Jet effects of homogeneous and multiphase media under conditions of combustion of gas-steam discharges

Al F Gaisin¹ N F Kashapov² D N Mirkhanov³ A I Gaisina¹ and A V Korneev¹

¹Faculty of Physics and Mathematics, Kazan National Research Technical University named after A.N.Tupolev - KAI, Kazan, 420111, Russia
²Kazan Federal University, Kazan, 420008, Russia

E-mail: almaz87@mail.ru

Abstract. In this paper, homogeneous and multiphase flows in the conditions of low-temperature plasma combustion of high-frequency (HF) and direct current gas-vapor discharges are presented. The types and forms of combustion of steam-gas discharges with jet liquid electrodes are presented. The features of the hydro-gasdynamic processes occurring at the interface between media are presented.

1. Introduction

Physics of vapor-gas discharges with liquid electrodes is one of the most intensively developing research areas in the world [1-5]. This type of discharge is generated in the interelectrode gap by direct or alternating current, where one or two electrodes are flowing or non-flowing liquid. As a rule, saline solutions with different concentrations in industrial or distilled water are used as a liquid. The researches in the field of homogeneous and multiphase media flows under the conditions of discharge burning; hydrogdynamic and heat processes at the media interfaces; types and modes of discharge burning; electrophysical and spectral characteristics of discharge; plasma components distribution by concentration and energy are of particular interest. The experimental data, in turn, are used to build and verify physical and mathematical models of vapor-gas discharges with liquid electrodes. In this field of science, the issues of understanding the processes occurring both in a plasma generated by a gas-vapor discharge and in flows of homogeneous and multiphase media in conditions of discharge combustion are urgent.

2. Experiment

The experimental studies of RF and DC vapor-gas discharges with jet liquid electrodes were carried out using an experimental plant (Figure 1). On the block diagram: 1-vacuum chamber, 2-viewing window, 3-hydraulic drive for lifting/lowering the vacuum chamber, 4-working area with discharge chamber, 5-rotary vane pump of "2NVR-5DM " brand. The DC generator ensuring an adjustable DC voltage of up to 4000 V at a nominal current of up to 10 A or RF generator of " RFG8-60/13" brand tuned to frequency $f = 13.56 \text{MHz}$ were used as power sources. Researches were carried out in the range of the set parameters: pressure $p = 10^5 \text{Pa}$, jet length $l_e = 5 - 30 \text{mm}$, jet diameter $d_e = 3 - 5 \text{mm}$, jet velocity $v_e = 0.1 - 0.2 \text{m/s}$, interelectrode gap $i = 0 - 10 \text{mm}$ and voltage
\[ U = 1.5 - 2 \text{ kV}. \] NaCl or (NH4)2SO4 solutions in process water were used as a liquid electrode. The potential for liquid was induced by a copper plate.

Figure 1. Functional diagram of the experimental setup for the study of steam and gas discharges of high-frequency and direct currents with liquid electrodes.

The following research methods were used to perform the set tasks:

1. The study of types and forms of vapor-gas discharge burning was carried out through photo-video shooting using the equipment of SONY FDR-AX33 brand and Casio EX-F1 digital high-speed camera. Since the processes in the vapor-gas discharge burning zone are swift-flowing, they were shot at 600 and 1200 frames per second.

2. Spatial visualization of the hydro-gas-dynamic processes occurring at the media interface in the conditions of the combustion of a gas-gas discharge plasma was carried out using the Schlieren method (Tepler method). As the source of radiation, an arc xenon lamp "DKSSh-250" with a power of 250 W was used, providing the necessary for suppressing its own luminescence of a gas-vapor discharge plasma, the intensity of translucent radiation.

The DC vapor-gas discharge with liquid electrodes was explored in two versions of the electrode configuration: 1 - between jet anode and liquid cathode; 2 – between jet cathode and liquid anode. In the first version of the electrode configuration a closing direct current \( I = 0.5 \text{A} \) without discharge ignition occurs in a circuit when voltage \( U = 250 \text{V} \) is supplied. With increasing voltage up to 700V there occurs a breakdown in the system with the discharge burning in two areas of the system depending on the jet electrode length \( l_c \), diameter \( d_c \) and flow velocity \( v_c \). At \( U = 700 \text{V} \), \( v_c \approx 0.35 \text{m/s} \), \( d_c \approx 5\text{mm} \) and \( l_c \approx 20\text{mm} \) the vapor-gas discharge burns at interface between the jet anode and the liquid cathode in the form of microchannels in rapidly formed vapor-gas bubbles (Figure 2a).

