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Modeling discharge length for GA plasma reactor

Streszczenie. *Wyznaczenie długości wyładowania w reaktorze plazmowym pozwala określić warunki przejścia sposobu jonizacji z termicznej na nietermiczną. Korzystne jest uzyskanie nietermicznej nierównowagowej plazmy w największej objętości komory wyładowczej reaktora. Znajomość długości krytycznej, przy której następuje zmiana sposobu jonizacji, pozwala właściwie zaprojektować układ zasilania. (**Modelowanie długości łuku w reaktorze plazmowym ze ślizgającym się wyładowaniem**).*

***Abstract**. Determination of the discharge length allows defining conditions for the thermal/non-thermal transition of the gliding arc (GA) discharge and then to determine power system parameters to ensure the non-thermal phase would dominate in the gliding arc discharge cycle. The discharge length can be easily evaluated at the assumption of sinusoidal discharge current and on the basis of simplified model of the power supply-two-electrode plasma reactor system.*

Słowa kluczowe: reaktor plazmowy, wyładowanie elektryczne, długość łuku, modelowanie.
Keywords: plasma reactor, electrical discharge, discharge length, modeling.

Introduction

For environmental applications, to carry out plasma-chemical processes, so called “cold” plasma in non-equilibrium state, as source of energetic electrons and chemically active species, turned out to be efficient and costly effective. Among the electrical discharges, generating this kind of non-thermal plasma, the GA discharges are well known representatives (1). They are produced directly in the treated gas at atmospheric pressure, at DC and AC power supply conditions, in the multi-electrode systems and can treat large volume of polluted gases, cold or hot, with moisture or dry, without any previous gas preparation. The power supply requirements are also not very sophisticated.

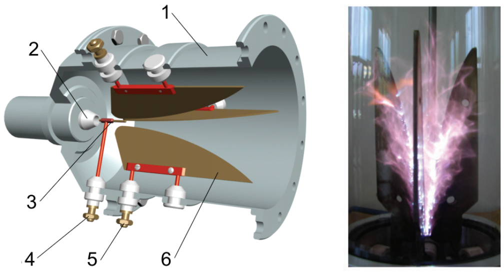

Fig.1. GA plasma reactor: 1 - discharge chamber, 2 - gas channel, 3 - ignition electrode, 4 - power supply of ignition electrode, 5 - power supply of working electrode, 6 - working electrode

The GA appears when plasma is generated between two or more diverging electrodes placed in fast gas flow. Discharges begin at the shortest distance (1-2 mm) between two electrodes. The high voltage generator provides the necessary electric field to break down the air between electrodes. Then arc moves in gas flow. The specific feature of the GA is increasing of plasma column length and transition between two plasma conditions: thermal and non-thermal.

The conventional GA (figure 1) starts in a narrow gap between two or more diverging electrodes in a gas flow, when the electric field in this gap reaches approximately 3 kV/mm in air [2], the arc current increases very fast and the voltage on the arc drops. If the gas flow is strong enough, it forces the discharge to move along the diverging electrodes and to elongate. The growing arc demands more power to sustain itself. At the moment when its resistance becomes equal to the total external resistance, the discharge consumes one-half of the power delivered by the source. This is the maximum power that can be transferred to the arc from the constant-voltage power supply [1].

Phenomena in GA discharge are extremely non-linear, their mathematical modeling is difficult, requires many simplified assumptions and is usually based on the experimentally measured characteristics on the physical model. The electrons’ temperature and its distribution in the discharge chamber is one of the fundamental parameters determining the non-equilibrium conditions of the discharge plasma.

Mathematical model

The discharge length depends on:

- geometry of working electrodes;
- material of electrodes;
- power supply system (current, voltage, power);
- gas velocity and its chemical constitution.

In case of the analyzed plasma reactor, some of above parameters could be constant, like geometry and material of the working electrodes, and others (power supply system parameters, gas velocity and its chemical constitution) can vary. The GA plasma reactor can be supplied by different transformer based power supply systems [2].

