Plasma generation in the arc discharge with a thermionic cathode in current stabilization conditions

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Abstract. The paper investigates plasma generation in a PINK plasma generator with thermionic and hollow cathodes under stabilized discharge current. The possibility of not completely closing of the thermionic electrons current into an external circuit is shown under these conditions. The current of emitted from the thermionic cathode electrons mostly closes inside the device, thus increasing the thermal and current load on the electrodes under such conditions. At this, the current direction in the hollow cathode circuit may change, which has no effect on external circuits. It is further shown that the redistribution of currents in the electrode circuits depends on the discharge conditions (including thermionic cathode heating current and voltage, as well as operating pressure and type of working gas), which, in turn, have influence on the instantaneous potentials of the cathode electrodes. Studies of the main plasma characteristics in different phases of the thermionic cathode heating current and under different plasma generation conditions have shown that changing the current direction in the hollow cathode circuit has in significant influence on the instantaneous values of the main plasma parameters, however, plasma generation is not optimal under these conditions.

1. Introduction
Plasma generators based on a non-self-sustained discharge with a thermionic cathode have been long and successfully used in science and industry [1, 2]. Extensive use of this type of discharge is ensured by its operation at different discharge currents varying from fractions to hundreds of amperes, which provides for a wide adjustment range of plasma density. The presence of a thermionic cathode allows increasing plasma concentration at relatively low discharge voltages in the absence of the microdroplet phase. It also becomes possible to control the discharge current independently of its voltage and the pressure in the working chamber. The operating pressure of such systems ranges from 0.01 Pa to 5 Pa and allows to realize efficient ion cleaning and ion-plasma nitriding, as well as ion-plasma assistance during vacuum arc or magnetron deposition of coatings. Due to separate discharge generation areas in such systems, it is possible to independently adjust current densities of gas and metal ions and, therefore, independently control both the intensity of ion bombardment and the stoichiometric composition of the obtained coating. At the same time, the kinetics of the film growth changes under the influence of a large number of gas ions during coating deposition. All this factors together under lays a potentially wide spread use of the thermionic cathode discharge in dense low-temperature plasma generators. The Institute of High Current Electronics SB RAS designed a PINK plasma generator that based on combination of thermionic and hollow cathodes [3, 4]. The PINK generator demonstrates high efficiency in generating bulk gas plasma in various technological applications. At
present, the efficiency of using plasma sources depends not only on the parameters of the produced plasma and the overall quality of their structures, but also on the utilized power supply systems and modes.

The paper investigates plasma generation in the PINK generator equipped with a power source used to stabilize a discharge current.

2. Experimental

The experiments were carried out in a vacuum setup NNV-6.6-I1 that was retrofitted with a coaxial PINK plasma generator mounted on the upper flange of the working chamber of 600×600×600 mm. The chamber was pumped out with a turbo-molecular pump with the pumping capacity of 500 l s⁻¹. (figure 1). A power supply source with a stabilized output current 5–100 A and an operating voltage of up to 75 V equipped with an arc suppression system was used to power the discharge. The inner walls of the vacuum chamber were the anode of a non-self-sustained arc gas discharge with a thermionic cathode. Four W-shaped tungsten filaments ⌀1 mm connected in parallel were used as a thermionic cathode. The thermionic cathode was heated from an AC power source of 50 Hz with an auto-transformer control. The total discharge current (Iₐ), the current in the hollow cathode circuit (Iₐ), the main discharge voltage (Uₐ) and the potential of the free end of the thermionic cathode (Uₜ) were directly measured during the experiments. The current in the thermionic cathode circuit (Iₜ = Iₐ – Iₕ) and the thermionic cathode heating voltage (Uₜ = Uₐ – Uₜ) were calculated from these the above values. The heating current of the tungsten cathode (Iₜ) was directly measured by current clamps S-Line M266 without the main discharge switching on, which excluded the influence of the discharge current (Iₜ) closing through the thermionic cathode circuit in the final measurement. The remaining values were controlled with a Techtronix TDS2024C oscilloscope; Hall sensors HONEYWELL CSNR161 were used to current measurement.