Given \( v_c \approx 0.15 \text{m/s} \), \( d_c \approx 3\text{mm} \) and \( l_c \approx 25\text{mm} \) the vapor-gas discharge can also burn along the jet electrode at the boundary between the forming drop and the electrolyte jet (Figure 2b) which is connected with an increase in the field strength in the area of jet narrowing.

Combustion of steam and gas discharges of high-frequency current with liquid electrodes has its own peculiarities. Like steam and gas discharges of direct current, the RF discharge can burn both at the boundary between the jet electrode and along the jet electrode in the form of microchannels (Figure 3a-d). This system of electrode configuration is characterized by the formation of vortex, ring and spiral discharges that pulsate and drift along the jet electrode, or combustion of a volume (diffuse) discharge with the formation of brightly luminous, contiguous bands on the jet surface (Figure 3e).
Figure 2. Photographs of the development of the DC vapor-gas discharge between the jet and liquid electrodes (a) and along the jet of liquid (b).

Figure 3. Development of RF vapor-gas discharge in the gas-liquid flow at $p = 10^5$ Pa, voltage on the loaded electrode $U = 3$kV: a - before discharge; b, c - with discharge; d - after discharge. Ring gas-vapor discharges of the high-frequency current along the jet electrode at $p = 10^3$ (e)

Apparently, this effect arises due to the following reason. The RF current flowing along the jet, in accordance with the Ampere-Maxwell Law, generates a RF magnetic field, which in turn generates a RF electric field. Free flowing symmetrical jet is gradually narrowing with disturbances developing in it, as a result the surface profile in the longitudinal section becomes similar to the sine wave with
increasing amplitude. The RF current density increases in inverse proportion to the square of the jet radius. Therefore, in the areas of the greatest narrowing, the electric field strength increases quadratically, which leads to the occurrence of rings discharges in this place. Figure 4 shows the image of the spatial visualization of hydro-gas-dynamic processes occurring at the media interface, in the zone of formation of a gas-vapor discharge. In this case, the combustion of the RF current discharge between two jet electrodes is accompanied by the intense formation of droplets of different diameters and convective vapor-air currents of various densities, where the bright portions correspond to the discharge region, and the dark seals. With the supply of potential in the circuit, an RF ripple current arises and, due to the joule heat release at the interface between the liquid electrodes, a vapor-gas shell is formed. If the input power is sufficient to ionize the vapor, a breakdown occurs in the gas-vapor cladding. As a result of breakdown, the pressure in the vapor-gas jacket sharply increases, which leads to the appearance of a process similar to the "hydraulic shock" with a characteristic acoustic clap and the formation of shock waves that propagate in different directions of space from the jet electrodes. Shock waves deform and repel jets from each other. The discharge goes out. Then the jets again intersect and the process repeats.

Figure 4. Spatial visualization of the development of hydro-gas dynamic processes between intersecting liquid jets in the conditions of burning of a steam-gas discharge of high-frequency current.

Acknowledgments
The reported research was funded by the Russian Foundation for Basic Research and the Government of the Tatarstan Republic (Grant No. 18-42-160004) and by the Russian Foundation for Basic Research (Grant No. 18-32-00033).

References
[1] Gaisin F M and Son E E 1989 Electrophysical processes in discharges with solid and liquid electrodes. / Sverdlovsk: Publishing House of Uralsk. University 432
[2] Gaisin A F, Son E E and Petryakov S Y 2017 Radio-frequency capacitive discharge with flowing liquid electrodes at reduced gas pressures Plasma Physics Reports 7 741-748
[3] Akishev Yu S, Grushin M E, Karal’nik V B, Monich A E, Pan’kin M V, Trushkin N I, Kholodenko V P, Chugunov V A, Zhirkova N A, Irkhina I A and Kobzev E N 2006 Generation of a nonequilibrium plasma in heterophase atmospheric-pressure gas-liquid media and demonstration of its sterilization ability Plasma Physics Reports 32 12 1052-1061
[4] Gaisin A F and Kashapov N F 2018 Investigation of physical processes in a gas discharge zone between liquid electrodes Journal of Applied Mechanics and Technical Physics 59 4 (350) 19-22
[5] Gaisin A F, Kashapov N F, Kuppotinova A I and Mukhametov R A 2018 The discharge between injecting liquid and metallic electrodes // Technical Physics. The Russian Journal of Applied Physics 88 5 717-721