On electro-hydrodynamic effects over liquids under influence of corona discharge

V L Bychkov¹, V I Abakumov², A R Bikmukhametova³, V A Chernikov³, D A Safronenkov⁴

¹Leading researcher, Lomonosov MSU, Physical faculty, Moscow, Russia
²Graduate student, Lomonosov MSU, Physical faculty, Moscow, Russia
³Associated professor, Lomonosov MSU, Physical faculty, Moscow, Russia
⁴Student, Lomonosov MSU, Physical faculty, Moscow, Russia

E-mail: bychvl@gmail.com

Abstract. Electrohydrodynamic effects over liquids under high voltage electrode are considered in experiments with corona discharge. Simple theory is applied for description of a funnel appearance over a liquid is presented. New types of electrohydrodynamic instabilities are revealed.

1. Introduction

Present investigations are devoted to formulation and undertaking of experiments with corona discharges realized over surfaces of different liquids. Investigations when a surface of one of the electrodes is covered by a liquid or is an electrode itself are of interest for hydrocarbon fuel activation and search of elimination of undesirable liquids in engines, problems of ecology and disinfection with a help of electric discharge. Such investigations are developing now, that is a reason for undertaking of these investigations. In this work we concentrated on electric-hydrodynamic features of corona discharges which are practically uninvestigated yet. However, there is limited information about any discharges over surfaces of liquids [1,2] and it is obtained mainly for electrolytes or water.

From the application point of view it is interesting to know how a surface of a liquid fuel acts under an impact of gas discharges. Therefore our work is devoted to investigations of electric-hydrodynamic (EHD) effects caused by corona discharges over liquid. We made several series of experiments with positive and negative coronas over surfaces of tap water, distilled water, alcohol, glycerin, kerosene, and their mixtures.

2. Electro-hydrodynamics phenomena with corona discharges

Corona discharges are typically obtained by applying a high potential between a small diameter wire, charged negatively or positively and plate or coaxial cylinder [3] charged appositively. Investigations of these discharges and their applications continue for more than hundred years. Recently corona discharges began to be applied for problems of plasma aerodynamics [2].

The principle scheme of the experimental device is represented in Fig.1.
Figure 1. Principle scheme of experimental device.

1-Ditch, 2- Liquid (water, alcohol, kerosene), 3-Anode, 4- Post, 5- Cathode, 6-Power supply

It consists of a ditch filled with a liquid (water, alcohol, kerosene, etc), and electrical circuit. Upper electrode or a set of electrodes of diameter 0.9 mm (with radius of the tip-0.2 mm) or 2 mm (with radius of the tip-0.4 mm) was located at height 5-15 mm over a liquid surface. A distance between electrodes in upper multi-electrode formulation was 11 mm. Electrodes were under positive or negative potentials. Ditches were either metallic or dielectric. The metallic ditches were: cylindrical $\Omega$ 130 mm, height 18 mm, rectangular $37 \times 70 \times 122$ mm; the dielectric plastic ditch was: rectangular $45 \times 95 \times 130$ mm.

A current in a discharge was measured by a milliampere meter $A_1$, a voltage was measured by a chain consisting of resistance $R_1$ and a milliampere meter $A_2$. We measured Ampere and Volt characteristics of the discharge and represented results in A-V$^2$ coordinates typical for corona discharges [2].

Experiments have been carried out with a help of different cavities: rectangular – dielectric, cylindrical – dielectric and steel. Sizes of the rectangular cavity, were $70 \times 20 \times 15$ mm (length, width and depth). Characteristics of cylindrical cavities were $\Omega$125, 10 mm and $\Omega$185, 20 mm, respectively. An investigating liquid was poured into a cavity, a negative or positive electrode was located directly over the liquid, a distance between the electrode and the liquid could be varied in a range (1- 30) mm. The upper electrode in the case of rectangular cavity was placed at the angle of 50° to the vertical. Its diameter was 3 mm, its angle at the vertex was 30° and a radius of a tip was 0,4 mm. An electrode of another polarity was located directly in the liquid. (A cavity was used as an electrode itself in the case of metallic cavity). It was connected with a feeding source through a hermetic unit. In this case the liquid becomes the second electrode. A high voltage generator was used as the feeding source, it allowed to measure a voltage on the electrodes from 2 kV to 50 kV with a step of 250 V. Typical range of the voltage was 5-25 kV. Appearance of the spark discharge was accompanied with a drop of the voltage at the capacity, which was detected by the voltmeter. In this device we used a ballast resistance, which value was 100 M$\Omega$. Typical values of a current were 50-100$\mu$A.

