High effective heterogeneous plasma vortex reactor for production of heat energy and hydrogen

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Abstract. This work is a continuation of our previous studies [1-10] of physical parameters and properties of a long-lived heterogeneous plasmoid (plasma formation with erosive nanoclusters) created by combined discharge in a high-speed swirl flow. Here interaction of metal nanoclusters with hydrogen atoms is studied in a plasma vortex reactor (PVR) with argon-water steam mixture. Metal nanoclusters were created by nickel cathode’s erosion at combined discharge on. Dissociated hydrogen atoms and ions were obtained in water steam by electric discharge. These hydrogen atoms and ions interacted with metal nanoclusters, which resulted in the creation of a stable plasmoid in a swirl gas flow. This plasmoid has been found to create intensive soft X-ray radiation. Plasma parameters of this plasmoid were measured by optical spectroscopy method. It has been obtained that there is a high non-equilibrium plasmoid: $T_e > T_v >> T_R$. The measured coefficient of energy performance of this plasmoid is about COP $= 2 - 10$. This extra power release in plasmoid is supposed to be connected with internal excited electrons. The obtained experimental results have proved our suggestion.

1. Introduction
Swirl flow control and vortex control near a flying vehicle realized by non-equilibrium plasma formation is a key task in plasma aerodynamics today. Experimental results obtained during this study can be used in aviation and plasma-assisted combustion [1-11]. Physical properties of a longitudinal plasmoid created by the capacity-coupled high-frequency discharge in the high-speed swirl flow were studied in our works [1-6] in detail. Measuring power budget in this plasmoid in swirl flow is very important for aluminum-hydrogen power generation [6] and extra power production [9]. One of the most promising technologies for hydrogen production is based on PVR [6]. This work is a continuation of our previous studies [1-10].

2. Energy release inside heterogeneous plasmoid in swirl gas flow
PVR was designed and elaborated on the basis of 20 years of experimental background [1-10]. Heterogeneous metal cluster plasmoid was created by combined discharge (HF+DC) in different gas flows. High value of COP $= 2 - 10$ was obtained namely by PVR [5]. Some of the experimental results obtained using PVR are considered in this work.

Scheme of this PVR is shown in figure 1. The experimental setup was described in the previous work [5]. Plasma-vortex reactor (PVR) is made of a quartz tube with a diameter of 60 mm. A swirl gas flow is created both by a tangential gas injector and an axial gas injector in this reactor. The swirl flow
in PVR is excited and heated by the combined discharge (HF+DC). A mass gas flow rate is measured in this experiment. The tested gases used in this setup are as follows: helium, nitrogen, argon, water steam and their mixtures. This mixture is used to obtain dissociated water steam and hydrogen atom and ions in the argon plasma and to study their interaction with metal clusters. The typical parameters of pulsed repetitive HF generator used in this work are as follows: maximal output pulsed voltage is ~60kV, a pulsed HF power is ~1÷10 kW, a HF frequency is \( f_{HF} \approx 0.3\text{-}10 \text{ MHz} \), a pulse repetitive frequency is \( f_{p1}=10\times10^4 \text{ Hz} \), and pulse duration is \( T_p=10\mu\text{s}+100\text{ms} \). Typical parameters of high-current pulse repetitive discharge are as follows: a pulse current is up to 100 Amp, a pulse duration is 1-100 \( \mu\text{s} \), and a pulse repetitive frequency is \( f_{p2}=10\times10^4 \text{ Hz} \). Typical parameters of the DC discharge are as follows: a current of ~1-2 Amp, and a mean power of 1-2 kW. Experimental conditions are as follows: gas mixture argon (or helium): water steam, mass gas flow rate < 10 g/sec, gas flow Mach number \( M < 0.2 \), static pressure \( P_s < 2 \text{ Bar} \), mean electric power input < 1 kW, mean thermal output power < 10 kW, and electrode mass erosion rate < 1 mg/sec.

