13. HYPERSONIC FLOW AND SHOCK WAVE STRUCTURE CONTROL BY LOW TEMPERATURE NONEQUILIBRIUM PLASMA OF GAS DISCHARGE

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Abstract. Shock wave -non-equilibrium plasma interaction is investigated and analysis of possible gas dynamics drag reduction under such conditions is provided. Experiments with controlled excitation of the translation-rotational and vibration electronic degrees of freedom of the gas by non-equilibrium glow discharge stabilized by gas flow in the hypersonic nozzle and investigations of the possibility of shock wave structure control by non-equilibrium plasma were performed. Stagnation pressure decrease up to 15% was determined for air flow at \( M=8.2 \). Temperature measurements shows the temperature increase due to gas excitation in the discharge and internal degrees of freedom relaxation. The conclusion was made that the gas discharge affects the flow mainly by thermal heating in the investigated range of parameters. Calculations support the conclusion about the thermal nature of the shock wave-plasma interaction.

Introduction

There are three main reasons for the drag reduction under the non-equilibrium plasma - shock wave interaction conditions. First - gas heating in the discharge (due to relaxation of internal degrees of gas or direct heating by e-impact) may leads to the local flow Mach number reduction. This may lead to the global flow and shock wave structure rearrangement. Second - molecules dissociation and ionization in the discharge may cause the mean molecular weight and number density of the gas change. Third - appearance of charged particles may lead to the upstream momentum transfer in the hypersonic flow.

Reports of anomalous shock wave behavior in weakly ionized plasmas have recently stimulated considerable interest due to possible applications for supersonic flow control. These may include drag reduction, varying lift-to-drag ratio, MHD energy extraction, and MHD boundary layer control. These effects have been reported in discharges in various gases (\( \text{Ar, He, N}_2, \text{air, and CO}_2 \)) at pressures of 3-30Torr, and for Mach numbers in the range 1.5-4.5. They also exist for significant time duration after the discharge is switched off (1ms in air). Molecular energy transfer processes, such as vibrational relaxation and excitation, electronic excitation, chemical reactions, ionization, and radiation are extremely important in nonequilibrium gas dynamic flows. Our ability to control strongly nonequilibrium environments, such as occur in molecular lasers, plasma chemical reactors, supersonic nozzles, rocket plumes, and reentry flows critically depends on understanding of such processes. In particular, it is important to know the rates of these processes and therefore to be able to model their kinetics predictively [1].

In pulsed discharges sustained by short high-voltage pulses, such as pulsed corona discharges, ionization efficiency can be several times higher. The main reason for this is that a strong electric field applied for a short time heats the electrons up to higher energies [2]. Efficiency of ionization by electron impact can be further increased using electron gun, where a beam of electrons is accelerated in vacuum by an electric field. The efficiency of ionization of the gas molecules by the beam electrons is very high, up to 50%.

High voltage glow discharge stabilized by the gas flow at ultra-high overvoltage may also be an effective source of highly excited spatially uniform plasma. Maximum values of reduced electric field in such a discharge may significantly exceed the threshold of electrons run-away. The discharge of this form was not used for the investigations of shock wave-plasma interaction till now. Due to high spatial homogeneity this type of breakdown is extremely interesting for the study of kinetics under the non-equilibrium conditions.

Experimental Setup

Experiment

In experiments we used continuous operating vacuum wind tunnel. Test chamber \(~0.5m^3\) in volume was connected by a valve of 350mm in diameter with main vacuum chamber \(~6m^3\) in volume. The volume was pumped by four oil-vapor booster vacuum pumps BN-4500 with 4500 l/s productivity at a pressure of 10^-2Torr and by two parallel mechanical pumps VN-6G. The total pump rate was 18000 l/s at a pressure of 0.1Torr. Additional rotary pump with a productivity of 5 l/s allowed to pump test chamber separately.

Hypersonic flow was formed when work gas expanded from forvacuum chamber to test chamber through the conical nozzle. The rated regime corresponded to Mach number of ~8.2. Pressure drop between forvacuum chamber and test
chamber was adjusted by a special valve and comprised 20-40Torr. This value was measured by an U-shape manometer. Gas flow was equal to ~0.5g/s. Pressure in a test chamber and in main chamber was measured by thermocouple gauges LG-2.

It was equal ~5×10⁻³Torr. Critical cross-section diameter of a nozzle was equal to 4mm, and outer diameter was 80mm. At our pressures it was necessary to take into account boundary layer, which is about of 12mm in the outlet section of the nozzle. As a consequence, isentropy kernel of the flow was less than outlet cross-section and was about of ~55 mm.

We performed experiments for a set of models.

In the first regime (Fig.1) cylindrical model was made from dielectric and was placed along the flow. Metallic plug was mounted along the axis of the cylinder, and high voltage of negative polarity was applied to the plug. There was hole in the middle of the plug connected to the Pitot tube, so that it was possible to control the pressure behind the shock wave. The length of dielectric cylinder was 150mm and the diameter was 40mm. Outer diameter of the steel plug was equal to 5mm, and hole diameter was equal to 2mm.