As the ignition electrode takes part only in ignition process and does not hold up discharge during operation cycle we can simplify the mathematical model by neglecting the ignition electrode in the reactor geometry.

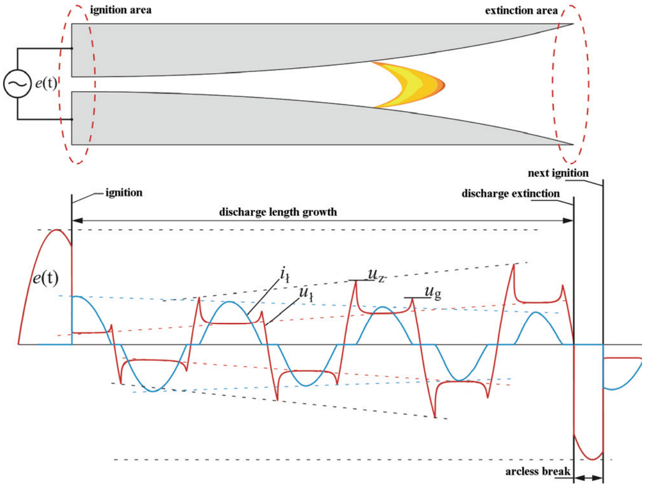

Fig.2. GA plasma reactor operation cycle

The mathematical model is based on the geometry presented on figure 2. The electrode resistance is neglected and energy losses occur only due to ionization and recombination processes in the chamber. A cylindrical chamber is filled with air at the atmospheric pressure and fast gas flow (about 10 m/s).

Electrical conductivity of dynamic arc is variable and can be described as a function of time for a single operating cycle of plasma reactor from Mayr's equation:

$$\frac{dG}{dt}+\frac{1}{\tau_M}G=\frac{1}{\tau_M P_O}i^2(t) \tag{1}$$

where: G – electrical conductivity (S), P_0 – power from the unit length of the discharge column (W/m), i – current (A), t – time (s), τ_M – Mayr const. (s).

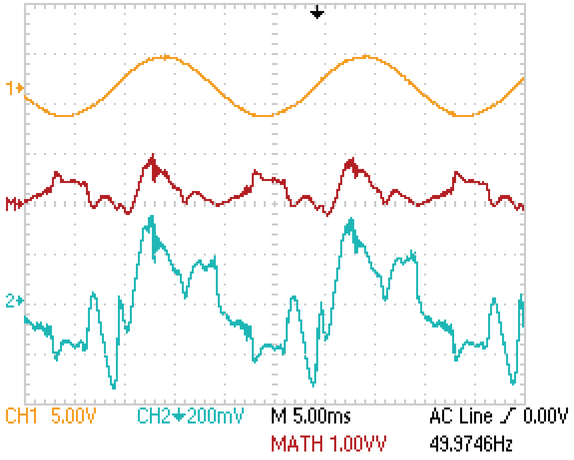

Fig.3. Discharge current (1), voltage (2) and power (M)

Assuming sinusoidal discharge current (figure 3):

$$i(t)=I_m\sin(\omega\cdot t) \tag{2}$$

where: I_m – current amplitude (A), ω –pulsation (1/s).

The electrical conductivity of arc discharge from equation (1) can be expressed by:

$$g(t)=\frac{I_m^2}{2P_O}\left[1-\frac{\cos 2\omega t+2\tau_M\varpi\sin 2\omega t}{1+(2\tau_M\omega)^2}\right] \tag{3}$$

The arc length as a function of time can be expressed by:

$$l(t)=l_0+\alpha\cdot v\cdot t \tag{4}$$

where: l_0 - discharge length (m) at t = 0 (ignition), v - gas velocity (m/s), α - angle between electrodes (rad), t – time (s).

