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Thermal Energy Release and Hydrogen Production in Swirl Heterogeneous Plasma-Chemical Reactor

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Abstract. Basic researches in field of plasma –assisted combustion and aluminum-hydrogen energetics have been carried out in JIHT RAS during last 10 years. Aluminium -hydrogen plasma vortex reactor (PVR) was designed, manufactured and tested in this Institute. We use this PVR with gas testing mixture argon- water steam to obtain of pure hydrogen and heat power. Plasma-assisted hydration reaction of different metals with water steam was realized in this reactor.

1. Experimental setup

The experimental set up PVR was considered in our previous works in detail [2-7]. Electric pulsed repetitive discharge is used in this reactor. The scheme of the experimental setup PVR is shown in the figure 1. Heterogeneous plasmoid (HP) is created near cathode in the setup PVR. Mean electric power used for HP's creation in this PVR is about of 1÷2 kW. Mean DC current is about of 1÷2 Amp. The tested gas mixture argon + water steam is used in this reactor. Argon mass flow rate equals to $M_{Ar} \sim 1 - 4$ G/s. Water steam mass flow rate equals to $M \sim 1 \div 3$ g/s. It was revealed that this HP consists of many tiny erosive charged metal nano-clusters (cathode erosive material) and hydrogen ions [2-7].

Hydrogen mass flow rate and its power budget of one hydrogen molecule production are measured in this work. Standard hydrogen analyser ABII-01 is used for hydrogen mass flow rate measurement, figure 4.

2. Thermal Energy Release in Vortex Heterogeneous Plasmoid

Physical properties, dynamics and structure of a heterogeneous plasmoid (HP) in swirl gas flow have been carried out in our previous works [2-7]. It was revealed that there is considerable energy release in this HP with hydrogen atoms and erosive metal nano-clusters. It is very important to note that there is high specific energy $q \sim 1$ KeV/atom in this HP, [4,6]. It was revealed that this energy release is connected with creation of intensive soft X-ray radiation in the HP. The typical quantum energy of this X-radiation is about of 1-10 KeV [4]. HP's parameters and its characteristics were measured by optical spectroscopy, X-ray spectroscopy, ESP method, IMS method and chemical analysis. Electric discharge parameters (current, voltage, power) were measured by Tektronix voltage probe and Tektronix current probe [2-7].

The present work is continuation of the previous ones [2-7]. The accurate measurements of a power balance in the PVR and a hydrogen concentration were realized in this work. We used two well-known calorimetric methods in our experiments, namely: (1) - thermocouple method and (2) - water pool calorimeter method with hot gas bubble barbotage, figure 3. Dry gas mixture (argon+ hydrogen) and



humid gas mixture (argon + water steam) were used in these experiments. Heat losses in this PVR were measured in the calibration experiment before each calorimetric one. Electric heater (or electric discharge) in a noble gas (argon) was used in these calibration experiments (see below). The typical argon flow rate was 1-3 g/s. The typical water steam flow rate was 1-3 g/s. The typical hydrogen flow rate was 1 mg/s.

Gas flow enthalpy (thermal energy) was measured before PVR's input and behind its nozzle in the first method (see below). Power efficiency K of the PVR was estimated by the ratio of energy release/ input electric power. Thermal energy losses in the PVR are taking account in this ratio also. Estimated accuracy of the thermocouple method was 10-15%

Thermal energy of the water in a pool calorimeter was measured in the second method (see below). Power efficiency K of the PVR was estimated by the ratio of water thermal energy/ input electric power. Thermal energy losses in the PVR are taking account in this value also. Estimated accuracy of this method was about of 30%.