**Figure 1a.** Schematic of experimental set-up. 1- swirl generator, 2- argon high-pressure tank, 3- nozzle-cathode, 4- quartz glass tube, 5- anode, 6 (TS) - valve with thermocouple, \( M_{H_2O} \) - water steam generator, \( M_{ar} \) - mass argon flow meter

Heterogeneous metal cluster plasmoid (HP) created by combined discharge in swirl flow is shown in figure 2. This plasmoid is revealed to consist of many metal charged micro-droplets and metal nanocluster particles (cathode electrode erosion). The typical size of these micro-droplets is about 10-100 \( \mu\text{m} \). The typical size of metal nano-particles is about 10-100 nm. It is obtained that these nano-clusters absorb hydrogen atoms and ions very effectively.

**Figure 1b.** Heterogeneous plasma created by pulsed repetitive combined discharge in swirl flow. Gas mixture Ar : H\(_2\)O = 10:1. Axial velocity \( V_x \) is closed tangential velocity \( V_t \) : \( V_x \approx V_t \approx 30\text{m/s} \), \( P_s \approx 1.5 \text{ Bar} \), 1-swirl generator, 2- water steam injector, 3- erosive metal clusters, 4- cathode.

Analysis of the optical spectra proves this conclusion. Measured gas temperature of this heterogeneous plasmoid is about \( T_g = 2000\text{-}5000\text{K} \). It is important to note that high value of COP=2÷10 was obtained in this PVR namely. The value COP = 0.5+0.7< 1 was obtained in a straight gas flow (non-swirl flow). So, swirl flow plays an important role in obtaining high COP in PVR.

**Measurement of power budget in the PVR.** Calorimetric method is used to measure power budget in the PVR. The measured parameters are as follows: thermal power \( N_t \) of gas flow behind PVR’s nozzle, electric power input in plasma \( N_e \), and mechanical power of swirl flow \( N_c \). It is well-known that there are many technical difficulties of power budget measurement in non-homogeneous
swirl flows. They result from reverse swirl flow creation in PVR. So, it is important to measure the output gas flow parameters by several independent diagnostic methods.

It is important to measure power losses in this reactor (calibration regime) at the first step of any calorimetric experiment. Traditional electric heater with the same geometry and the same power as plasma formation ones is used in this experiment. The typical temperature of this electric heater is about 900°C. It is close to gas temperature in argon flow at plasma on. An overall view of the experimental setup with this electric heater is shown in figure 2. The heater is arranged between two electrodes. The measured electric parameters in this experiment were: - electric current $I$, electric voltage $U$ and average electric power $N_e$ of the heater. The measured gas flow parameters were: - flow mass rate $M_g$ and average output gas flow temperature $T_g$.

![Figure 2. An overall view of the experimental setup with this electric heater.](image)

The calorimetric results obtained in calibration regime are shown in table 1. One can see that there are large power losses in this vortex reactor of about 20-60% of electric heater power. This heat loss results from reverse flow creation in this reactor at power on and heat transfer from hot reverse gas flow to cold metal walls of this PVR.

**Table 1. Calibration regime with electric heater**

| $M_g$, G/s | $\delta P_{st}$, Bar | $T_{g1}$, °C | $I$, Amp | $U$, V | $N_e$, W | $N_T$, W | $K_{0b}$% |
|------------|----------------------|-------------|----------|-------|----------|----------|-----------|
| 10.5       | 0.2                  | 92          | 4        | 119   | 475      | 182      | 40        |
| 15.5       | 0.4                  | 104         | 4        | 117   | 467      | 373      | 80        |

where $T_{g3}$ is the final airflow temperature behind the nozzle, $\delta P_{st}$ is the excess static pressure in the vortex reactor, $N_e$ is the electric power input to plasma, $N_T$ is the heat power of hot gas flow behind nozzle, and $K_{0b}=N_T/N_e$.

