EXTENDED CAPABILITIES OF THE IPG-4 PLASMATRON IN SUPERSONIC REGIMES FOR RE-ENTRY SIMULATION

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Introduction

The 100-kW IPG-4 plasmatron is generally used for simulation of the thermochemical interaction of air and CO_2 plasma flows with thermal protection materials under the Earth and Martian atmospheres entry conditions. In general, aging and catalytic tests of reusable thermal protection materials (TPM) were carried out in subsonic high-enthalpy flows [1-3]. Application of both supersonic and subsonic regimes of plasmatron operating reveals new capabilities for duplication of gas-surface interaction for hypersonic flight conditions [4, 5].

Systematical comparative study of the IPG-4 plasmatron operating envelopes for supersonic and subsonic regimes in coordinates "pressure in discharge channel - anode power of RF-generator" was carried out in [6] and it turned out an application of a set of the sonic nozzles with different throat diameter together with changing anode power and air mass flow rate in supersonic regime permits to obtain almost all points within the operating envelope for subsonic regime. Presented paper deals with operating envelope of the IPG-4 plasmatron in coordinates "stagnation pressure – stagnation heat flux", and some new results obtained using the IPG-4 plasmatron.

The IPG-4 plasmatron

Two plasmatrons of IPG series are in operation in the Laboratory for Plasma/Surface Interaction (IPM RAS). The IPG-3 and IPG-4 plasmatrons belongs to 1-MW and 100-kW classes respectively. The IPG-3 and the IPG-4 plasmatrons differ in their technical potentiallities so it leads to different applications.

The IPG-3 facility is used to solve problems of practical character, i.e. testing of working capacity of large samples of thermal protection materials and full-scale (150-500 mm) elements of thermal protection system.

The IPG-4 plasmatron was developed for R&D works such as non-equilibrium heat exchange between high-enthalpy dissociated flows and surfaces of metals, quartz, ceramics, carbon-carbon materials with antioxidative coatings. Also thermochemical stability of thermal protection materials have been studied including determination of maximum working temperatures of TPM, studies of surface degradation after aging tests together with changes of surface emissivity and catalycity as the functions of temperature and time.

The IPG-4 plasmatron has been in operating in IPM RAS since 1984 up to now. It corresponds completely to modern requirements in performances and potentialities, and permits to solve wide spectrum of problems in experimental high temperature gas dynamics.

Main operating parameters of the IPG-4 plasmatron in subsonic regime are presented in table 1.

Table 1

Anode power, kW	12-76
Frequency, MHz	1.76
Discharge channel diameter, mm	80
Flow rate of air, g/s	2-6
Pressure, hPa	12-1000
Enthalpy of air plasma flow, MJ/kg	10-40
Working gases	Air, N_2, O_2, CO_2, Ar

Outward appearance of the IPG-4 plasmatrons is presented in fig. 1.

Fig. 1

Operating envelope of the IPG-4 plasmatron in terms “stagnation pressure – stagnation heat flux”

The operating envelopes of the IPG-4 plasmatron in subsonic and supersonic regimes in coordinates "pressure in discharge channel - anode power of RF-generator" were studied in [6] and present work continues this activity by investigation of operating envelope in coordinates “stagnation pressure – stagnation heat flux” that is of interest for experimental modeling of re-entry conditions.

When using high flow rates of air it is possible to obtain very complicated shock-wave pattern. For example supersonic air plasma flow around water-cooled flat-face copper model is presented on fig.2, where throat diameter of sonic nozzle – 30 mm, anode power – 64 kW, flow rate of air – 6 g/s, model diameter – 20 mm, distance between nozzle and model – 25 mm, ground pressures - 12 hPa.