3. Experiments with discharges over tap water surface

Our experiments have shown that application of negative and positive corona discharges over water surfaces in plastic or metallic cavities lead to appearance of a rotating funnel, it was evidently caused by the ion wind, see Fig.4.2-4.3. Vortices over surfaces of liquids appeared in case of non-central position of the upper electrode with respect to the cavity and in rectangular cavities.
Figure 2. Appearance of a funnel over water surface covered with wooden powder, metallic cavity, a distance between the upper electrode and a surface 5 mm, electrode central

Figure 2 represent appearance of a funnel over water surface covered with wooden powder. Figures 3-4 represent a transformation of a funnel into water surface excited by surface waves at rise of the voltage.

Figure 3. Appearance of a funnel over a water surface, plastic cavity, a distance between the upper electrode and a surface 5 mm. Negative corona.

Figure 4. Appearance of waves over a water surface, plastic cavity, a distance between the upper electrode and a surface 15 mm. Negative corona.

4. Experiments with alcohol

In case of the alcohol in plastic or metallic cavities corona discharges lead to appearances of different EHD effects over the surface of the liquid.
Funnels appeared at both polarities of the upper electrode. In Fig. 5, we represent such a phenomenon.

![Image of cavity over alcohol surface](image1)

**Figure 5.** Appearance of a cavity over alcohol surface, metallic cavity, a distance between the upper electrode and a surface 5 mm. Positive corona.

In case of the negative upper electrode firstly a rotating funnel usually appeared (it was evidently caused by then ion wind). Later some nuclei of jets in a form of tips were observed. Then bursting jets arose from the nuclei. The sprouts develop on sides of the funnel. This finishes either appearance of jets, see Figures 6-9, or liquid columns, see Figure 10-11. Usually this takes place at high applied voltage (20-30 kV). These columns are either standing on a place of the post funnel center or make some rotation motion being on a side of a funnel.

Liquid columns have sometimes widening at tip, sometimes there appears a violet-bleu glow on the column tip, see Figures 10-11. It speaks about breakdown field conditions realization near the tips.

Images were obtained with a help of digital video camera Sony DCR-TRV730 with frame duration 33 ms. Appearance of jets and columns stopped at the upper electrode distance of 17-18 mm from the surface.

Similar phenomena are known in EHD from literature [46]. They are connected with a development of Rayleigh, Taylor, Tonks and Frenkel electrostatic instabilities on surfaces of charged drops and jets when Coulomb forces of accumulated charges become greater than the surface tension.

![Image of jet over double distilled water surface](image2)

**Figure 6.** Appearance of a jet over a double distilled water surface, plastic cavity, a distance between the upper electrode and a surface 5 mm. Negative corona.
Figure 7. Appearance of a jet over alcohol surface, metallic cavity, a distance between the upper electrode and a surface 7 mm. Negative corona. First stage.

Figure 8. Appearance of a jet over alcohol surface, metallic cavity, a distance between the upper electrode and a surface 7 mm. Negative corona. Second stage.

Figure 9. Appearance of a jet over alcohol surface, metallic cavity, a distance between the upper electrode and a surface 7 mm. Negative corona. Third stage.
Figure 10. Appearance of a column over alcohol surface, metallic cavity, a distance between the upper electrode and a surface 7 mm. Negative corona.

Figure 11. Appearance of a discharge between the upper electrode and the column over alcohol surface, metallic cavity, a distance between the upper electrode and a surface 7 mm. Negative corona.

5. **Short theoretical discussion of obtained results**

Let us consider impact of the ion wind to a surface of a liquid, and suppose that the ion wind creates a funnel. A scheme of the corona discharge and a liquid are represented in Fig.4.27.

