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PLASMAGASDYNAMIC EXPERIMENTS IN RUSSIA AND PROSPECTS OF PLASMA TECHNOLOGY APPLICATIONS IN AERODYNAMICS

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The investigations in the field of a plasma gas dynamics performed by MRTI RAS and other organizations during last 20 years are considered. The following experimental schemes were used: probing of discharge plasma by a sound, weak shock wave and strong shock wave, including experiments on shock tubes, body flight through plasma region in ballistic stand, a flow around a body in the wind tunnels provided by section with plasma discharge, etc. The direct current sources, the high-frequency and microwave generators were used for creation of plasma. The results of the experiments are considered and the positive conclusions about prospect of use of the plasma technology in aerodynamics are done.

Introduction

The problem of the discharge influence on the conditions of flight of supersonic apparatus develops in Russia for a comparatively long time. From the very beginning it was supposed that influence on a flow must be remote. One could see that a quite effective influence on a flow can be created if energy is included into flow at the optimal region near the flying body. The remote energy addition into a flow can be easy transported by means of some kind of directed beam of radiation (in particular electromagnetic). The main difficulty represents the question how transported radiation beam will find the needed place where we want to include the additional energy. It is clear that medium of propagation (in our case it is an air) must be transparent for radiation and only the nonlinear processes are able to create the needed adsorbing. The electric discharge can perform this role if the radiation is focused in the pointed place and specific power at focus is quite enough for the air breakdown. One could elect between microwaves and laser sources. These sources satisfy the formulated demands. The preference was given up to microwave (MW) radiation. The initial estimations had shown that significant influence could be reached if a specific energy addition is comparable with air enthalpy. For study of the nonlinear phenomenon at the radiation focus the raw of installations with MW sources was constructed in Moscow Radiotechnical Institute (MRTI). The first experiments shown that microwave discharge is very complicated phenomenon with strong dependence on a set of circumstances. It needed the special studies separately from aerodynamics problem. The electrodeness discharges - direct current (DC) and high frequency (HF), continuous and pulse - were used for preliminary study of a discharge influence on the gasdynamic flows. Step by step it was standing clear that electrodeness discharges from one side do not able to model the microwave discharges but from other side can play independent role in a plasma aerodynamics. Both this directions are developed to this day. The significant experience is saved in this area to the present time [1]

Microwave installations

All constructed MW installations have the same principal scheme. The usual MW installation consists from MW generator, wave guide and focusing antenna system, displaced into a vacuum tank, that is fulfilled by a gas with needed pressure. A supersonic jet, injected from Lavale nozzle, can flow through focus region or a shock wave, sound et cetera can propagate through one.

The biggest MW installation "TOR", is located in MRTI. The generator power is 20 MW in continuous regime and can work with any kind of modulation. The wave length of radiation is near to 4 cm. The electronic controlled phase grid allows to create any field distribution in the radiation beam focus. The minimum focus radius was defined by diffraction limit. The detail description of the installation "TOR" one can find in the paper [2]. The major part of preliminary knowledge about the powerful MW discharge plasma (especially with high average power) was got on the installation and its smaller prototype. But detail information about physics of a pulse MW discharge in a wide diapason of parameters was got on the smallest installation "E-1", displaced in MRTI too [3].

The principal scheme of E-1 is the following. The magnetron generator is fed by pulse modulator. It generates microwave radiation with wave length 8.9 cm. The MW energy goes through wave guide with circulator and attenuator to the antenna system and farther into vacuumed tank. The output power of generator is 10 MW with pulse duration 40 μs. Repetition frequency is less than 1 Hz. The parabolic metal mirror focuses the radiation. The discharge erects in the field maximum. The tank has the couple windows for diagnostics and the gas flow equipment. The gas pressure in the vacuum volume can be varied from small value up to atmosphere. The most part of experiment was performed in air, nitrogen and hydrogen. Usually the diagnostics consists from MW field measurements, photo camera, microwave and optical interferometer, spectrometer, various probes et cetera.*

* The similar installations worked in Institute of Applied Physics (Nizniy Novgorod), General Physics Institute RAS and MSU (Moscow), Ioffe Institute (St.-Petersburg).

One can understand that displacement in the frame of one experimental installation a power MW source and full scale shock wave tube or a wind tunnel is a very difficult task not expedient at recent time period. Therefore some MW installations was equipped by the little scale supersonic nozzles, which did create the supersonic jets across the focused beam, or sound and shock wave sources, which generated the gas wave perturbations across the focus region for study of MW discharge influence on a gas dynamics.

