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Влияние щелевого сопла на устойчивость индукционного разряда в канале высокочастотного безэлектродного плазмотрона

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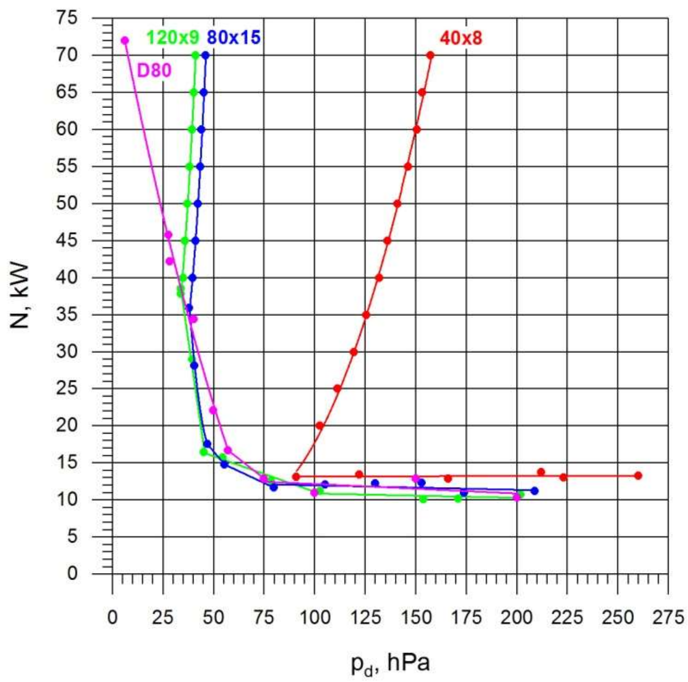
Аннотация

Исследованы области существования разряда в цилиндрическом канале индукционного плазмотрона ВГУ-4 при установке за ним щелевых сопел с размерами выходных сечений 40 × 8, 80 × 15 и 120 × 9 мм. Для каждого сопла измерены давления в разрядном канале в зависимости от мощности анодного питания ВЧ-генератора плазмотрона при сверхзвуковом режиме истечения. В дозвуковых режимах истечения для различных давлений в разрядном канале определены значения мощностей, при которых происходит срыв разряда. Проведено сравнение полученных областей существования с данными для режимов, реализуемых без установки щелевых сопел за разрядным каналом плазмотрона. Щелевые сопла вопреки ожиданию слабо влияют на границу срыва разряда в области высоких (более 100 гПа) давлений в разрядном канале.

Ключевые слова: ВЧ-плазмотрон, щелевое сопло, индукционный разряд.



Область существования разряда. N − мощность ВЧ-генератора плазмотрона по анодному питанию; p_d − давление в разрядном канале

Slit Nozzle and its Effect on the Stability of Induction Discharge in the Channel of a High-Frequency Electrodeless Plasmatron

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Abstract

This paper studies the discharge existence domain in the cylindrical channel of the IPG-4 inductively coupled plasma facility when slit nozzles with outlet sections of 40×8, 80×15 and 120×9 mm are installed behind it. For each nozzle, the relationship of the pressure in the discharge channel vs the power of the anode supply of the HF-generator was measured under the supersonic outflow regime. The power values of the anode supply of the HF-generator at which discharge extinction takes place were determined for various pressures in the discharge channel under subsonic outflow regimes. The obtained discharge existence domain was compared with the data for the regimes with no nozzle behind the discharge channel of the facility. It was shown that slit nozzles (contrary to expectation) have a weak effect on the discharge extinction boundary in the region of high (> 100 hPa) pressures in the discharge channel.

Keywords: HF-plasmatron, slit nozzle, induction discharge.

1. Introduction

Inductively coupled plasma (ICP) facilities are widely used in testing of materials under conditions simulating the motion of a body at high Mach number in the atmosphere. Their advantages are chemical purity of the flow, long operation time, and a good repeatability of test conditions.

Most test configurations are axisymmetric [1−4]. The axisymmetric test configurations are used to simulate a stagnation point heat transfer. However, it is often necessary to explore objects having the shape of plates or tiles [5, 6]. The plate as an object of study is of particular interest in simulating the heat transfer of dissociated gas with the side surface of an aircraft. In this case, slit nozzles can be installed behind the discharge channel of the facility to make the distribution of heat flux on a flat surface more uniform [7, 8]. The influence of these nozzles on the facility operating envelope has to be determined. Experiments were carried out to determine this effect.