![Scheme of the ion wind impact on a liquid surface](image)

**Figure 12.** A scheme of the ion wind impact on a liquid surface

Appearance of the funnel can be a result of the ion wind impact on the liquid surface. Disregarding air heating by the corona discharge one obtains from the Euler equation a following equation for air stream velocity [5,6]
here \( \rho \) is air density, e- electron charge, \( E \) - electric field, \( \mu \text{ion} \) - a mobility of ions, \( I \) – discharge current, \( A(x) \) – a cross section of air stream at a distance \( x \) from the tip of the upper electrode. Taking an area of the ion wind as a cone with a radius of a base \( R_s \), and the cone side surface touches a base of the tip’s hemisphere with the radius \( r_0 \) one can obtain a following equation for a pressure head, see Figure 12, one gets:

\[
\frac{\rho u^2}{2} \approx \frac{I \cdot d}{\mu \text{ion} \cdot \pi \cdot r_0 \cdot R_s},
\]

(2)

where \( d \) is a distance between a surface of liquid and a tip of the upper electrode. For experimental conditions \( I \approx 5 \cdot 10^{-5} \) A, \( d \approx 10 \) mm, \( r_0 \approx 0.2 \) mm, \( R_s \approx 3 \) mm, \( \mu \text{ion} = 2 \cdot 10^{-4} \) m² V⁻¹s⁻¹ one obtains from (3):

\( \frac{\rho u^2}{2} \approx 1.3-103 \) Pa.

Using a scheme in Figure 12 one obtains the following equation

\[
\delta p = 1/2 \cdot \rho u^2 = I \cdot (R - r)^2 / (\pi \cdot \mu \text{ion} \cdot H \cdot r \cdot R).
\]

(3)

Inserting air density \( \rho = 1.2 \) kg/m³, experimental values of the current \( I = 50 \) µA, the radius of the funnel \( R = 2 \) mm, the radius of the tip \( r = 0.4 \) mm of the upper electrode, the distance between the tip and the surface \( H = 7 \) mm and air ion mobility \( \mu \text{ion} = 2 \cdot 10^{-4} \) m² V⁻¹s⁻¹ into (3) one obtains the following value of an average velocity in conditions of our experiment \( u \approx 7.8 \) m/s. It is in a reasonable agreement with measurements [7-8] where the values of the ion wind at farer distances from the upper tip were about 3-5 m/s.

The pressure drop given by (3) is \( \delta p \approx 36 \) Pa.

From another point of view one can find it using a volume of the compressed liquid at a formation of the funnel:

\[
\delta p = \rho \cdot g \cdot h \cdot S / S = \rho \cdot g \cdot h
\]

where \( h \) is a depth of the funnel. In case of water in our experiment \( h \approx 3 \) mm, and \( \delta p \approx 30 \) Pa, it is in reasonable agreement with the estimate given on a basis of the ion wind. So one can conclude that the funnel is created by the ion wind.

According to [1,3] an electric field \( E_{\text{max}} \) at a distance \( x \) between the tip of the parabolic form with curvature radius \( r \) being and the perpendicular plane at a distance \( d \) is connected with the voltage \( V \) between the tip and a plane by the formulae

\[
E_{\text{max}} = 2V /((2x + r) \ln(2d / r + 1)).
\]

(4)

Electric field in the corona discharge can be described by this formula [3] when there is no developed discharge channel.

One can see that the electric field influences the charged surface of the liquid. It will attract charged surface, against the gravitational force and the force of surface tension, causing the electric instability. It is so called Tonks – Frenkel instability of the charged surface of a liquid [4,6]. A condition for realization of this instability has a form

\[
E^2 > 2 \sqrt{\rho \cdot g \cdot \alpha / (\varepsilon \varepsilon_0)}.
\]

(5)

\( E \) is electric field strength near a surface of a liquid, \( \varepsilon \) 0 is air dielectric permeability, \( \alpha \) is a surface tension of the liquid, \( \rho \) is its density. Using this formula one can obtain thresholds of Tonks-Frenkel instability over different liquids, such estimates for the critical electric fields are represented in Table 1.
The edge height reaches 1 mm size. From (4) one obtains conditions for the development of the instability at the edge of the funnel. Observations show that appearance of bursting jets and destruction of columns in case of negative coronas are different. It is well known that a liquid is drawn to a region of a high field in a capacitor 

corona, and they will neutralize. However, ions in the positive corona are transported to the lower electrode quicker than in negative corona. Analysis of Volt-Ampere characteristic of obtained experimental data shows that appearance of jets and columns can be easier originated at the edge of the funnel. Observations show that the edge height reaches 1 mm size. From (4) one obtains a ratio of electric fields between the tip and the funnel bottom and the tip and the edge:

$$\frac{E_{\text{edge}}}{E_{\text{bottom}}} \approx \left(1 + \frac{\Delta s_1 + \Delta s_2}{d}\right),$$

where $\Delta s_1$ is the depth of the funnel and $\Delta s_2$ is the size of the edge. If $\Delta s_1 \approx 1.5\;\text{mm}$, $\Delta s_2 \approx 1.0\;\text{mm}$ and $d=7\;\text{mm}$ then $\frac{E_{\text{edge}}}{E_{\text{bottom}}} \approx 1.35$, so conditions for the development of the instability at the edge of the funnel are favorable. That we also see in the experiment.