![Figure 1. Experimental scheme.](image)

In addition to oscillography the main discharge parameters have been produced by probe plasma studies. Instantaneous currents and potentials of a single Langmuir cylindrical probe powered from a separate source were fixed using a device of an original design [5]. The walls of the working chamber (anode) were used as a supporting electrode. The probe with dimension of ⌀ 0.4×4 mm was made of tungsten and located at the half-height of the working chamber (150 mm from the external end of the hollow cathode) and was perpendicular to the plasma generator axis. The current-voltage characteristics of the probe were measured in a predetermined phase of the thermionic cathode heating
3. Results and discussions

Previous studies of plasma generation in a PINK generator with a non-stabilized discharge power source showed that main discharge current mostly close on the thermionic cathode when the discharge voltages lower than ≈ 65 V, which causes amodulation of the output current and discharge voltage by the heating voltage of the thermionic cathode [4]. However, under the stabilized discharge current $I_d$, the oscillograms look different. The principle of output current stabilizing is based on the output voltage ($U_d$) amplitude decreasing when the monitored current ($I_d$) exceeds some set value and $U_d$ increasing when $I_d$ getting lower the set value. The discharge current, however, remains almost unchanged over time and the voltages on the electrodes ($U_d$ and $U_t$) change with a period that corresponds to the period of the thermionic cathode heating voltage ($U_w$) (figure 2, all voltages on the oscillograms are inverted). The currents in the electrode circuits ($I_h$ and $I_\gamma$) can also have a complex appearance but most of the discharge current always closes on the thermionic cathode ($I_t > I_h$). It can be seen that when the discharge current stabilizes, the currents in the cathode circuit ($I_h$) can remain unchanged in time (figure 2b), can significantly change over the period of the thermionic cathode heating voltage ($U_w$) while remaining unchanged in the direction (figure 2c, 2d, 2f); otherwise the current in the hollow cathode circuit ($I_h$) changes not only its amplitude, but also the direction while the current in the thermionic cathode circuit ($I_t$) exceeds the discharge current ($I_d$) (figure 2a, 2e).

Changes in the current direction in the hollow cathode circuit can be explained by the fact that the current to the hollow cathode consists not only of ions coming from the plasma (and, accordingly, the $\gamma$-electrons emitted from its surface), which can be designated as $I_{ha}$ (figure 3), but also from a certain reverse electron current ($I_\gamma$) that closes on the hollow cathode when the voltage amplitude $U_h$ exceeds $U_d$. Thus, the current in the thermionic cathode circuit ($I_t$) should also be represented as the sum of the currents closing through the plasma on the hollow cathode ($I_{ha}$) and the anode ($I_\gamma$). The ratios of these currents depend on the discharge conditions such as the type of gas, operating pressure, thermionic cathode heating current and voltage, the amplitude of the stabilized discharge current, etc.

At a sufficiently high thermionic cathode heating current 130 A and, accordingly, heating voltage up to ≈20 V, the discharge voltage drops to values below 15 V (figure 2a), which is close to the argon ionization potential. As a result, when the hollow cathode potential is ≈18 V and a thermionic cathode potential exceeds the hollow cathode potential by ≈5 V, the amplitudes of currents $I_{ha}$ and $I_\gamma$ become equal (i.e. the current in the hollow cathode circuit ($I_h$) becomes 0) and the current in the thermionic cathode circuit ($I_t$) becomes equal to the total discharge current ($I_d$). It should be noted that the conversion of $I_h$ to 0 does not mean the conversion of the current of plasma-emitted ions ($I_{ha}$) to 0 since the plasma in the cathode cavity continues to be generated, which is confirmed by the emission from the thermionic cathode, which is impossible without plasma at the applied voltages (up to 60 V). Under these conditions, the energy of electrons accelerated from the thermionic cathode increases and the potential barrier near the hollow cathode, which rejects electrons, decreases. Under the conditions when the accelerated electrons do not have time to lose their energy on collisions with the operating gas inside the cavity, an increase of the current $I_h$ is observed. A further increase of the voltage $U_\gamma$ leads to a decrease of the hollow cathode potential and an increase of the current $I_\gamma$; therefore, the current direction in the hollow cathode circuit changes.