2. Experimental facility

The experiments were carried out in the IPG-4 facility (plasmatron). The conceptual sketch of the test chamber of the IPG-4 facility is shown in fig. 1, its main parameters are presented in table 1. A detailed description of the IPG-4 facility is given in [9].

The pressure in the discharge channel and the test chamber were measured using capacitive pressure sensors «Elemer AIR-20M» with an error of 0.1 %. The air flow rate was measured by an orifice plate calibrated using a flowmeter MKS-1559. A high-voltage temperature compensated high-precision voltage divider was used as a voltage sensor. High-precision shunts were used to measure electric currents.

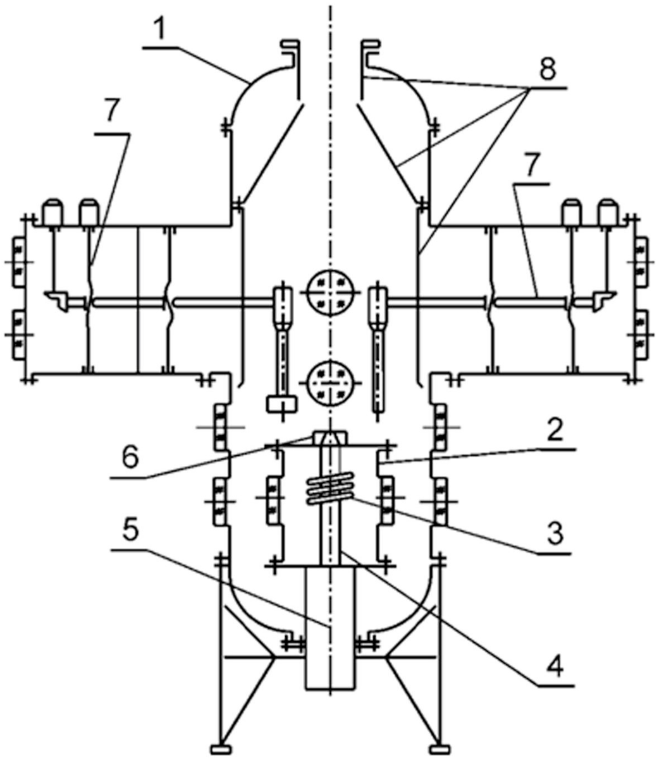

Fig. 1. Conceptual sketch of the test chamber of the IPG-4 facility. 1 – low-pressure test chamber wall, 2 – inductor chamber, 3 – inductor, 4 – discharge channel, 5 – gas flow formation device, 6 – nozzle unit, 7 – positioning devices, 8 – cooled shields

Table 1

Main parameters of the IPG-4 plasmatron

Electric power supplied to plasmatron, kW	100
Generator anode power supply, kW	72
Frequency, MHz	1.76
Discharge channel, mm	80
Stagnation pressure, hPa	6 ÷ 1000
Gas mass flow rate, g/s	2 ÷ 6
Working gases	Air, N_2, O_2, CO_2, Ar and their mixtures; Ar + organic gases

Slit nozzles with outlet sections of 40 × 8, 80 × 15 and 120 × 9 mm can be installed behind the discharge channel during the experiment (fig. 2). Subsonic air plasma jet created by the IPG-4 plasmatron, when the slit nozzle with the outlet section of 80x15 mm was installed, is shown in fig. 3. Discharge in the subsonic air flow, quartz discharge channel and inductor of the IPG-4 plasmatron are shown in fig. 4.