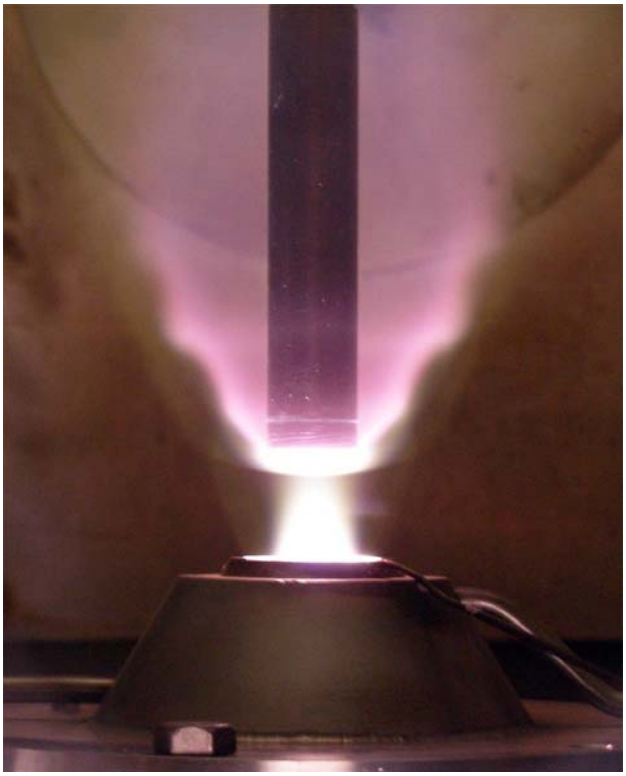

Fig. 2

Operating envelope of RF inductively coupled plasma in discharge channel closed with sonic nozzle was extended using new water-cooled sonic nozzles and high mass flow rate of air via discharge channel.

Data on the stagnation point heat flux along supersonic air plasma flow axis were obtained using a set of the sonic nozzles with different throat diameters. Water-cooled flat-faced cylindrical model of 20 mm diameter equipped with the 11.8 mm diameter water-cooled copper calorimeter were used in our experiments. Similar water-cooled model with 6 mm hole was used as Pitot probe as well. Because two positioning devices are available in the IPG-4 plasmatron, measurements of heat flux and stagnation pressure in each regime specified by governing parameters such as anode power N_{ap} and air flow rate G were made one after another in one experiment. Typical results obtained using one sonic nozzle are presented in fig. 3, 4.

Stagnation point heat flux to 20-mm diameter flat-faced copper model ($T_w \approx 300$ K) along a supersonic flow axis using sonic nozzle of 16-mm throat diameter at different anode powers of RF-generator and flow rates of air is given at fig. 3.

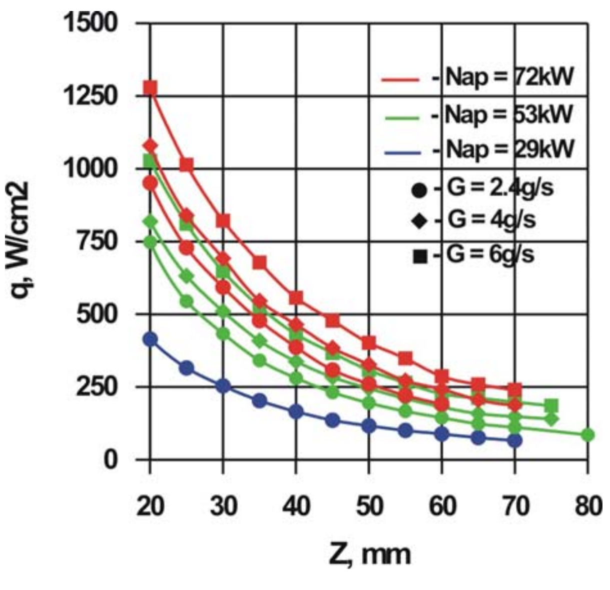

Fig. 3

Stagnation pressure on 20-mm diameter flat-faced copper Pitot ($T_w \approx 300$ K) along a supersonic flow axis using sonic nozzle of 16-mm throat diameter at different anode powers of RF-generator and flow rates of air is given at fig 4.

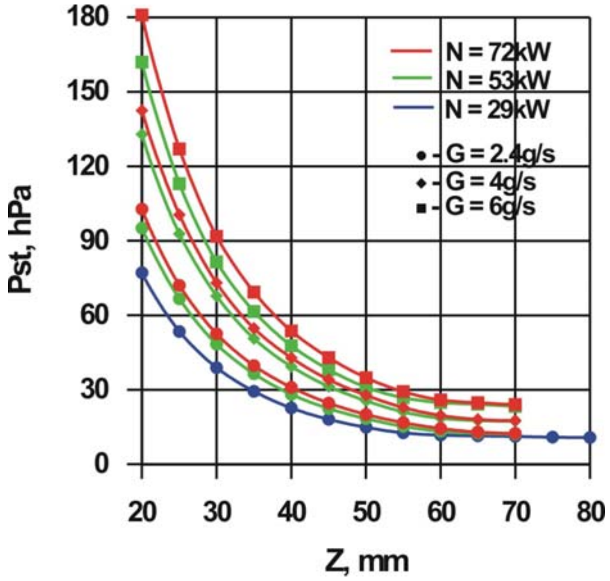

Fig. 4

Data presented in fig. 3, 4 permit to build fig. 5 presenting family of curves "heat flux against stagnation pressure" for 16 mm nozzle