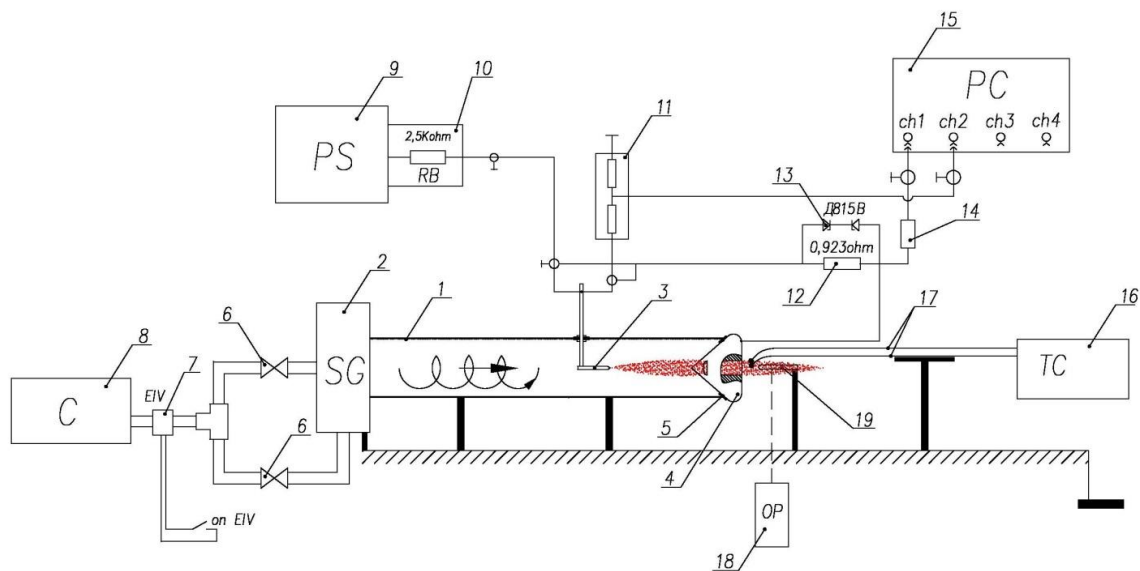


Figure 1 The experimental set up PVR. 1 – quartz tube 60 mm; 2 – swirl generator (SG); 3 – anode; 4 – cathode and nozzle; 5 – rubber; 6 – mechanical valves; 7 – electromagnetic valve (EIV); 8 – gas mixer + steam generator + argon tank, (C); 9 – power supply; 10 – resistor 2,5 K; 11 – resistor divider 1:1000; 12 – current probe; 13 – diodes (Д815В); 14 – resistor 0,923ohm; 15 – oscilloscope TDS 2014B; 16,17 – thermocouples (CENTER 304); 18 – IR pyrometer (MS6560A), 19 – thermocouple holder

2.1. Thermocouple method. Experimental conditions.

The following parameters of an initial tested gas are measured before PVR's mixer, (figure 1 (2)) in this experiment: argon mass flow- G_1 (g/s) and its initial temperature T_1 (°C), water steam mass flow- G_2 (g/s) and its initial temperature T_2 (°C).

The following parameters of tested gas mixture are measured before discharge zone (duct cross section after mixer (2) in this experiment: - gas mixture temperature T_3 (°C).

Input mean electric power N_e (W) and integral electric energy input Q_e (J) to plasma in the PVR are measured in this experiment also.

Mean temperature of output gas mixture $T_6 = (T_{61} + T_{62})/2$ (where T_{61} - axial gas temperature and T_{62} - nozzle wall gas temperature) is measured by two thermocouples.

M_{k1}, M_{k2} - cathode mass before experiment and after it are measured by balance. We used the published values: - Q_c - specific chemical oxidation energy of cathode material and C_{p1}, C_{p2} - specific heat capacities of argon and water steam in our simulations.

2.2. The typical experimental results on power measurements obtained in the PVR.

Calibration regime. Pure argon is used in the PVR only. Thermal power in the PVR are estimated by the following formula:

$$Q_{1T} = C_{p1} G_1 (T_6 - T_1) . \quad (1)$$

Calorimetric working regime. Gas mixture water steam + argon are used in this experiment. Thermal power in the PVR are estimated by the following formula:

$$Q_{2T} = (C_{p1} G_1 (T_6 - T_1) + C_{p2} G_2 (T_6 - T_2)) .$$

The typical experimental results are shown in the table 1.

Table 1

$M_{Ar}, \text{g/s}$	$M_{H_2O}, \text{g/s}$	$T_1, ^\circ\text{C}$	$T_6, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	N_e, W	Q_T, W
<i>Pure argon. Calibration regime.</i>						
1.80	0.0	25.5	202.4		248	159.2
<i>Water steam+ argon. Calorimetric working regime.</i>						
1.80	1.43	25.5	377.3	85.3	624	1098

where initial water steam temperature $T_2 = 102 ^\circ\text{C}$, measured cathode material erosion rate less than 1 mg/s