![Fig.1. Geometries investigated.](image)

To understand how transverse uniformity of the discharge influences on the flow we investigated model with a needle (Fig.2). In this case practically all electric current closed to the needle provided high energy input along the flow axis.

So, oblique shocks attached to different models placed in a steady state cold plasma flow in a supersonic nozzle were investigated. The stable diffuse plasma was created by a low-pressure aerodynamically stabilized DC discharge between nozzle and model in the supersonic test section. The experimental data for the low-temperature nonequilibrium plasma influence on the flow pattern around the model were obtained.

Pressure behind the shock wave was measured by thermal resistive manometer MG-6. The manometer was connected with the Pitot tube by a long (3m) dielect ric tube to avoid discharge development in the manometer volume.

To control space distribution of excited molecules created by the discharge we used emission spectroscopy technique. We used VNC-702 CCD camera, which allowed to work with low luminosity level (0.00004 lux) at signal/noise ratio equal to 10. Signal from the camera was controlled by a computer.

Camera was calibrated in the wave-length range 240-510nm with the help of calibrated deuterium lamp. In the region 350-500 nm camera sensitivity is practically constant.

Discharge influence becomes clear at current values about of 50mA, at this power input into the gas reached 150-300Wt at decreasing volt-ampere characteristics of the discharge.

Fig.2 demonstrates the stagnation pressure change in dependence on the discharge current in air and CO₂.

![Fig.2. Stagnation pressure change in dependence on the discharge current in air and CO₂. Geometry 1.](image)

At decrease of the high voltage electrode discharge do not transforms into the arc discharge and remains in a form of abnormal glow discharge. In this regime we also observed significant change in stagnation pressure at high discharge power. Taking into account that applied voltage was about of 3 kV, in is possible to estimate reduced electric field as $E/n=1.7×10^{-13}$V·cm⁻² ahead of and $E/n=4×10^{-14}$V·cm⁻² behind the shock wave. At these reduced
electric field values major part of energy is spent for excitation of electronic degrees of freedom, dissociation and ionization. Only ~10% of the energy is consumed on vibrational excitation, and heating is negligible [3]. So, at these conditions gas heating does not take place immediately in the discharge and to analyze the heating it is necessary to consider relaxation of internal degrees of freedom of the gas.

Temperature Measurements

To analyze temperature distribution in the flow we used technique of a temperature determination from resolved vibrational spectra of first negative system of molecular nitrogen [4].

Modeling

The non-equilibrium hypersonic flow around the cylinder was investigated numerically.

2D axially-symmetric calculations of the flow were performed. We analyzed regimes with independent variation of vibrational temperature in the hypersonic flow. Mac-Cormak scheme with FCT correction was used for solving the components, mass, momentum and energy conserve equations.

Uniform Flow

Figure 5 shows results of calculations with vibrational temperature equal to the translational one (A), and $T_{vib}=1800, 1900$ and $2000K$, respectively. We assume dissociation degree to be in equilibrium with vibrational temperature of the gas. It is clearly seen that energy release behind the shock wave leads to the flow field change. This calculations support our conclusion about the thermal nature of the shock wave-plasma interaction.
Model with Needle

It is interesting to analyze non-uniform discharge development in geometry No.2. Significant transverse gradients of temperature, density and gas composition lead in this case to considerable increase of charge influence on the flow parameters (Fig.6).

![Graph](image)

**Fig.6.** Stagnation pressure change in dependence on the discharge current in air. Geometry 2.

Numerical model of the flow development in this geometry and analysis of the influence of layer thickness were performed. It was shown that thin discharge region may cause sufficient flow reorganization and stagnation pressure decrease.

The influence of the layer thickness was analyzed numerically for air flow at $M=8.2$, $T_v=21K$, $T_{nv}=2000K$. Layer thick-ness was varied from $h_{layer}=10$, to 100% and $\infty$ with compare to the model thick-ness. The stagnation pressure decreases in all cases and was 21%, 34% and 29% lower than for undisturbed flow, correspondingly. This values are in reasonable agreement with experiment. Relatively high value of pressure decrease for very thin layer (10% from the diameter of the model) shows the possibility to reduce the energy consumption for flow control.

Conclusions

Experimental data on the non-equilibrium plasma - gas flow interaction for hypersonic flows and the gas parameters during shock wave - non-equilibrium plasma interaction were obtained. The numerical code that describes interaction of the shock wave and non-equilibrium plasma for different mixtures was constructed. Basic factors that determine the interaction process in such a system and the effect of charged and excited particles on the interaction dynamics were revealed. An experimental data for the gas discharge influence on the flow pattern around the model in the wind channel with Mach number $M \sim 8$ were obtained. The measurements of the drag force for different gas discharge parameters were performed. The conclusion was made that the gas discharge affects the flow mainly by thermal heating in the investigated range of parameters. Calculations support the conclusion about the thermal nature of the shock wave-plasma interaction.

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References