If we take into account the discharge length changes l(t) in the relation (3), we obtain:

$$g(t)=\frac{I_m^2}{2l(t)P_O}\left[1-\frac{\cos 2\omega t+2\tau_M\varpi\sin 2\omega t}{1+(2\tau_M\omega)^2}\right] \tag{5}$$

From relation (5) the gliding arc discharge instantaneous power $p_{arc}(t)$ can be calculate:

$$p_{arc}(t)=\frac{i^2(t)}{g(t)} \tag{6}$$

By comparing the arc power consumption with the power delivered by the power supply system we can obtain the critical arc length.

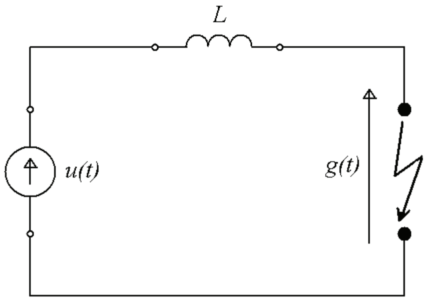

Fig.4. Equivalent circuit with two electrodes reactor

For two-electrode reactor supplied from power system with internal reactance ωL (figure 4), the assumption of sinusoidal discharge current (2) is justified, therefore if we represent the gliding arc discharge by the mean conductance, according to:

$$\tilde{G}_{arc}=\frac{1}{T}\int_0^T g(t)\,\mathrm{d}t=\frac{I_m^2}{2l_{crit}P_O} \tag{7}$$

the critical length of the arc discharge can be estimated by making the comparison of internal susceptance of the supplier and mean conductance of the discharge:

$$\frac{1}{\omega L}=\tilde{G}_{arc}\,, \tag{8}$$

from the relation:

$$l_{crit}=\frac{\omega L I_m^2}{2P_O} \tag{9}$$

In the simplified model of two electrode reactor powered from sine voltage source, presented in figure 4, the transition from equilibrium to non-equilibrium state of the gliding arc discharge can be observed at the critical length described by relation (9).

Simulation results

The start-up values are given below:
- current amplitude 2A,
- power from the unit length of the discharge 2kW/m,
- arc length at ignition area 6 mm,
- gas velocity 10 m/s,
- angle between electrodes π/6,
- internal reactance 500Ω.

Discharge in the GA can be divided into two areas:

- arc length less then critical length – generated plasma is in equilibrium state;
- arc length greater then critical length – generated plasma is in non-equilibrium state.

In practical application the time after discharge reaches its critical length (critical time) is more useful. We simulate the critical time depends on internal reactance (figure 5), maximum current value (figure 6), power from the unit length of the discharge (figure 7) and gas velocity (figure 8).

To obtain non-equilibrium plasma as fast as possible we need to decrease the critical time. We can do that by developing the power supply systems with low value of internal reactance (figure 5). However, decreasing the value of internal reactance leads to currentless breaks and discharge instability. In conclusion, the stable operation of GA plasma rector depends on power supply system configuration [3].

