

Plasma Control of Shock Wave Configuration in M=2 Inlet at Off-Design Mode

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Abstract

Particular objective of this work is to demonstrate the steering effect of weakly-ionized plasma on supersonic flow structure in a two-dimensional aerodynamic configuration with three-shock compression ramp at off-design operational mode. The model air inlet, designed for M=2 flow, was tested at M=2-3 and angle of attack AoA=0-8deg. Multi-electrode quasi-DC electrical discharge at power $W_p=2-10\text{kW}$ was arranged upstream the compression surface. Significant plasma effect is considered on shocks configuration and flow parameters after the compression. CFD efforts manifest extra 3D information about particular details of flow parameters' modification due to plasma thermal impact. Such a technique can be posed as a feasible method for expanding of supersonic inlet's operational limits.

1. Introduction

The purpose of the work is to study the gasdynamic phenomena associated with near-surface plasma – high-speed flow interaction and to demonstrate a steering effect of electrical discharge in a model high-speed inlet. The principal idea consists in returning of an air inlet to proper operation at Mach number of incident flow greater than design Mach number. Up to now the problem of an inlet of fixed geometry operation in wide range of Mach number and pressure is far from resolving [1-2].

Currently the airflow actuation by weakly-ionized plasma of electrical discharge is widely discussed in terms of drag reduction, lift/drag augmentation, BL separation, transition control, etc. [3-9]. Several publications are also related to the problem of high-speed inlet regulation, including high-speed boundary layer actuation, shock wave (SW) interaction with boundary layer / shock-induced separation, separation control at plane-wedge conjunction [10-15]. In this work authors present the experimental results on the plasma-based control of the model of supersonic inlet under free-stream conditions.

A scheme of three-shock (two-rupture) plane inlet is shown in Fig.1a-c. If the Mach number of external flow is higher than the design value, the figure of shock wave reflections have a complex construction, including local shock-induced separation (indicated by blue colour) and irregular shocks interaction. In some cases the point A in Fig.1b degenerates into a direct shock with consequent unstable behaviour of internal airflow or even the choking of the inlet. Figure 1c demonstrates how a near surface power deposition (read - plasma generation) may “heal” the previous state: a soft plasma layer simulate an almost isentropic pattern of the flow compression and collects weak shocks on the cowl lip. The second shock looks like disappeared due to plasma “screening” effect [16]. In the last case the total pressure losses should be less than without the flow control. Having a sensors' set and feedbacks the control system may adjust the magnitude of plasma power for the best performance.

The first experiments [17-18] were made in connection pipe scheme to solve technical issues with the plasma generator and to study main particularities of the plasma-flow interaction. There were shown that plasma, being included to a control system, may potentially steer the angle and location of external and internal shocks within the compression ramp, redistribute the pressure, and reduce the pressure losses in core airflow. The second test, considered in this paper, was aimed to study a model inlet in free stream and to measure as much characteristics as possible in frames of specific experimental approach. The experiments are supported by 3D Navier-Stokes simulations. Particular objectives of present work include (but not limited) the following issues:

- The discharge monitoring and attainment of its stability in supersonic flow.
- Estimation of effect of near-surface electrical discharge on flow structure, pressure distribution on external compression surfaces and at inlet exit.
- Explore of the limits of regulation.
- Study of plasma impact on mass flow rate, pressure recovery coefficient and flow homogeneity.

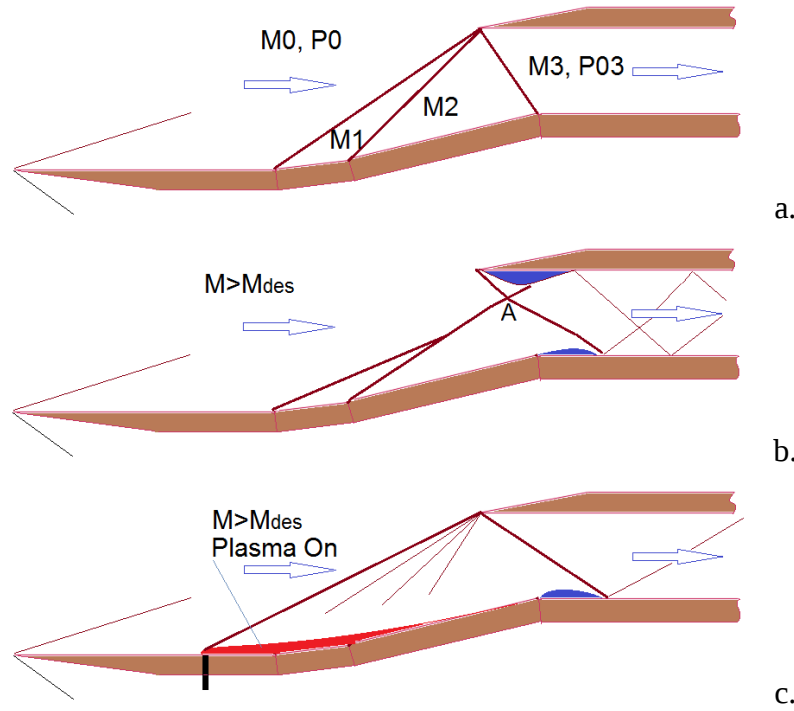


Fig.1. Draft scheme of experiment for demonstration of plasma steering effect in inlet.
a – “ideal” operation at $M=M_{des}$; b – typical SW structure at $M>M_{des}$;
c – plasma-based correction at $M>M_{des}$.