Gasdynamic installations with the electrodeness discharges

The electrodeness discharges are studied significant better than MW one. The sources of such discharges are not expensive and simpler than MW one. These aids can be easy located in the wind tube or shock tube or displaced on aerodynamic models and apparatus. It is the main reason why the electrodeness discharge is widely used in the plasma aerodynamic investigations although this kind of discharges can create the energy addition zone only near the body surface between the electrodes.

The wide program of experiments with electrodeness discharges was performed on the shock tubes, wind tunnels and ballistic tubes in the row of Russian Institutes. The following formulations of experiments were used:

Shock tubes [4,5,6,7]

sonic, weak and strong shock waves propagation through the longitudinal or transversal electrodeness discharge region.

Ballistic tubes [8]

blunt, spherical or conical body flight through the plasma region of transversal electrodeness discharge.

Wind tunnels [9]

supersonic and undersonic flows around blunt or streamlined body with the electrodes of discharge source location on the body or ahead one.

Many interesting results were got on the shock tube of MRTI (stand "E-3)

The main result of experiments with the electrodeness discharges

The generalization of plenty of work devoted to experimental study of the electrodeness discharge influence on a supersonic flow (both free and bow shock waves) guides to following conclusions.

In the overwhelming majority of the works the shock wave increasing in the plasma region can be explained successfully by usual heating and detonating relaxation of excited molecules and atoms [10]. Data extracted from averaged results of row of installations definitely shows us that this side of phenomena is defined basically by thermal effect and in some cases by the detonation. (The special measurements of translation and excitation temperatures was performed in the discharges with the same parameters [11]; this measurements confirmed that at the low pressure the gas and vibration temperature of the glow discharge are equal 500K and 5000K accordingly.) Recently this point of view is accepted by many authors [12,13,14].

The same result was got on the wind tunnel. The one of key experiments was performed on the wind tube equipped by the longitudinal DC discharge. The discharge was created between external electrodes located ahead the body. The longitudinal discharge was elected because a transversal discharge in supersonic flow is very unstable [15]. The product of discharge forms the plasma channel that overflows the body. The goal of the experiment was simulation of energy including outside the body by means of some kind of radiation for study of its influence on the drag force, [16]. The important conclusion follows from the measured dependence: the efficiency coefficient for blunt and streamlined body equals ~0.35 and ~0.15 accordingly almost independently on the discharge power. The detail measurements of spatial-temporal distribution of the perturbed flow parameters (temperature and density) and temperature of the blunt body shown that approximately only half of energy addition goes on the gas heating. According to usual estimations other part goes on vibration exciting of molecules [17]. The computer simulations confirmed this conclusion [18].

The similar experiment in the wind tunnel was performed for the case when electrodes were located on the body surface [19]. Anode was located on the top of the needle, partitioned cathode – on the blunt body periphery. Comparison of experimental and numerical simulation data shows that the drag force decreasing can be explained in frame of thermal model. The main difficulty at simulation is the absence of the trusty theory model of a discharge in supersonic flow.

But at the same time the experiments demonstrate some not clear details that have not the reliable explanation now. It means peculiarities of shock front (precursor and double shock) and unusual bow shock stand off in a glow plasma flow (at pressure below 30 Torr).

Insufficiency of data about experimental details (spatial-temporal measurements of many parameters of the discharge plasma) opens the ways for many different explanations of these phenomena. Now it is not clear the role of these peculiarities of phenomenon in the aerodynamic applications but of course from the physics point of view it needed the farther investigations.

The experiment MRTI-TsAGI also shows that hot plasma tail is very inhomogeneous. The flow density in the tail varies strongly. It causes the strong instability of the bow shock and the drag force pulsation with frequency near 1kHz. The photo by exposed lens averaging the shadow picture does not record any shock in plasma tail. Only time resolved diagnostics can show the jumping shock. This example means that every experiment demands a deep attention and the very careful interpretation.

The main result of experiments with electrodeless MW discharges

A lot of works is devoted to study MW discharges in the various gases at the wide diapason of pressure (0.1-760 Torr) and the wave length (0.2-30 cm). The lower part of the pressure diapason is interest for the industrial technology. For the aerodynamic applications the high pressure discharges in a high intensity MW radiation are actual [2021,2223,24]. The main goal of those works is the definition of conditions of the discharge creation, the absorbing and reflecting properties, its behavior in a supersonic flow, the gas dynamics initiated by the MW discharge, influence of the perturbations on waves in a gas and the flow around body, et cetera.