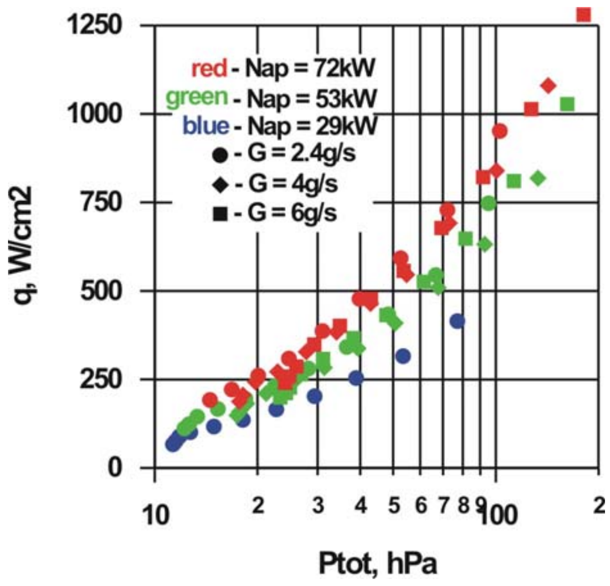

Fig. 5

where points of one curve are obtained by changing of model distance from exit section of nozzle at constant anode power and flow rate of air. Note, that curves obtained at constant anode power and different flow rates of air are nearly coincident, but the higher flow rate of air the higher heat flux and stag-nation pressure as well. Air flow rate increase from 2.4 g/s to 6 g/s gives ~30% increase of heat flux and stagnation pressure as well.

Maximum heat flux 1280 W/cm^2 was achieved using sonic nozzle of 16-mm throat diameter and 20-mm diameter flat-face copper model at anode power 72 kW, flow rate of air 6 g/s and 20-mm distance between nozzle exit section and model. This value was found nearly two times as large as previous maximum value [6].

All data obtained using sonic nozzle with throat diameter D = 16 mm and the others sonic nozzle diameters (D = 20, 24, 30, 40, 50, 60 mm) were used to build operating envelope of the IPG-4 plasmatron in terms "stagnation pressure - stagnation point heat flux" for supersonic regime. Operating envelopes of the IPG-4 plasmatron for supersonic and subsonic regimes using 20-mm diameter flat-faced copper model ($T_w \approx$ 300 K) are presented in fig. 6.

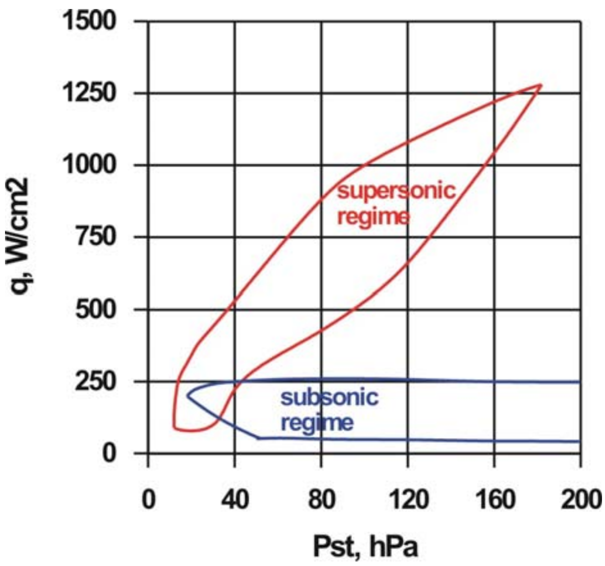

Fig. 6.

Non-stationary regimes of supersonic plasma flow over model

Non-stationary regimes of plasma flow over model and heat exchange were found during heat flux and stagnation pressure measurements in underexpanded supersonic flow of air plasma issuing from 30 mm diameter sonic nozzle of whereas mass flow rate of air 2.4 g/s, anode power 64 kW and pressure in discharge channel were constant.