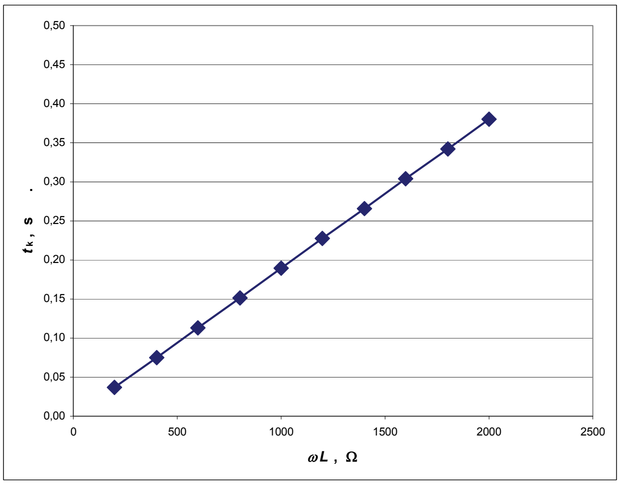

Fig.5. Critical time as a function of the internal reactance

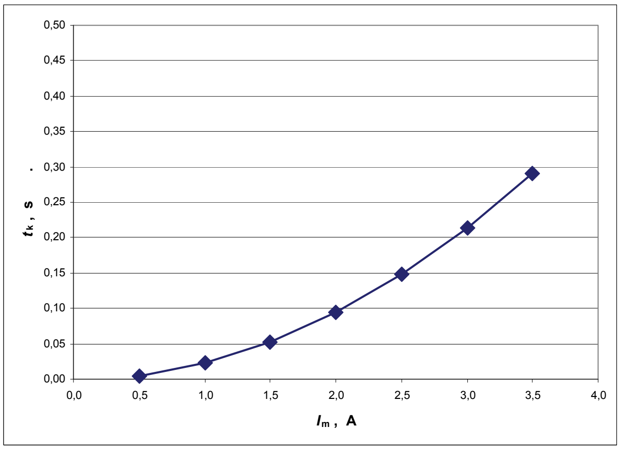

Fig.6. Critical time as a function of the current value

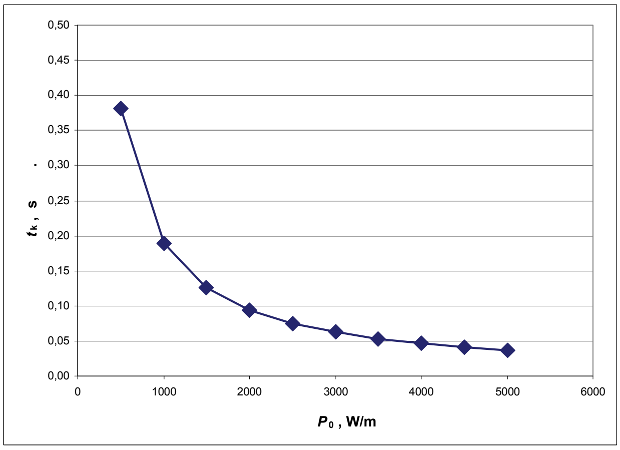

Fig.7. Critical time as a function of the power from the unit length of the discharge

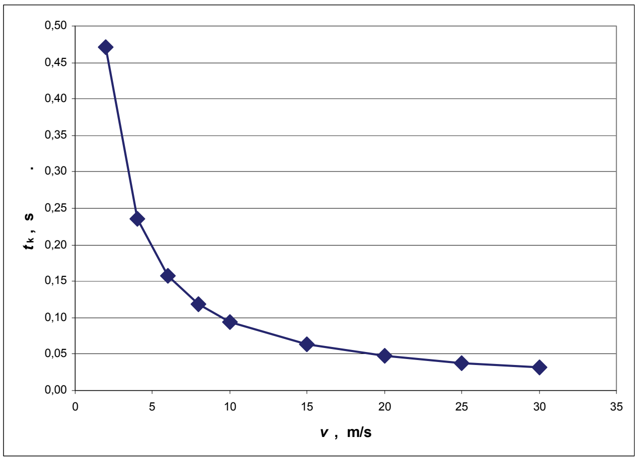

Fig.8. Critical time as a function of the gas velocity

Increasing the current value causes increasing the critical time (figure 6). The GA plasma reactor requests high voltage for discharge ignition and low current value to obtain non-equilibrium plasma. Increasing the current value also increases the power transferred to GA, but on the other hand, it heats the processing gas. Therefore, generated plasma is near to the equilibrium state. Properly selected current value and gas velocity depend on chosen application [1, 4].

Conclusion

The non-equilibrium GA is a very sophisticated physical phenomenon. The simplified mathematical model presented in the paper can be applied to estimate the discharge length that would be useful to determine conditions for which the transition from equilibrium to non-equilibrium state in the GA plasma reactor is observed.

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