**Power budget in the PVR.** The typical experimental results on heat power output in the PVR at plasma on obtained by calorimetric method are shown in table 2. One can see that power output release exceeds unity: $COP=1.3÷1.8$ (taking into account heat losses in this reactor). It is revealed that there is the value of $COP=0.8÷0.9<1$ in non-swirl airflow at the same experimental conditions. Note that maximal value of COP measured in our calorimetric experiments with PVR was about 10-12.

**Table 2. Heat power of output swirl flow measured by calorimetric method**

| $M_g$, G/s | $T_{g1}$, °C | $T_{g3}$, °C | $\delta P_{st}$, Bar | $N_e$, kW | $N_T$, kW | COP     |
|------------|-------------|-------------|----------------------|----------|----------|---------|
| 12.5       | 21          | 80          | 0.4                  | 2.63     | 2.97     | 1.33    |
| 20.4       | 21          | 95          | 0.6                  | 3.17     | 4.13     | 1.54    |
| 11.4       | 18          | 100         | 0.4                  | 1.56     | 2.87     | 1.84    |

where $M_g$, G/s is the mass gas flow rate, $T_{g1}$ is the initial airflow temperature, $T_{g2}$ is the final output gas flow temperature behind the nozzle, $\delta P_{st}$ is the excess static pressure in vortex reactor, $N_e$ is the
electric power input to plasma, Nr is the total heat power of hot gas flow behind the nozzle, and COP = Nr/Nc.

3. Analysis of the optical spectra obtained in vortex heterogeneous plasmoid

It has been revealed that there is chemical element transmutation in cluster plasmoid. This transmutation may be connected with LENR or chemical reaction with excited internal electrons in the PVR [10-14]. Optical spectra, ion mass spectra, and soft X-spectra prove this conclusion.

The typical optical spectra form heterogeneous plasmoid obtained in the experimental setup are shown in figure 2. The tested gas mixture used in this experiment was helium+ water steam. This gas mixture is very interesting in terms of obtaining lithium Li and zinc Zn in the PVR. In fact the following transmutation (synthesis) reactions are possible according to [13,14]:

\[
Ni^{28}_{60,64}+He^{2}_4 = Zn^{30}_{64,68}, He^{2}_{3,4}+H^{1}_{1,2} = Li^{3}_{6,7}
\]

So, registration and study of the optical lines of Li and Zn are very important in our experiment. The typical optical spectra obtained in the setup with PVR are shown in figures 3, 4. One can see that there are the optical lines of Zn, Ni, Ca, Ca II, Mg, He, Na, H, O, K and molecular band OH in the spectrum in figure 3. Note that the optical lines of Zn in heterogeneous plasmoid can be explained by equations (1). This chemical element (Zn) is absent in initial Ni electrodes (99.99%) and reactor’s wall material (quartz). Note that this element (Zn) is not detected/recorded in heterogeneous plasma in the gas mixture flow: argon+ water steam. Remind that it is intensive optical lines of cuprum ions Cu II that were registered in gas mixture: argon+ water steam (but not zincous lines), [10]. This element (cuprum) is the final chemical element in the following synthesis reaction [see Rossi A.& Co]:

\[
Ni^{28}_{64}+H^{+}_{1} = Cu^{29}_{65}
\]

So, possible transmutation (first reaction (1)) is realized in this experiment and it explains the appearance of zincous optical lines in the spectrum, figure 3.

Processing of this optical spectrum gives the value of gas temperature \(T_e\) is \(~3000\)K (where \(T_R\) is the rotation temperature of OH-radical) and the value of electron temperature \(T_e\) is \(~7000-11000\)K. So, there is non-equilibrium plasmoid created in the setup with PVR. Typical optical spectra obtained in the heterogeneous plasmoid (helium-water steam mixture flow) at high concentration of \(H_2O\) molecules (up to 50%) are shown in figure 4. One can see that there are optical lines of \(Mg I, Na I, H I, Li I, K I\) and continuous spectrum connected with the large number of metal nano-clusters created by cathode’s erosion in these figures. It is interesting to note that the optical Li I line appears in this spectrum. Note that the optical line Li I is recorded in rich helium-water steam mixture flow only. This line is absent in argon-water steam mixture flow. So, second reaction (2) is realized in this experiment and it explains the appearance of zincous optical lines in the spectrum, figure 3. Processing of this optical spectrum gives the value of black-body temperature \(T_e\) is \(~5000\)K and the value of electron temperature \(T_e\) is \(~7000\)K. So, there is a non-equilibrium plasmoid also created in this experiment.