Mach disk position fluctuates together with flow pattern around 20 mm diameter flat-face cylindrical model at distances Z = 80-95 mm between model and exit section of 30 mm diameter nozzle as it is seen in fig. 7 for Z=85mm.

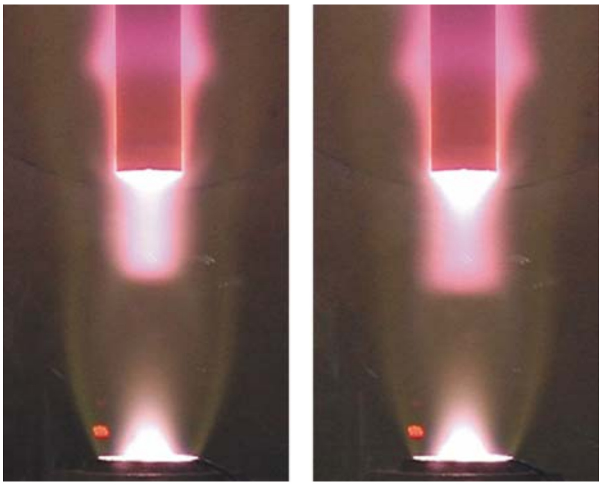

Fig. 7

Time dependency of the distance between model and exit section of 30 mm diameter nozzle is given at fig. 8 (see next page) and one can see that found oscillations are not harmonic with detected frequencies about 10 Hz.

Preliminary study of fluctuation zone ahead flat face of model was carried out using analysis of photos made at expositions which were selected to obtain best view of this zone in details and it allowed to suggest these oscillations are coupled with appearance of flow separation zones ahead of flat-face cylindrical model when model is located behind Mach disk.

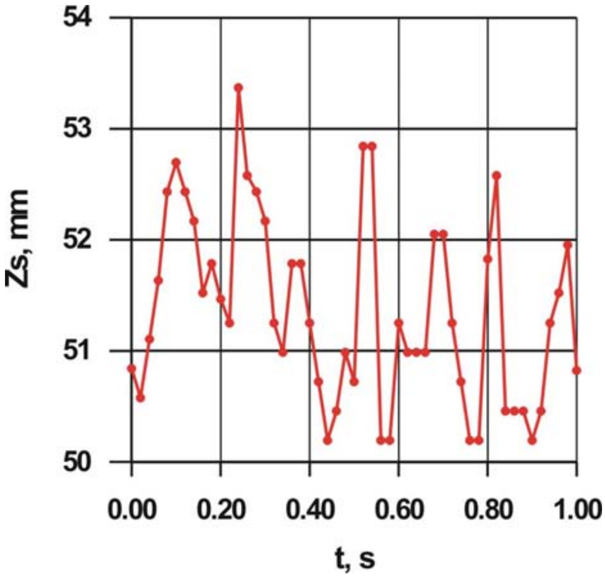

Fig. 8

It is reasonable to continue experimental study of found oscillations and to compare obtained flow patterns and other data with results of CFD modeling similar to that one described in [5].

"Transparent" sonic nozzle and its application for spectral measurements of air plasma in the IPG-4 plasmatron

"Transparent" sonic nozzle has been invented as modeling entity which gives an opportunity to make spectral measurements along the full length of plasma flow accelerated from near equilibrium state and Mach numbers $M \ll 1$ in discharge channel to supersonic velocities and Mach numbers $M = 2$-3 in free supersonic jet and in shock layer on water-cooled model introduced into supersonic jet as well. Experimental verification of "transparent" nozzle availability was made in the IPG-4 plasmatron.

Photography of "transparent" sonic nozzle in operation and schematic diagram of "transparent" sonic nozzle are presented on Fig. 9 a,b respectively. Fig. 9a shows outward appearance of "transparent" sonic nozzle in operation for conditions as follows: orifice diameter - 40 mm, model diameter - 20 mm, distance between exit section of nozzle and model - 30 mm, anode power - 45 kW, air flow rate - 2.4 g/s, pressure in discharge channel - 36 hPa, ground pressure chamber - 8.3 hPa. Fig. 9b presents schematic diagram of "transparent" sonic nozzle.

Spectral data logging was carried out using spectrometric set-up which includes 0.3 m ACTON RESEARCH spectrometer with spectral resolution 0.1nm, PRINCETON INSTRUMENTS CCD-matrix (scientific grade, 16-bit, 1340x1300, spectral range 200-1050 nm, thermoelectric cooling to -40^{o}C) and appropriate software as well.

