7. EXPERIMENTAL METHODS FOR INVESTIGATION PLASMA-BODY INTERACTION IN SUPERSONIC AIR AND CO₂ FLOWS

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Abstract: Diagnostic methods and results of experimental investigation of plasma formations created by impulse-periodic MW discharge in front of the bow shock wave of blunt body in supersonic flows of air and carbon dioxide are presented. Detailed spatial-temporal data of evolution of the discharge regions at active and glow phases and their interaction with the bow shock wave are given.

Last years research attention was attracted to physics of microwave (MW) discharge in supersonic gas flows [1,2,3]. The main advantages of MW range for modifying the processes in supersonic flows consist in high enough efficiency of generating devices, wide opportunities in transportation of MW-power and control of MW-plasma parameters.

Research team from IHT RAS (Moscow), S-PbSU and VNIIRA (St.-Petersburg) carry out investigations of MW discharge physics in supersonic gas flows since 1997, using experimental installation, which was described previously [3,4]. The general scheme of this installation with the most essential elements of the diagnostic equipment is presented in Fig.1.

Fig.1. The General scheme of plasma-dynamic installation with basic elements of diagnostics

Electromagnetic radiation with wavelength 3 cm enters the working chamber through a waveguide from MW generator. A parametric modulator increases the MW pulse power about 200 W. The direction of the field polarization vector in the discharge region at the present arrangement can be only at 90 degree angle in relation to the flow velocity vector. The desirable characteristics of the working flow are approached by the pumping action of external jet [4]. Along with this useful function the jet creates certain difficulties for application of optical and several intrusive methods of diagnostics. The ways of these problems overcoming are discussed below. The diameter of internal working flow is equal to 27mm, Mach number 1.6-1.7, static temperature 180-200K, static pressure 50-80 Torr, run time in a working mode 60-90s. Installation is equipped by three-coordinate balances, allowing to provide measurements of integral load on AD model in three directions: X - along flow axis, Y - perpendicular to flow vector in a vertical direction, and Z - perpendicular to flow vector in a horizontal direction [2].

For testing of pure gas flows, such as Ar, CO₂, N₂, the internal nozzle is connected with a working gas balloons (40 litters, 150 bars). During experiment the pressure of a working gas in the internal nozzle is regulated manually, the control of its pressure being providing by the sensor, located near the critical section of the internal nozzle.
Parameters of MW radiation

Emission characteristics of MW plasma

Dynamics of stagnation pressure

Dynamics of flow pictures near the model.

The most important features of the developed measurement methods and results of their application will be considered below in a certain sequence.

1. Gas-dynamic characteristics of a working flow

Local gas-dynamic characteristics of the working flow without MW discharge are measured by the standard intrusive sensors of stagnation and static pressure and stagnation temperature. Spatial characteristics of the working flow are analyzed by the Shlieren system. All these data allow to obtain the density, temperature, and velocity distribution fields in the investigation area of the internal (working flow).

2. Microwave radiation parameters control

Spatial distribution of the electric field created by parabolic reflector in the working zone is investigated at rather small levels of MW power with the mobile detector. The circuit of measurements is shown in Fig.2. The signal of the master oscillator on the carrier frequency passes through the preliminary amplifier, in which the output radiopulses have a power of about 30 W. The signal passes through a coaxial cable and is detected by a probe moving inside the research area. For calibration of the measuring circuit, several operations are performed:

2. Measurement of the near-field of the same horn radiator in the gas-dynamic chamber under the circuit of the amplifier.
3. Measurement of maximum voltage in the horn radiator near the nozzle.

Spatial distribution of MW-power output, carried out at the near-field stand in VNIIRA has shown that the radiation levels outside a zone with a radius more than 50 mm do not exceed -25 dB from the maximum. It means that the area for calculating radiator fields with dimensions 100 × 100 mm² is sufficient. Knowing the power level of the radiator input \( P_0 = 210 \text{ kW} \) and data obtained at the performance of

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Fig.2. The circuit of MW parameters measurement in the working area

Fig.3. Distribution of electrical field in the working area.
1) and 2) as well, it is possible to show that the maximal value of electrical field intensity in the focus area is about $4.47 \times 10^3 \text{V/cm}$. Axial distributions of electric field in reflector focal area at radiator input of pulse power 210 kW shown in Fig. 3. The axis X is directed along the nozzle axis, the axis Y is directed from the nozzle axis upwards, and the axis Z is horizontal.