4. Analysis of soft X-ray spectra obtained in vortex heterogeneous plasmoid

It was mentioned in our previous work [10] that an extra heat release in the PVR can be connected with LENR (low energy nuclear reactions) in the heterogeneous cluster plasmoid. In order to study this question in detail it is necessary to measure the X-radiation from this plasmoid [10,13,14].

The calculated wave range of this X-radiation is within 100÷10000 eV. A spectrometer X-123 is used to measure the X-radiation from the heterogeneous plasmoid in the swirl flow. The typical X-spectra are shown in the figure 5. It was revealed that the intensive X-radiation (figure 5) is created namely by the heterogeneous plasmoid. This radiation is absent in the diffuse plasma. Remember that the heterogeneous plasmoid is created by the combined discharge in the following gas mixture: Ar : water steam ~ 1 : 1. Dissociated hydrogen atoms are created by the cathode plasma in this regime (2, figure 1). Recorded optical spectra proved this conclusion. There are some maxima in the recorded X-spectra. The first main maximum is located near \(\lambda_1 = 1.3\) keV. The second maximum is located at \(\lambda_2 = 4.6\) keV. The X-spectra are also recorded behind the reactor nozzle. Note that an electric discharge is absent in this region but there the excited hydride metal clusters are drifted away by swirl flow. So, these excited and charged cluster particles are responsible for X-radiation generation. An intensity of X-radiation is controlled by the polarity of the erosive (or evaporated) electrode. The maximal
intensity of X-radiation is measured near the cathode electrode. A positive hydrogen ion flux (protons) bombarded its surface in this regime.

**Figure 3.** The typical optical spectrum of heterogeneous plasma in the test gas mixture flow: helium+water vapour, (small concentration of water steam, about 1%).

![Graph of optical spectrum](image)

**Figure 4.** Typical spectrum obtained in heterogeneous helium-water steam plasma. Concentrations He : H₂O= 1:1.

The maximal extra energy release (maximal COP) is measured in the PVR at the maximal X-radiation intensity. The X-radiation is absent in the swirl plasmoid without the water steam injection at the same electric discharge and the argon flow parameters.

Summarizing all obtained experimental results one may suppose that the soft X-radiation results from metal hydride cluster creation near the erosive electrode. So, the theoretical model considered in the work [13,14] may be used to clarify the physical mechanism of extra energy release in our
experiment. According to this model bi-nuclear atoms may be created by proton-heavy metal atom interaction with high extra energy release (several 100 eV/ atom).

**Conclusion**

Parameters of heterogeneous non-equilibrium plasma were measured in the experimental set up with PVR. An electronic temperature estimated by processing the optical spectra is about $T_e \approx 7000-10000$ K. Plank’s temperature estimated by the continuous cluster spectrum is about $T_B \approx 2000-5000$ K. So, it has been revealed that there is non-equilibrium heterogeneous plasma in the swirl flow: $T_e \gg T_B$.

Supposedly, plasma-chemical kinetics in cluster plasmoid may be connected with extra energy release in the PVR [10, 13, 14]. It has been found that the heterogeneous non-equilibrium $H_2O$-Ar plasmoid creates soft X- radiation with quantum energy $E \approx 1-10$ keV. High threshold chemical reactions with internal excited electrons in metal clusters are found to play an important role in extra energy release in the PVR or LENR.

![Figure 5. X-radiation from heterogeneous plasma in PVR. Combined discharge (DC+HF); mean power – 500W; hot electrode-cathode.](image)

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