Intensity field along the full length of accelerated plasma flow including subsonic flow in discharge channel, transonic flow near nozzle exit section, free supersonic jet and shock layer in front of model is presented in fig 10 for flow regime shown in fig. 9a. These data permit to study plasma temperatures and plasma flow radiation along the jet using comparison of "reference" radiation of equilibrium (or close to equilibrium) subsonic flow in discharge channel. In general, radiation intensity of all atomic lines and molecular bands decreases dramatically with distance from the nozzle exit section and increased sharply in shock layer. The most flat dependence is shown by atomic line of oxygen OI 777 нм, because upper energy level of this triplet is minimal among observed lines.

However main aims of future application of "transparent" nozzle are (i) an investigation of electronic and rotational-vibrational temperatures evolution along flow axis from low subsonic speeds in discharge channel via transonic speeds near orifice to supersonic speeds after nozzle and in shock layer on model as well and (ii) analysis of reacting flow freezing using comparison of experimental data on plasma temperatures and spectral intensity of radiation with CFD results.

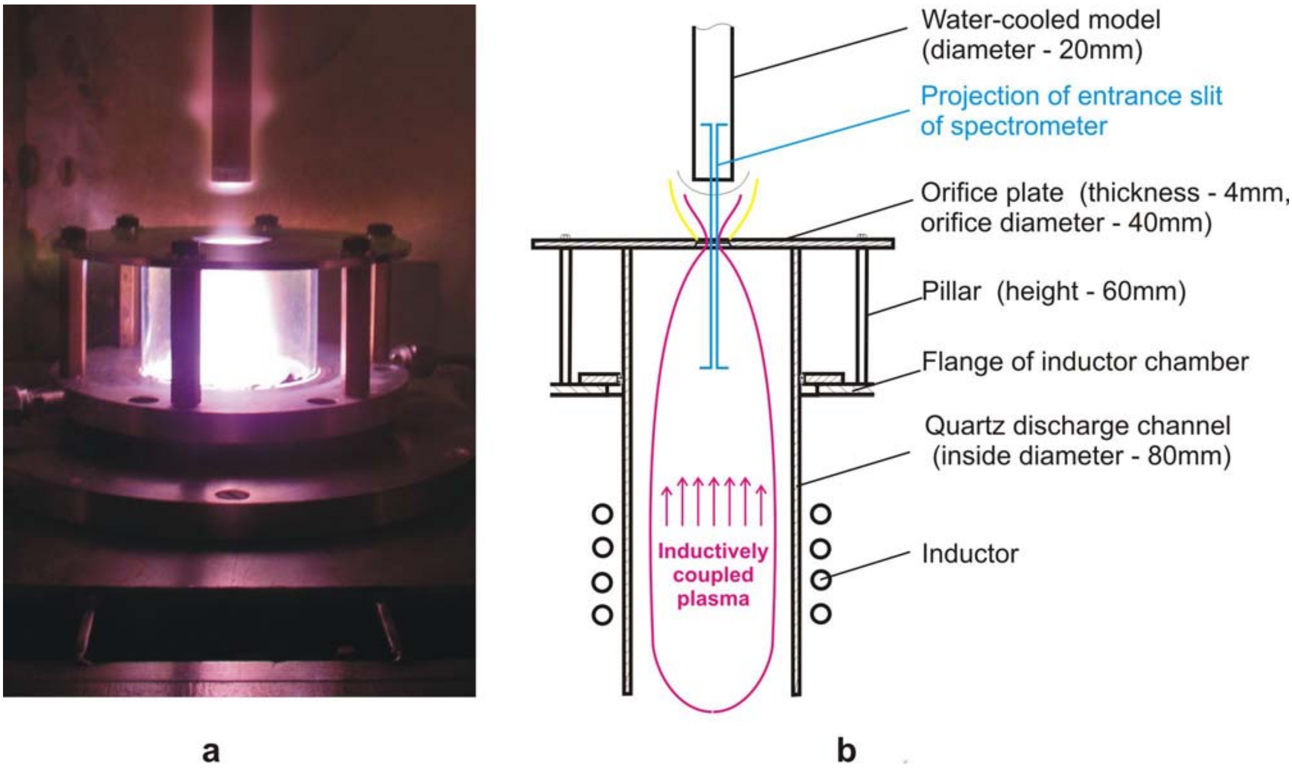
Water-cooled model
(diameter - 20mm)
Projection of entrance slit
of spectrometer
Orifice plate (thickness - 4mm,
orifice diameter - 40mm)
Pillar (height - 60mm)
Flange of inductor chamber
Quartz discharge channel
(inside diameter - 80mm)
Inductor
Inductively
coupled
plasma
a
b