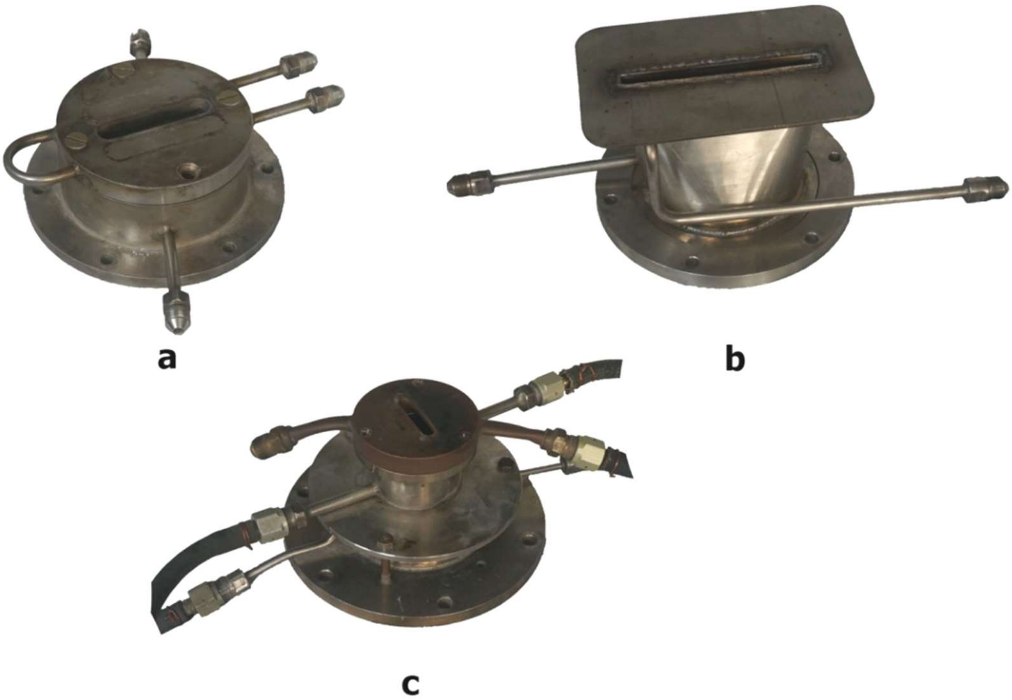

Fig. 2. Water-cooled slit nozzles with different outlet sections: a – 80 × 15 mm, b – 120 × 19 mm, c – 40 × 8 mm

Fig. 3. Subsonic air plasma jet created by the IPG-4 plasmatron, when the slit nozzle with the outlet section of 80 × 15 mm was installed

Fig. 4. Discharge in the subsonic air flow, quartz discharge channel and inductor of the IPG-4 plasmatron

3. Discharge existence domain

One of the most important characteristics of a plasmatron is its operating envelope. This operating envelope for the IPG-4 facility without any nozzles installed behind the discharge channel was taken from [10] (fig. 5).

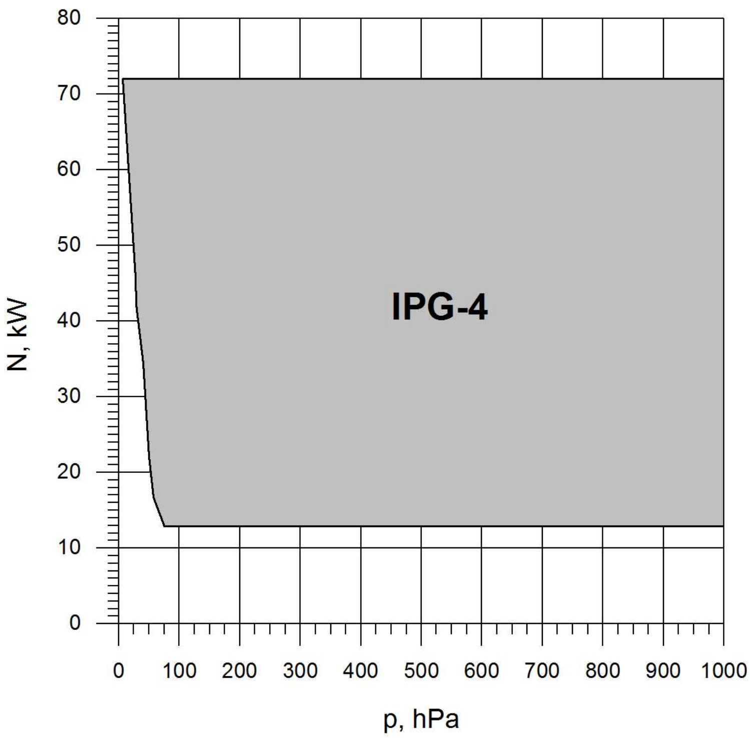

Fig. 5. Operating envelope of the IPG-4 facility

The upper bound of the operating envelope is determined by the capabilities of the HF-generator. The right bound is determined from the design requirements for the facility, which did not involve experiments at pressures above atmospheric pressure. Left and lower bounds mainly depend on the stability of the discharge and partially depend on the-gas flow formation device design.

Testing specimens in the shape of flat plates requires installing slit nozzles behind the discharge channel of the facility. A question arises whether the nozzles affect the operating envelope of the facility.

