, Fig. 2a and 2d) and placed close to th needle tip(s) (planes 3, Fig. 2a and 2d) the bubbles moved in the needle direc tion. No vortices were observed in the planes 2 (Fig. 2d) and 3 (Fig. 2a an 2d) close to the needle tip(s) (Fig. 14c, based on Horizontal3_1needle.avi movie Fig. 15b, based on Horizontal2_3needels.avi movie; Fig. 15c, based on Horizon tal3_3needels.avi movie). Only in the corners of the plane 2 in Fig. 14b (base on Horizontal2_1needle.avi movie) small vortices were observed.

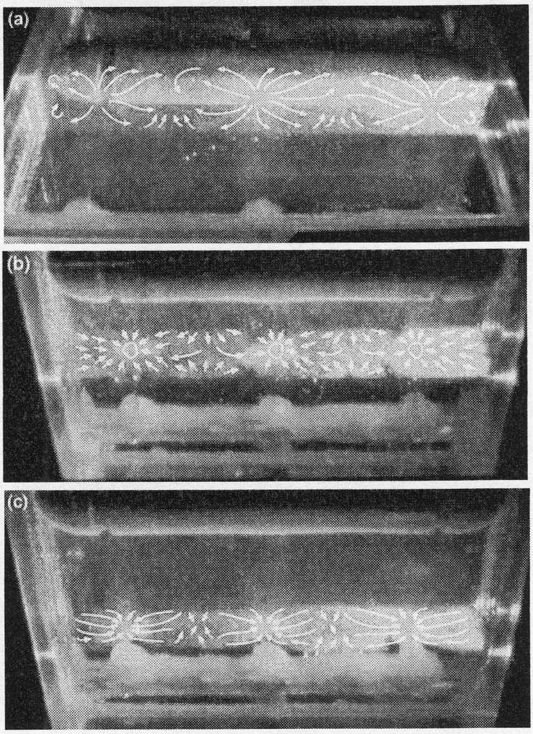

Figure 15. The trajectories of the flow of bubbles in horizontal plane of the reactor with needles (Fig. 2d): (a) the laser sheet under the cylindrical electrode, plane 1 (ex tracted from the video movie Horizontal1_3needels.avi); (b) the laser sheet in th middle of the needle-cylinder spacing, plane 2 (extracted from the video movie Hor izontal2_3needels.avi); (c) the laser sheet above the needles plane 3 (extracted from the video movie Horizontal3_3needels.avi). The discharge voltage up to 31 kV, th discharge current up to 3 A.

4 Conclusions

The experiment was focused on the formation and movement of the bubbles in the streamer discharge in the reactor filled with distilled water.

We observed that the bubble flow from the needle tip towards the cylindrical electrode is the stronger stream. Under the cylindrical electrode vortices appear, which transport scattered bubbles back towards the discharge region(s) and they cause mixing the water in the whole reactor volume (Fig. 16). During the discharge the whole reactor volume is filled with the bubbles and some of them was going out to the water surface.

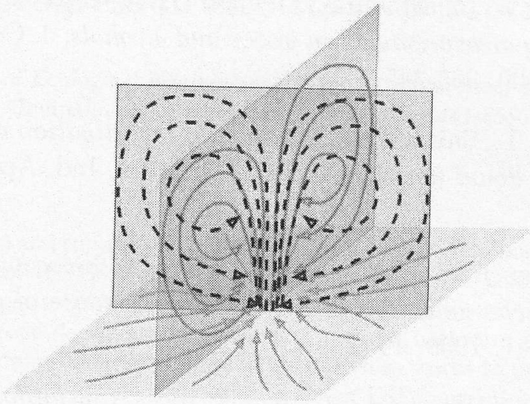

Figure 16. The sketch of the 3-dimensional movement of the bubbles in the reactor with one needle.

We found that the bubbles production and the streamer size increased with increasing applied voltage, regardless of the needle electrode numbers. However, in 3-needle reactor more gas bubbles were produced than in the reactor with single needle, probably due to higher currents (0.4 A and 0.2 A for 3 and 1 needle(s) at the voltage of 25 kV, respectively) and higher number of the generated streamers.

Received 10 November 2006

References

[1] Sugiarto A.T., Ito S., Ohshima T., Sato M., Skalny J.D.: *Oxidative decoloration of dyes by pulsed discharge plasma in water*, J. Electrostatics, 58, 2003, 135-145.

[2] Grymonpre D.R., Sharma A.K., Finney W.C., Locke B.R.: *The role of fen-ton's reaction in aqueous phase pulsed streamer corona reactors*, Chem. Eng J., 82, 2001, 189-207.

[3] Sunka P., Babicky V., Clupek M., Lukes P., Simek M., Schmidt J., Cernak M.: *Generation of chemically active species by electrical discharges in water*, Plasma Sources Sci. Technol., 8, 1999, 258-265.

[4] Locke B.R., Sato M., Sunka P., Hoffmann M.R., ChangJ.-S.: *Electrohydraulic discharge and nonthermal plasma for water treatment*, Ind. Eng. Chem. Res., 45, 2006, 882-905.

[5] Tsouris C., Shin W., Yiacoumi S., DePaoli D.W.: *Electrohydrodynamic veloc-ity and pumping measurements in water and alcohols*, J. Colloid and Interface Science, 229, 2000, 335-345.

[6] Sato M., Hatori T., Saito M.: *Experimental investigation of droplet formation mechanisms by liquid-liquid system*, IEEE Trans. Ind. Appl., 33, 1997, 1527-1534.

[7] Jomni F., Aitken F., Denat A.: *Dynamics of microscopic bubbles generated by a corona discharge in insulating liquids: influence of pressure*, Journal of Electrostatics, 47, 1999, 49-59.

[8] Sun B., Sato M., Harano A., Clements J.S.: *Non-uniform pulse discharge induced radical production in distilled water*, J. Electrostatics, 43, 1998, 115-126.