When the amplitude of the stabilized main discharge current reduces (figure 2e), all the above effects manifest themselves even more clearly to the extent when the hollow cathode potential almost matches the anode potential ($U_d$ ≈ 0). In this case, not only electrons accelerated in the cathode layer near the thermionic cathode, but also plasma electrons produced in the cavity by ionizing the working gas can close on the hollow cathode. The excess of the current $I_h$ over the discharge current $I_d$ indicates a large loss of accelerated thermal electrons on the walls of the hollow cathode and is undesirable. An increase in the electrons free path with the operating pressure decreasing is partially compensated by
an electron energy increasing with the discharge voltage ($U_d$) (figure 2c). As a result, the average plasma concentration inside the hollow cathode remains the same as evidenced by the almost constant current $I_h$ when $U_d$ exceeds $U_t$ (i.e. the current in the hollow cathode circuit is completely determined by $I_h$). An increase of the discharge voltage ($U_d$) reduces the probability of electrons accelerated from the thermionic cathode reaching the hollow cathode (i.e. $I_h$ decreases) when $U_t$ exceeds $U_d$. Reducing the thermionic cathode heating current by reducing its voltage leads to a decrease in the thermal emission current (which largely determines the current $I_t$). This leads to an increase in the discharge voltage $U_d$ when the discharge current is stabilized (figure 2b). It can be seen that the potential of the cathode electrodes does not fall below ≈35 V in this case. This is sufficient to ensure the absence of a significant effect of the hollow and thermionic cathode potentials on the currents in their circuits at the operating pressure of argon of 1 Pa.

**Figure 2.** Oscillograms of currents and voltages in the plasma generator at the discharge currents: $I_d = 75$ A, $p_{Ar} = 1$ Pa, $I_w = 130$ A (a); $I_d = 75$ A, $p_{Ar} = 1$ Pa, $I_w = 110$ A (b); $p_{Ar} = 0.25$ Pa, $I_w = 130$ A (c); $I_d = 75$ A, $p_{Ar} = 0.6$ Pa, $I_w = 120$ A (d); $I_d = 5$ A, $p_{Ar} = 1$ Pa, $I_w = 130$ A (e); $I_d = 75$ A, $p_{N2} = 1$ Pa, $I_w = 130$ A (f).
A simultaneous decrease in the thermionic cathode heating current $I_w$ down to 120 A and the argon pressure down to 0.6 Pa (figure 2d) leads to the situation similar to that when the argon pressure decreases down to 0.25 Pa (figure 2b) with a slight difference in the amplitudes of the cathode voltages.

The use of nitrogen instead of argon results in a significant change in the shape of the cathode voltages (figure 2f). Since the ionization cross section of nitrogen is lower than that of argon, and, on the contrary, the probability of inelastic collisions of electrons with nitrogen molecules is higher, the ion energy rate of nitrogen is higher than that of argon. Ceteris paribus, this leads to an increased voltage of a non-self-sustained arc discharge with a thermionic cathode in the nitrogen atmosphere. The oscillograms of the hollow cathode voltage $U_d$ demonstrate a shelf $\approx 30$ V when the thermionic cathode potential ($U_t$) exceeds the hollow cathode potential ($U_d$) and the current in its circuit ($I_h$) is close to zero. It is known that the potential of an object placed in plasma, when the currents of its ionic and electronic components are equal, is called floating. Thus when the current in the hollow cathode circuit ($I_h$) turns to zero, i.e $I_{tha} = I_{th}$, its potential is a floating potential. It can be seen (figure 2f) that under the given conditions, it remains constant regardless of the current in the thermionic cathode circuit ($I_t$) and its potential ($U_t$), which at this moment is the discharge voltage. The behavior of the cathode potentials under these conditions when the potential of the hollow cathode exceeds the potential of the thermionic cathode is of interest. A decrease in $U_t$ down to $\approx 30$ V leads to a decrease in the efficiency of nitrogen ionization, which in turn requires the discharge power supply to raise the output voltage ($U_d$) in order to stabilize the discharge current, which leads to an increase in both cathode potentials. It should be noted that a similar behavior of the cathode potentials is observed when working with argon at $p_{Ar} = 0.6$ Pa and $I_w = 120$ A (figure 2d); however, it is manifested to a less extent.