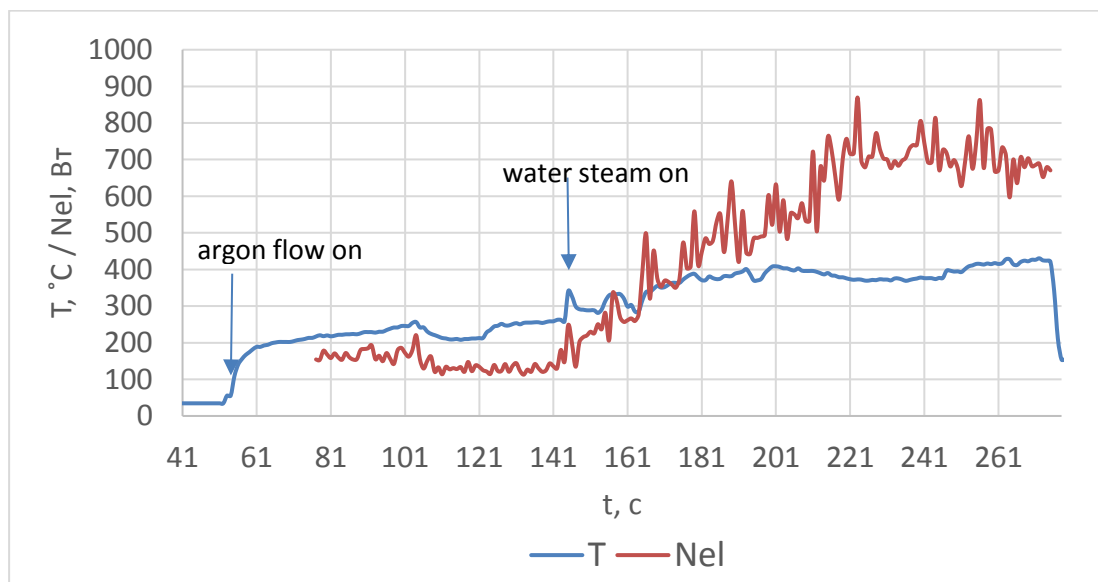


Figure 2 The typical signals of the time evolutions of the output axial gas mixture temperature T_{61} and electric power N_e input in plasma

The closed experimental results were obtained in second water pool calorimeter method, see figure 3. The value of thermal power was measured by following formula:

$$Q_{2T} = C_{pH_2O} M_{H_2O} (T_2 - T_0) / \tau = 1000 - 1200 \text{ W} \quad (3),$$

where M_{H_2O} – water mass in the calorimeter, $Q_{H_2O} = C_{pH_2O} M_{H_2O} (T_2 - T_0)$, T_0 - initial water temperature, final water temperature - T_2 , τ - experimental time.

$$Q_{1T} = C_{pH_2O} M_{H_2O} (T_{2L} - T_0) / \tau = 300 - 340 \text{ W}, \quad (4),$$

where calibration coefficient K_L obtained in the calorimeter with pure argon flow (without water steam). These results were obtained at value $N_e \sim 200-500 \text{ W}$.

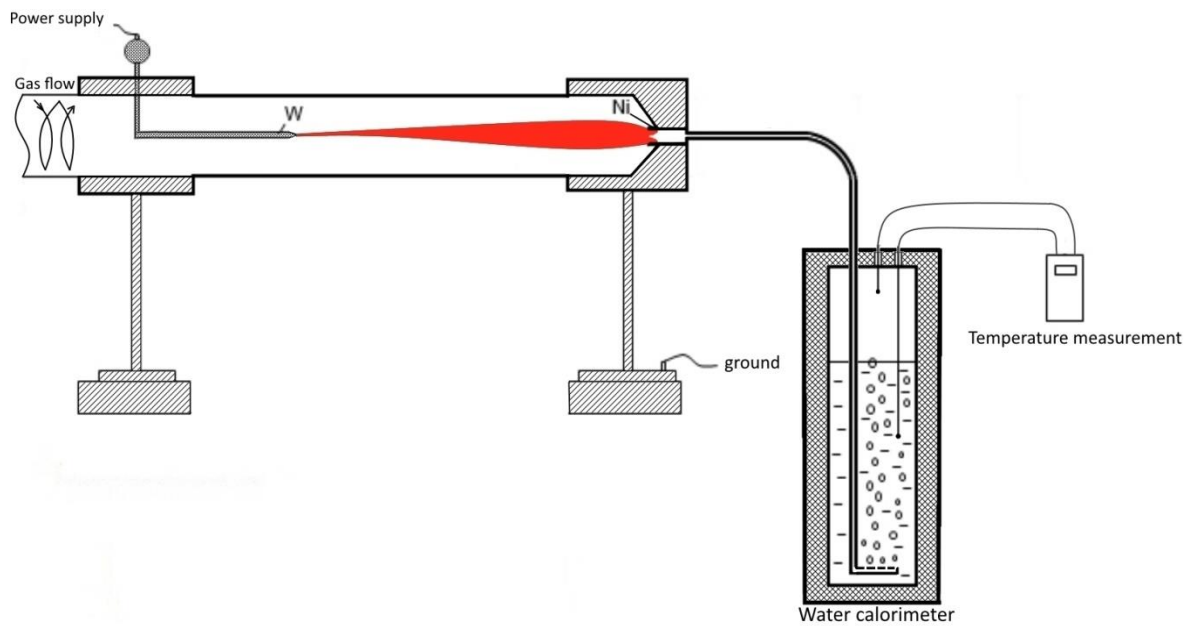


Figure 3 Scheme of the PVR with water calorimeter. W-tungsten anode, Ni- Nikole cathode, 1-PVR, 2-water bath, 3- thermocouple with recorder CENTER 306

Parametric study of PVR's design and its operation modes at different electrode configuration and electrode materials were obtained in this work also. It was revealed that the optimal electrode configuration is realized at its location near PVR's nozzle. Numerical simulation results obtained in Samara State University prove this conclusion [7].