Looking at the Table one can see that the thresholds for glycerin and distilled water are close to those of the air breakdown, which in real conditions varies in the range $E \approx 2.6-3/0\;\text{MV/m}$. At the same time its threshold in alcohol is $E \approx 1.7\;\text{MV/m}$ -much smaller. This shows that the development of air breakdown and formation of plasma channel can damp the development of the instability. However, one can expect a development of this instability in alcohol and kerosene and their mixtures. What we see in our experiments.

Using formula (4) and Figure 12 one can understand why jets and columns can be easier originated at the edge of the funnel. Observations show that the edge height reaches 1 mm size. From (4) one obtains a ratio of electric fields between the tip and the funnel bottom and the tip and the edge:

$$\frac{E_{\text{edge}}}{E_{\text{bottom}}} \approx \left(1 + \frac{\Delta s_1 + \Delta s_2}{d}\right),$$

where $\Delta s_1$ is the depth of the funnel and $\Delta s_2$ is the size of the edge. If $\Delta s_1 \approx 1.5\;\text{mm}$, $\Delta s_2 \approx 1.0\;\text{mm}$ and $d=7\;\text{mm}$ then $\frac{E_{\text{edge}}}{E_{\text{bottom}}} \approx 1.35$, so conditions for the development of the instability at the edge of the funnel are favorable. That we also see in the experiment.

Analysis of Volt $2\;\mu\text{Ampere}$ characteristic of obtained experimental data shows that appearance of jets and columns over alcohol in negative corona take place at voltages when in the positive corona the discharge channel is already realized. So, conditions in the negative corona are similar to those realizing in the capacitor $[3,5]$ with high electric field causing the instability and in the positive corona – in the quasi-neutral plasmas with lower electric field, which cannot cause a development of this instability.

Appearance of bursting jets and destruction of columns can be connected with development of instabilities of charged drops (we consider that tips of these structures represent quasi-drops). Conditions of their development have a form [4]:

$$\varepsilon_{\text{air}}\varepsilon_0 E^2 / 2 \geq 0.7 \cdot \alpha / R$$

in the case of large deformations (Rayleigh problem) and

$$\varepsilon_{\text{air}}\varepsilon_0 E^2 / 2 \geq 2 \cdot \alpha / R$$

in the case of small deformations, $E$ is electric field strength on the drop surface, $\varepsilon$ is the dielectric constant of air, $\alpha$ is the surface tension coefficient, $R$ is the radius of the drop. Assuming that the alcohol drop radius is equal to the radius of the column one obtains $E \approx 2.6-4.5\;\text{MV/m}$. These values are close to the typical breakdown values realized in air discharge near the electrodes. So we can connect these destruction mechanisms with the phenomena observed in the discharge.

Appearance of jets and columns over a surface in negative corona discharge case can be connected with a time of electric charge relaxation in a liquid. According to electrodynamics this time is $\tau \sim \varepsilon_{\text{liq}}\varepsilon_0 / \sigma_{\text{liq}}$, here $\varepsilon_{\text{liq}}, \varepsilon_0$ are a dielectric constant of a liquid and vacuum, respectively, $\sigma_{\text{liq}}$ is electric conductivity of a liquid. For example, inserting values of corresponding values one obtains a typical time of charge relaxation in alcohol $\tau \approx 22\;\text{s}$ and $\tau \approx 7-10\;\text{s}$ in tap water. So in case of alcohol a state of a quasi-capacitor can be realized, and a surface of liquid can stay charged during a long time. However, ions in the positive corona are transported to the lower electrode quicker than in negative corona, and they will neutralize the charge in the liquid. So the situations with positive and negative coronas are different. It is well known that a liquid is drawn to a region of a high field in a capacitor that can be the reason for appearance of jets and columns in case of negative corona over a surface of alcohol.