The installation of the nozzle creates a supersonic outflow regime when the pressure in the test chamber falls below a specific critical value. This moment can be easily detected in the experiment from the data of pressure sensors installed in the discharge channel and in the test chamber (fig. 6). It is known that flow disturbance cannot be transmitted upstream, so after the transition to the supersonic outflow regime, the further pressure change in the test chamber does not affect the pressure in the discharge channel. In this case, the pressure in the discharge channel of constant geometry only depends on the flow rate and the supplied power. It is noteworthy that the pressure in the test chamber can still be maintained within the capabilities of the vacuum pump. However, the left bound of the operating envelope in coordinates «pressure in the discharge channel – anode power of the HF-generator» will transform and move to the right in this case.

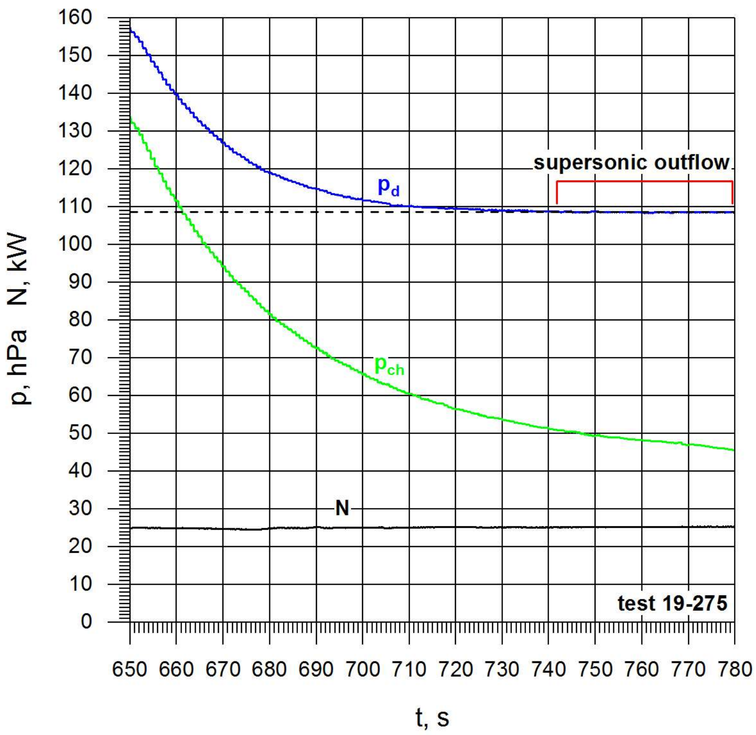

Fig. 6. Transition from the subsonic to the supersonic outflow regime with a 40 × 8 nozzle. p_{ch} – pressure in the test chamber; p_d – pressure in the discharge channel; N – anode power of the HF-generator

The slit nozzle can potentially reduce the stability of the discharge and cause its extinction for some regimes. This is due to the specifics of the flow emerging after the installation of the slit nozzle behind the cylindrical discharge channel. The air at the inlet to the discharge channel is swirled to stabilize the discharge and push the hot part of the flow away from the walls of the uncooled quartz tube. The swirling flow passing through the narrow slit of the nozzle can form vortices in the discharge channel, which can cause the extinction of the discharge. Modeling these processes numerically is difficult. Therefore, the discharge existence domain for each nozzle has to be determined experimentally. A measurement campaign was performed for the IPG-4 plasmatron to identify this domain for each of the three slit nozzles.

All experiments were carried out at a constant air flow rate of 2.4 g/s. Subsonic and supersonic flow regimes have been studied. During the experiment, the facility was set to the specified pressure mode in the discharge channel and the test chamber at the maximum (or close to the maximum) anode power of the HF-generator. After that, the anode power was gradually reduced by the operator until the discharge extinction. An example of the experimental data without post-processing is shown in fig. 7.