It was revealed in these experiments also:

- Considerable gas temperature decrease in a recombination heterogeneous plasma jet behind nozzle. The typical decrement value is about of 200°C/m ;

- Plasma jet gas temperature is increased at initial static pressure increase in PVR's testing chamber.

These two important results may be explained by relaxation and phase processes in the recombined heterogeneous plasma probably. This question will be studied in our future experiments in detail.

3. Measurement of hydrogen gas concentration

The scheme of hydrogen concentration measurement is shown in the figure 4. Tested gas goes from the PVR's nozzle to water bath (4) with storage tank (5). Residual water steam in this gas flow is cooled and condensed by cold water liquid. Then dry gas is stored in the tank (5). Then this gas goes to gas analyser (9) with the help of a vacuum pump (7). Residual gas flow ($\text{H}_2 + \text{Ar} + \text{O}_2$) behind sensor (7) is burned by an igniter (8). Electric signal from gas analyser's sensor is recorded by PC.

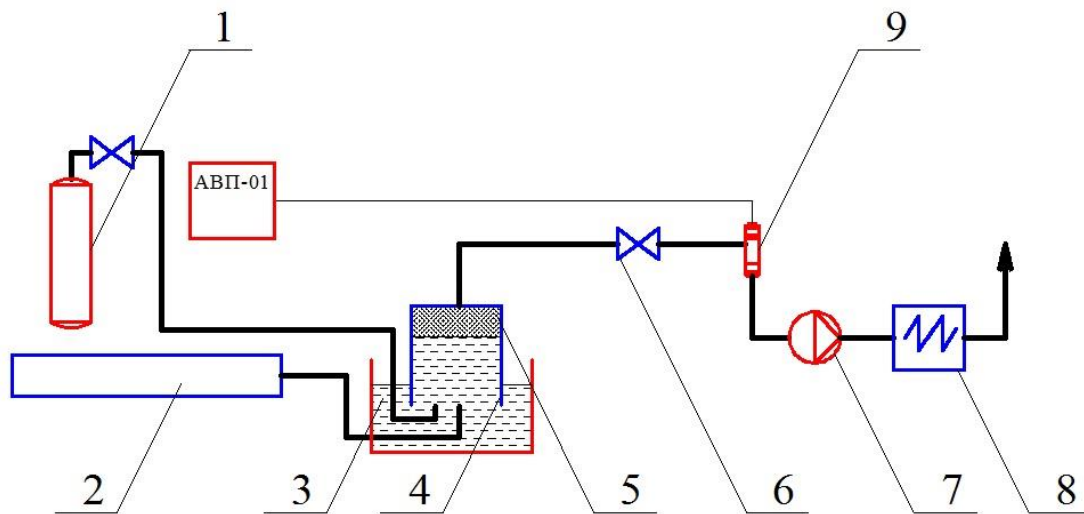


Figure 4 Scheme of hydrogen concentration measurement. 1 – balloon with hydrogen for calibration of gas analyser, 2 – setup PVR, 3 – water bath, 4 – gas tank, 5 – gas mixture, 6 – valve, 7 – vacuum pump, 8- igniter, 9 – gas analyser sensor.

It was measured that the typical hydrogen concentration is about of $\sim 20 \div 30 \%$ in output gas mixture. Note that estimated maximal hydrogen concentration should be $[H_2] \sim 33 \%$ at the total water steam dissociation in hot plasma region. Therefore, definite part of hydrogen (3-13%) is absorbed by metal clusters probably. In a result metal hydride is created in the PVR. It was measured that maximal H_2 mass flow rate creation by the HP in the PVR is about of 10^{-3} g/s at water steam flow rate 1 g/s.

4. Conclusions

1. It is measured considerable thermal energy release in the PVR according formulas (1) and (2), see section 2.2. The closed experimental results were obtained in second water pool calorimeter method by formulas (3) and (4). The typical value of a thermal power release in this reactor is about of ~ 1 kW. It is measured that the typical mass flow rate of an erosive cathode material is about of 1 mg/s. Therefore, specific energy release of “nano-cluster fuel” is about of 1 KeV/metal atom.
2. Hydrogen production is realized in the setup PVR by a heterogeneous plasmoid. The typical value of a hydrogen mass flow rate is about of 1 mg/s at water steam dissociation in the discharge zone.
3. According our opinion high-energy chemical reactions with internal electrons are responsible for obtained extra power release in the setup PVR. Experimental results on analysis of the soft X-ray radiation spectra and the optical spectra recorded in this plasmoid prove this conclusion [4].

Acknowledgments

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