At the graph of field distribution along X-axis three areas of the maximal intensity are clearly observed. The general view of MW discharge, which corresponds to the given field distribution is presented in Fig. 4.

Fig. 4. General view of MW discharge

Fig. 5. Output signals of MW detectors. A - detector of input power, B - detector of passed power

The instant values of the input radiator MW power and the instant values of the power having passed through plasmoids in a flow are registered by standard MW detectors with a bandwidth 50MHz. Their output signals are analyzed in a CAMAC system. At a level of 2.5V the signal amplitude of several single realization of MW power signals are presented. At a level of 2.5V the average value of signal amplitude under 200W decreasing of amplitude under 200W corresponds to an absorbing and scattering of MW power in a flow.

3. Emission characteristics of MW plasma

Investigation of emission radiation of MW plasma permits to obtain the number of very important plasma characteristics such as electron gas temperature, vibrational and rotational electron concentrations, electron temperature and others. All these data are of great necessity for creating a numerical model of processes in plasma flows on supersonic flows.

One of the most difficult problems existing in optical measurements in the presence of MW plasma is strong influence of parasite scattering MW field to sensitive optical sensors - photomultipliers (PM) and CCD devices. For eliminating this influence, we widely use the fiber optic. This way allows to place the main part of the sensitive measuring devices at a comparatively long distance (about 20m, in another room) from the MW generator and gas-dynamic installation. The second important advantage - very simple construction of optical signals input/output from the gas-dynamic test section. Only several small orifices are to be made in the vacuum test chamber wall for measuring spectral and spatial characteristics of MW plasmoids.

We use quartz-polymer fibers with numerical aperture 0.4 and core diameters 125 and 400 μm. The wave length range of 300nm to 1100nm. Two identical optical systems are placed on the coordinate device in the vicinity of the working flow inside of the test section. The distance between plasmoids and the input lenses of the both optical systems is chosen as small as possible - 230mm. The relative orifice of the optical systems is about 1/2, in a good correspondence to the high numerical aperture of the fiber in use. Both channels collect the emitting light from the same area of plasmoids. The distance between the end of the internal nozzle and the investigation point (X
3.1. Temporal and spatial characteristics of radiation emitting by MW discharge

The first optical channel is used for temporal and spatial measurements of the emitted light. Its short wave spectral limit is determined by the fiber (300 nm), the long wave limit - by sensitivity of using FM (750 nm). The angle between the flow axis and the channel optical axis is 81°.

The output signal from FM passes through the fast amplifier (equivalent load resistor is 1 kOhm, bandpass about 20 MHz). Signal from amplifier goes either to flash-ADC F4226 (temporal measurements in discharge light emitted), or to Sample - Hold (S-H) device (spatial distribution of emitted light in plasmoids). The sample-time of S-H is 100 ns, and the delay time - for sample moment - 2.5-3 μs. The last corresponds to the maximum level in emitting light for most part of discharge realizations. Instantaneous level of light intensity is converted in ADC FK-72 (12 bit, 70 μs) and is stored in PC memory, where the necessary number of realizations are summing for achieving of a good level of S/N.

High sensitivity of this optical channel permits to use it both for investigations of integral luminescence processes in supersonic flow and for measurements in comparatively narrow spectral range, for example 5-10 nm. In this case, the light being collected by the optical system then passes through the spectrometer. This operation mode permits to investigate the temporal and spatial behavior of the most essential vibration - rotational spectral bands of discharge radiation.

At Fig. 6, the spatial distribution of MW discharge intensity in airflow along the X-axis is presented. Curves correspond to different levels of MW power in discharge. Difference in these levels are less than 5%. The first peak of intensity at 3 mm is connected with the discharge on the edge of the nozzle. It corresponds to 0-2 transition of the second positive system of N₂ for the plasmoid in airflow, placed at 45 mm. The spectral width of the spectrometer slits is 4 nm. The beginning of MW impulse - at 4.5 μs, the end - at 6.25 μs (noted by "row").