It is important to note that at the pressure more than 30-50 Torr it is very difficult (almost impossible) to sustain the spatial homogeneous discharge during time duration near 1 ms. The strong heat instability transforms the discharge. In elecrodeness discharges the unit filament arise and forms the usual electric arc or spark. This kind of discharge is unsuitable for aerodynamic applications at pressure above 30 Torr But high pressure MW discharge represents a net of filaments [25,26,27,28,29,30,31]. The filament net is a good absorber of MW radiation. Almost all radiation beam energy is absorbed by the discharge. It is explained by resonant character of process. The net consists from electrodynamic resonant elements with length near half of radiation wave length. The elements appear one after another at front of discharge [32]. The gas temperature and ionization degree are very high in the filaments. The thin filaments after heating explode and form a net of hot thin channels that live in the flow a long time (above 0.1 s). The filament discharge can propagate with velocity above several km/s [33,3435]. It means that this kind of discharge is able to exist in supersonic flow. The direct experiment confirmed it. The important property of a filament MW discharge is its possibility to propagate in a region where the field amplitude is much less than breakdown value. It means that one can include power into a gas at a small level of MW radiation in focus. It is consequence of the streamer effect. The field at the ends of filaments is much more than unperturbed one.

A discharge arising near an edge of metal needle propagates far away from needle at the MW field with the under-breakdown level [36]. This kind of MW discharge was named “initiated (or “undercritical”) MW discharge”. The undercritical discharge has the tendency to self organization. The filament net forms the complicated resonant "antenna system” of spiral type [37,38]. The filament net sustains the point with high field amplitude on the rising ends of such plasma “antenna system” constantly. It allows to plasma filaments to rise continuously.

This circumstance strongly expands the area of MW discharge applications in aerodynamics and aircraft technology (for example, for fuel ignition in a jet engine [39]). The high temperature filaments sparkling in the combustion camera are able to ignite a fuel mix and to control the detonation front or combustion front. By the way the “initiated” MW discharge is can be used for solving of important global problem such as preservation of the ozone layer [40.,41]

As it was marked the consequence of MW discharge in flow represents a complicated net of hot filaments in a cold air. This medium is very unusual for the sound and shock wave propagation. The experiments show the strong suppression of a shock wave by the filament MW discharge [42,43]. The effect is explained by the strong vortexes exciting when shock wave crosses the region with the net of the hot filaments. Each filament is converted to toroidal vortex. The energy of directed movement of gas in shock wave absorbed by the vortexes. The effect of a shock wave reduction was demonstrated by measurements of temporal profiles of explosion type wave performed on “E-1”. This effect can be useful for the design of the board aids for reduction of the bow shock of a civil aircraft.

Summary

Of many years experience of study of various kinds of the gas discharges at intermediate and high pressure for definition of theirs application ability in aerodynamics allows us to have formulated several theses.

The electric discharge can strongly influence on the characteristics of a supersonic flow and stream around body.

The MW discharge gives us the greatest possibilities for different applications in aerodynamics because it allows to insert the additional energy into the flow not only near the body surface but at any region around body without contact with it: ahead, aside, under and above body at any distance and at intermediate and high pressure. It is important that it need not the electrodes for discharge creation. The gasdynamic simulations show that addition of energy into flow is able to increase the efficiency of a aircraft supersonic flight

The MW discharge creates the sparks (filaments) with very high gas temperature at the intermediate and high gas pressure. The temperature is quite enough for ignition of fuel combustion and can be used for a control of a combustion (detonation) front in a jet engine.

The complicated net of the hot filaments appears in the MW discharge. The propagation of shock wave through the net is accompanied by the strong its reduction. It is possible that effect can be used for bow shock reduction or strong its attenuation on entrance of a jet engine.

The electrodeness kinds of discharges are able to create discharges only between electrodes. So far as electrodes are located on the aircraft the discharge can be excited only near surface of aircraft. The electrodeness discharges can be used at low pressure of gas only. The direct current source does not able to feed electrodeness discharge because it must have a large inner active resistance and its efficiency is bad. The incomprehensible peculiarities of the shock front in the low-pressure electrodeness discharges need additional investigations. That experiment must be repeated at other experimental situation with more detail diagnostics and the conditions control.

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