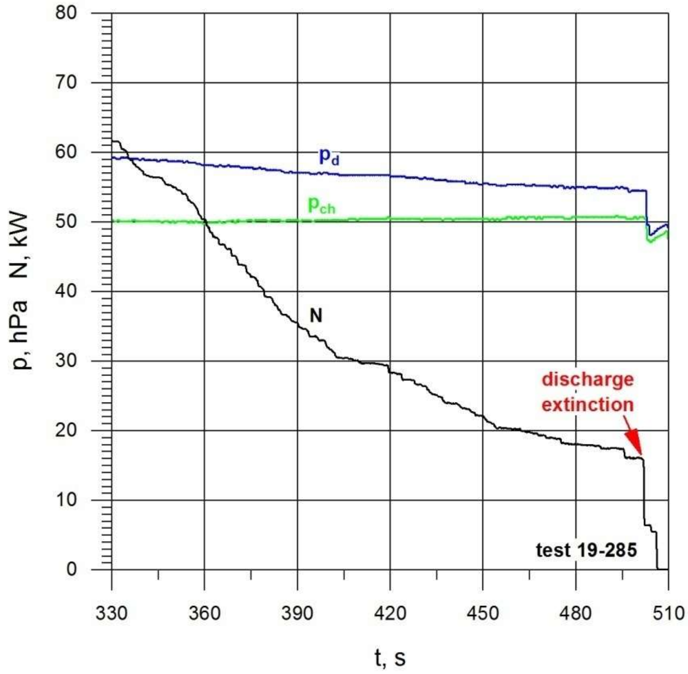

Fig. 7. Data on discharge extinction by reducing anode power of the HF-generator: p_{ch} – pressure in the test chamber; p_d – pressure in the discharge channel; *N* – anode power of the HF-generator

The moment of extinction of the discharge can be identified by a rapid pressure drop in the discharge channel.

The main results of the experiments are shown in fig. 8 in comparison with the data for the regimes realized without installing the nozzle behind the discharge channel of the plasmatron.

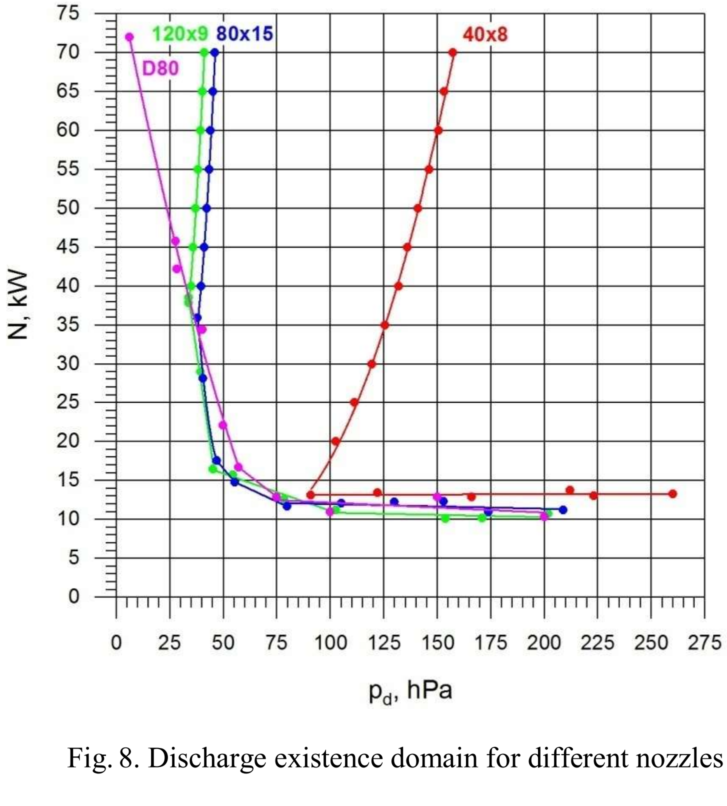

Fig. 8. Discharge existence domain for different nozzles

Contrary to the expectation, the slit nozzles have a weak effect on the lower bound of the operating envelope. At pressures above 100 hPa, the discharge extinction for the considered slit nozzles occurs at an anode power supply from 11 to 13 kW, depending on the selected nozzle. In the case of outflow from a cylindrical discharge channel with a diameter of 80 mm, the discharge extinction at a pressure above 100 hPa occurs at an anode power supply of 11 ÷ 12 kW. Since the discharge is not stable enough in the regimes close to extinction, long tests of materials are performed at powers from 16 kW and above.

The left bound of the operating envelope transformed more significantly because of the supersonic flow regimes that have been mentioned. This is most evident for the nozzle with the outlet section of 40 × 8 mm since the outlet diameter of the equivalent conical nozzle for it is just ~ 20 mm, and the critical value of the ambient pressure is higher. The bounds of operating envelopes of the nozzles with outlet sections of 80 × 15 and 120 × 9 mm are very close to each over. In subsonic flow regimes, they are almost equivalent to the case of an outflow from a channel without a nozzle installed.

4. Conclusion

The installation of slit nozzles behind the discharge channel of the IPG-4 plasmatron has a minimal effect on the discharge existence domain of the facility. In subsonic regimes the discharge extinction for the considered slit nozzles occurs at an anode power supply from 11 to 13 kW, which is almost equivalent to the case of an outflow from the channel with no nozzle installed. Since the discharge is not stable enough in the regimes close to extinction, long tests of materials are performed at powers from 16 kW and above.

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