Instantaneous plasma parameters (table 1) for all discharge conditions were investigated when the thermionic cathode heating voltage ($U_w$) was equal to zero (sync "0", 0 ms in figure 2), which corresponds to the equality of the potentials of the thermionic and hollow cathodes. For the cases when a significant repolarization of the current $I_h$ was observed, current-voltage characteristics of the probe were additionally fixed when the heating voltage $U_w$ was at its maximum (sync ",-", -5 ms in figure 2) and minimum (sync "+", +5 ms in figure 2) in order to determine the possible changes in plasma parameters over a period of the heating voltage. Plasma concentration was determined by the electron saturation current. It can be seen (table 1) that a significant redistribution of currents in the electrode circuits under a stable discharge current and an argon pressure of 1 Pa does not lead to reliable changes in the plasma parameters. It can only be noted a slight increase in the floating potential at ",-" synchronization. Against the background of a constant temperature in the main group of plasma electrons, this may indicate the appearance or amplification of the second group of electrons in the plasma generated by the device under study due to a high current of accelerated thermionic electrons [6] amplified at the maximum thermionic cathode heating voltage. The decrease in argon...
pressure, as well as the replacement of argon with nitrogen lead to a slight increase in the electron temperature. This can be explained by an increase in the free path of electrons accelerated from the thermionic cathode and an increase in their energy when operating in argon, or an increased ion energy rate when operating in nitrogen. At the same time, the floating potential increases and the plasma concentration slightly decreases, which is due to the necessity to preserve the anode electron current density from the plasma with an increase in the electron temperature. Reducing the thermionic cathode heating current and, therefore, the heating voltage leads to a noticeable increase in plasma concentration without changing the electron temperature and the floating potential. This is primarily due to an increase in the discharge voltage. With a constant discharge current, this leads to an increase in the energy imparted to thermionic electrons in the cathode layer. Constant electron temperature in the plasma indicates that the primary electrons have time to lose their energy when moving to the probe. Accordingly, more energy is spent on inelastic collisions with gas, including ionization. In constant operating pressure, this leads to an increase in plasma concentration. Thus, the optimization of thermionic cathode heating current and voltage leads to an increase in the efficiency of gas plasma generation in the device under study. A decrease in the discharge current leads to a significant decrease in plasma concentration due to a decrease in the number of gas ionization events; the repolarization of the current $I_h$ does not lead to a significant change in the plasma parameters.

**Table 1.** Discharge plasma parameters at different discharge conditions and voltage $U_w$ phases.

| Sync | Plasmapotential $U_p$ (V) | Electron temperature $T_e$ (eV) | Plasma concentration $n$ ($10^{17}$ m$^{-3}$) | Floating potential $U_f$ (V) |
|------|--------------------------|-----------------------------|---------------------------------|------------------------|
| Figure 2a | “–“ 4 | 1.4 | 5 | -7.8 |
| | “0” | 3.7 | 1.3 | 4.8 | -6.6 |
| | “+” | 3.4 | 1.3 | 4.6 | -6.7 |
| Figure 2b | “0” | 3.6 | 1.5 | 5.7 | -6.3 |
| Figure 2c | “0” | 4.3 | 1.8 | 3.9 | -13.8 |
| Figure 2d | “0” | 4 | 1.8 | 5.3 | -8.8 |
| | “–“ | 1.7 | 1.3 | 0.2 | -19.3 |
| Figure 2e | “0” | 1.2 | 1.7 | 0.2 | -18.2 |
| | “-” | 0.5 | 1.2 | 0.2 | -13.7 |
| Figure 2f | “0” | -0.7 | 1.6 | 2.3 | -18 |

**4. Conclusion**

The research has found that the use of the discharge power source that enables current stabilization in a PINK plasma generator can lead to a significant redistribution of currents in the circuits of thermionic and hollow cathodes up to a change in the direction of the latter. Such a redistribution depends on the instantaneous ratio of the potentials of the thermionic and hollow cathodes, as well as on the absolute potential of the hollow cathode (discharge voltage), which affect the efficient reach of the hollow cathode by electrons ejected from the thermionic cathode. It has been further established that there is no significant change in the plasma parameters under changes in the direction of the current in the hollow cathode circuit. However, this operation mode of the plasma generator is not optimal due to both the increased thermal and current loads on the electrodes, which are not reflected in the external circuit, as well as the reduced efficiency of plasma generation.
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