At Fig. 8, the results of weak luminescence investigation of MW discharge in free supersonic flow are shown. The delay of chemiluminescence signal for different points of the flow axis determines the flow velocity and its dynamic [6].
3.2. Spectral investigations of MW discharge in supersonic flows

The second optical system is used for spectral measurements. It operates with high-light gathering power spectrometer MDR-2 which has relative orifice 1/2, grids with 1200 1/mm, dispersion 2nm/mm and spectral width of instrumental profile 0.2nm for slit 100 μm. Spectrometer is controlled by a CAMAC system.

One of the serious problems in spectral measurements in supersonic flows is comparatively short run-time of the working gas-dynamic regime. Usually, this time is limited to about 50-70 ms, and it does not allow to get high resolution in wide spectral range. In this situation the spectral velocity of tuning is chosen comparatively fast - 0.03 nm/step with step frequency 250 Hz. Output light of spectrometer is detected by photo-multiplier (FM FEU79). It can work in two operation modes. The first is the analogue regime, the second – the digital regime (photocounter).

In the analogue regime the output signal of FM passes through trans-impedance transducer (equivalent transducer resistor is 4.7 MOhm, bandwidth frequency 1 MHz) and goes to S-H CAMAC device, mentioned above. Time-delay for this channel corresponds to the maximum of signal on transducer output. The digital regime is used comparatively rare, only for registration with maximal spectral resolution.

Optical axis for this spectral channel is perpendicular to the flow axis. At Fig. 9 the review spectrum of MW discharge for plasmoids placed at 60 mm is shown. It is registered with wide spectrometer slit and recording time 30 s. This spectrum demonstrates the most important analytical emitting lines in the second positive system of N2 commonly using for diagnostic in our experiments.

For the determination of gas temperature in a discharge the method of optical emission spectrum shape fitting has been adopted [3,4,6]. The exact full spectrum of 0-0, 0-3 and 1-4 transitions of the second positive nitrogen system, including R-, P- and Q-branches (the last is very weak) is generating under the defined temperature and is then convoluted with the spread function of the spectral device. The synthetic spectrum obtained in such a manner is then compared with the real one. It is made in a procedure of best fitting of the spectrum contour by variation of the defined temperature. In this case the special attention is paid for the best coincidence of the spectral shape at the lower rotational numbers, where the distribution over the rotational levels is known to establish at a temperature practically equal to that of the gas.

The results of such fitting can be summarized as follows:

1st plasmoid (45 mm):
- 0-0 transition, \( T = 200 \text{ K} \) (\( \tau = 3.2 \mu \text{s} \)),
- 0-3 transition, \( T = 240-250 \text{ K} \) (\( \tau = 3.2 \mu \text{s} \)),
- 0-3 transition, \( T = 250-270 \text{ K} \) (\( \tau = 4.0 \mu \text{s} \)).

2nd plasmoid (60 mm):
- 0-0 transition, \( T = 270 \text{ K} \) (\( \tau = 4.0 \mu \text{s} \)),
- 1-4 transition, \( T = 300 \text{ K} \) (\( \tau = 4.0 \mu \text{s} \)),
- 0-3 transition, \( T = 320 \text{ K} \) (\( \tau = 4.0 \mu \text{s} \)).
The accuracy of temperature determination by this procedure can be estimated in 20 K. It should be noted that 0-0 transition has given lower temperature in comparison with 0-3 transition, but the difference between temperatures in the first and the second plasmoids is approximately the same – about 70 K.

The data obtained from spectral measurements in MW discharge allow to make estimates for vibration temperature levels as function of energy input and calculate the relative population of N\textsubscript{2} vibration levels [5-9].

4. Dynamics of stagnation pressure at AD body in MW discharge

Two main problems dramatically increase when sensitive pressure transducer is using for stagnation pressure measurements in presented experimental installation. The first is strong (3-4 kV/cm) MW field in the area where transducer is placed, making the essential electromagnetic influence on it. The second is the transition gas-dynamic processes at input and output of the working regime for both jets - internal (working) and external (pumping). For some moments of these regimes, the pressure level acting on the transducer (more than 5 atm) is essentially higher than its ultimate undamaged level. The schema of pressure sensor, which allows measuring in conditions, mentioned above, is shown at Fig. 11.