Fig. 9

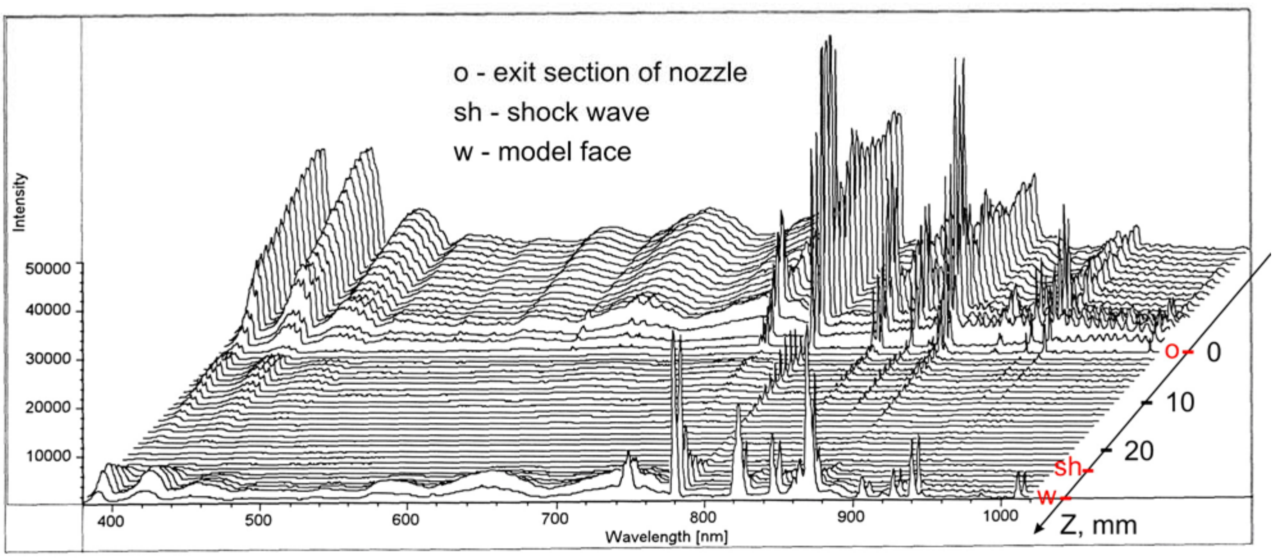
o - exit section of nozzle
sh - shock wave
w - model face
Intensity
50000
40000
30000
20000
10000
400
500
600
700
800
900
1000
Wavelength [nm]
o
0
10
20
sh
w
Z, mm

Fig. 10

Acknowledgements

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Conclusions

Operating envelope of the IPG-4 plasmatron HF inductively coupled plasma in discharge channel closed with sonic nozzle was significantly extended using new water-cooled sonic nozzles and high flow rate of air through discharge channel.

Maximum heat flux 1280 W/cm^2 was achieved using sonic nozzle of 16-mm throat diameter and 20-mm diameter flat-faced copper model at anode power 72 kW, flow rate of air 6 g/s and 20-mm distance between nozzle exit section and model. This value was found nearly two times as large as previous maximum.

Non-stationary regimes of plasma flow over model and heat exchange were found in the IPG-4 plasmatron during heat flux and stagnation pressure measurements in underexpanded supersonic flow of air plasma issuing from sonic nozzle of 30 mm diameter whereas mass flow rate of air, power injected to plasma and pressure in discharge channel were constant. These oscillations are coupled with appearance of flow separation zones ahead of flat-face cylindrical model when model is located behind Mach disk. Found oscillations are not harmonic and detected frequencies do not exceed 10 Hz.

"Transparent" sonic nozzle has been invented as modeling entity which gives an opportunity to make spectral measurements along the full length of plasma flow accelerated from near equilibrium state and Mach numbers $M \ll 1$ in discharge channel to supersonic velocities and Mach numbers $M = 2$-3 in free supersonic jet and in shock layer on water-cooled model introduced into supersonic jet as well. Experimental verification of "transparent" nozzle availability was made in the IPG-4 plasmatron and spectra of air plasma flow were recorded.

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