| Table 1. Values of the critical electric field for Tonks-Frenkel instability |
|-----------------|------------------|-----------------|------------------|
| Liquid          | Distilled water  | Alcohol         | Glycerin         |
| E, MV/m         | 2.4              | 1.7             | 2.5              |

In the case of large deformations (Rayleigh problem) and

$$\varepsilon_{\text{air}}\varepsilon_0 E^2 / 2 \geq 0.7 \cdot \alpha / R$$

in the case of small deformations, $E$ is electric field strength on the drop surface, $\varepsilon$ is the dielectric constant of air, $\alpha$ is the surface tension coefficient, $R$ is the radius of the drop. Assuming that the alcohol drop radius is equal to the radius of the column one obtains $E \approx 2.6-4.5\;\text{MV/m}$. These values are close to the typical breakdown values realized in air discharge near the electrodes. So we can connect these destruction mechanisms with the phenomena observed in the discharge.

Appearance of jets and columns over a surface in negative corona discharge case can be connected with a time of electric charge relaxation in a liquid. According to electrodynamics this time is $\tau \sim \varepsilon_{\text{liq}}\varepsilon_0 / \sigma_{\text{liq}}$, here $\varepsilon_{\text{liq}}, \varepsilon_0$ are a dielectric constant of a liquid and vacuum, respectively, $\sigma_{\text{liq}}$ is electric conductivity of a liquid. For example, inserting values of corresponding values one obtains a typical time of charge relaxation in alcohol $\tau \approx 22\;\text{s}$ and $\tau \approx 7-10\;\text{s}$ in tap water. So in case of alcohol a state of a quasi-capacitor can be realized, and a surface of liquid can stay charged during a long time. However, ions in the positive corona are transported to the lower electrode quicker than in negative corona, and they will neutralize the charge in the liquid. So the situations with positive and negative coronas are different. It is well known that a liquid is drawn to a region of a high field in a capacitor that can be the reason for appearance of jets and columns in case of negative corona over a surface of alcohol.
6. Conclusions

Creation of corona discharges of positive and negative polarity has been realized over tap and distilled water, alcohol, glycerin and their mixtures.

Special devices for undertaking of experiments with several electrodes have been developed.

Conducted experiments and their analysis show that the corona discharge over different liquids can cause different hydrodynamic phenomena including appearance of the ion wind and different instabilities.

Appearance of funnels is a result of the ion wind this was proved on the basis of the Euler equation. Funnels appear both in positive and negative coronas and independent of the discharge type.

Appearance of liquid jets and columns is a result of the Tonks–Frenkel instability in conditions of negative and positive corona. This phenomenon depends on a value of electric field strength and is better realized in liquids with low density and surface tension.

Separation of these jets and columns in drops are connected with instabilities of charged drops.

Experiments show that conditions in the negative coronas in air are more favorable for creation of hydrodynamic phenomena than those in the positive coronas, since in the negative coronas can be achieved higher values of electric fields at which is still no realization of the discharge plasma channel connecting the electrodes.

These experiments helped to clarify modes of discharges realization and their connection with appearance of funnels on the surfaces of liquids and columns in case of alcohol.

References

[1] Lebedev Yu A, Plate N A, Fortov V E Encyclopedia of low temperature plasma. Applied Plasma Chemistry. Ed. 2009 9(5) Yahys-K publishers Moscow
[2] Bychkov V, Chernikov V, Ershov A Esakov I, Kostiuk A 2009 Corona discharge over a surface of a liquid. AIAA-2009-1554. 47th AIAA Aerospace Sciences Meeting. 5-8 January 2009. Orlando World Center Marriott. Orlando. Florida.
[3] Raizer Yu P Gas discharge physics. Nauka, Moscow 1992.
[4] Saranin V A Equilibrium of liquids and its stability. Institut Kompiuternykh Issledovanii Publishers. Moscow 2002.
[5] Landau L D, Lifshitz EM Electrodynamics of continuous media. Moscow, Nauka 1982.
[6] Levich V G Physical and Chemical Hydrodynamics. Fizmatlit Publishers. Moscow 1959.
[7] Lacoste D A, Pai D, Laux CO 2004 AIAA-2004-354. 42-nd AIAA Aerospace Sciences Meeting and Exhibit. 5-8 January 2004, Reno, Nevada.
[8] Kozlov B A, Solov’ev VI Zhurnal Tekhnicheskoi Fiziki 2007 77(7) P.76.