The pressure sensor has been created on base of low impedance wide band tenzo-resistive differential pressure transducer Kulite, XCS-093, 5 PSI (about 260 Torr). The upper frequency for it is 150 kHz, static sensitivity - 0.3 mV/Torr. Transducer is placed in external steel cylindrical case and isolated from it by the Teflon ring. At the same time, this ring separates the values of measuring pressure and basic pressure (static pressure in working chamber). Internal value of pressure sensor is connected with the flow area under investigation by the orifice in steel case. The orifice diameter is 2 mm. Position of the transducer inside the sensor's case determines the bandpass of pressure sensor and has been chosen as a compromise between its maximum meaning and minimum influence from MW impulse, i.e. to measuring error. Measurements of stagnation pressure made in our previous work [3] showed that these pressure sensors have been operated in the pressure range 80-100 % of the working regime. The transducer's output signal was analyzed by the differential amplifier with bandpass 0.01-100 kHz and gain level +30 dB. The recording of this signal was made by fast flash ADC F4227 in CAMAC system, mentioned above. Flash ADC begins to work simultaneously with synchronization.
impulse from MW generator nears a measure to single realizations of pressure signals with low level S/N and to averaged signals of single levels of pressure overload essentially less than 0.5 atm and can not damage the transducer. A proper arrangement of the working regime sensors proved to be able to make measurements very long for a short time. The measurements were done on a nozzle on a low-speed flows. The sensors were located on the nozzle at a distance of about 0.5 m. So, long-term gas dynamics makes these experiments rather expensive.

As we note above, the second problem arising in such measurements is connected with a low-level pressure transducer overload capability. For resolve of this problem, before the beginning of each test we placed the transducer inside of internal nozzle. In this position the levels of pressure overload essentially less than 0.5 atm, and can not damage the transducer. After achieving the working regime, sensor is moved in the investigation points, where measuring are to be done and after it is returning back to the initial position. Unfortunately, comparatively low-speed of coordinate transducer device (about 2 mm/s for X-axis) do such measurements very long. For example, measuring in 8-10 points at the distance of 80-100 mm from the nozzle exit section has a duration about 100-150 s. So long time of gas-dynamic regime makes these experiments rather expensive.

Fig. 12. Stagnation pressure for different points of flow with MW discharge.

Fig. 13. The stagnation pressure signals for Carbon Dioxide flow with MW discharge.

5. Dynamics of flow pictures near the model

We present gas on the now shown behavior was obtained with a planar, designed glass 80 mm in diameter 80 mm was based on the zero regime AR 450. An infrared light-emitting diode (LED) with output power of about 2 W was placed in the nozzle exit of MW discharge. The time delay interval from 1 to 500 μs of light impulse was controlled by a program. The measurement region of MW discharge was scanned very slowly (0.1 s/m) and was not to be seen on the MW discharge. A good arrangement on the front face of the sensor was used to scan the compression of MW discharge. The pattern could be seen on the nozzle at a distance of 50 mm. The same signals for Carbon Dioxide flow were presented at Fig. 13.

The presence of an external pumping jet on a nozzle of the flow regime was conducted with the aid of a specially designed digital Schlieren system, which was based on the serial device IAB-450. An infrared light-emitting diode (LED) with output power of about 2 W was placed in the nozzle exit of MW discharge. The time delay interval from 1 to 500 μs of light impulse was controlled by a program. The measurement region of MW discharge was scanned very slowly (0.1 s/m) and was not to be seen on the MW discharge. A good arrangement on the front face of the sensor was used to scan the compression of MW discharge. The pattern could be seen on the nozzle at a distance of 50 mm. The same signals for Carbon Dioxide flow were presented at Fig. 13.

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5. Dynamics of flow pictures near the model
Fig. 14. The dynamic flow in CO2 for Z polarization of MW field.
Conclusions

The complex diagnostic system for investigation of MW-plasma-body interaction processes has been created. The methods used in this system include both intrusive sensors of stagnation and static pressure and temperature, AD balances, and non-intrusive spatial-temporal registration and analysis of the emitted light radiation from MW discharge and wide-dynamic-range impulse digital Schlieren system. The essential part of the presented diagnostic system is the MW sensors group which allow to control the parameters of MW power both at the entrance to the test gas-dynamic section and after absorption and scattering there. By the present time the created system has allowed to obtain new interesting data on MW discharge physics in supersonic flows and, undoubtedly, will be very useful in further investigations.

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