2. Test Facility Description

The experimental configuration is close to the geometry of a simple two-dimensional inlet of supersonic air-breathing engine. The test was performed in wind tunnel T-313 of ITAM SB RAS [19]. The model of the inlet with design Mach number 2 was installed in wind tunnel on bottom strut thus that it was possible to visualize flow in the area of the discharge (the first shock wave) and in the area of the channel intake/cowl leading edge. Incoming flow streamlines the model inlet with height $Z_0=60\text{mm}$ and width $Y_0=72\text{mm}$ at following free stream flow parameters: Mach number $M=2.0, 2.5$ and 3.0 ; static pressure $P_{st}=250\text{--}110\text{mBar}$; angle of attack $AoA=0\text{--}8\text{deg}$. The model ramp consists of two consequent planar wedges $\alpha_1=7^\circ$, $\alpha_2=14^\circ$ and divergent part. The electrodes' row includes 11 cooper tabs arranged by sequence cathode-anode-...-cathode and locates in $X=18\text{mm}$ upstream of the first wedge. All electrodes were flush-mounted and don't affect the flow themselves. The scheme and the photo of the model are shown in Fig.2.

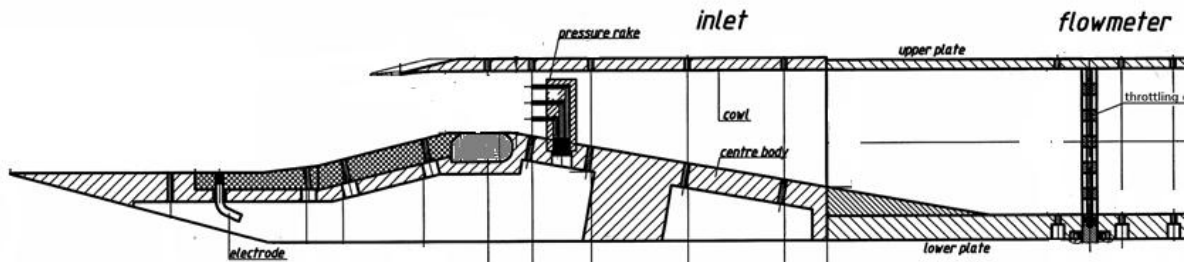


Fig.2. Draft scheme of the model

The disassembled model with row of electrodes and discharge photo are presented in Fig.3. Discharge photo was obtained under 1ms exposure is figured as well. The major properties of the near-surface quasi-DC electrical discharge were described in [17, 20]. The discharge appears in the form of oscillating plasma filaments. The individual filaments are blown down due to main flow at velocity a bit less than the core value. The frequency of oscillations depends on flow speed, inter-electrodes gap, and parameters of power supply. In the most cases this value was $F=10\text{-}50\text{kHz}$ under the experimental conditions. In this test series the total electrical power deposition was in a range $W_{pl}=2\text{-}10\text{kW}$. The measured maximal translational gas temperature in discharge zone was about $T_g \approx 3000\text{K}$ (it is a maximal value), so the V-T relaxation length is expected to be around a few centimeters [16]. Typical oscillograms of the discharge's voltage, current and recalculated power are shown in Fig.4.

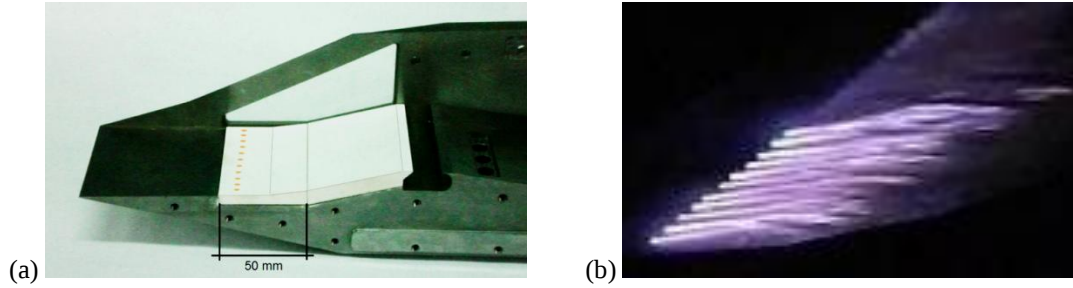


Fig.3. a – photo of disassembled model: the body is made of steel, white part is made of refractory ceramics with the copper electrodes; b – discharge photo gotten from right-top side, airflow direction is from left to right, the reflection from backward optical window is visible.

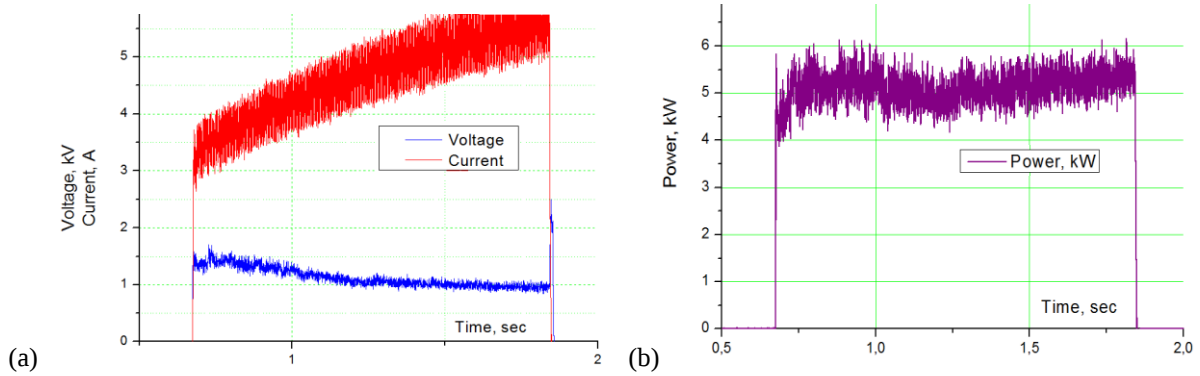


Fig.4. Typical oscillogram of current, voltage (a), and power (b) at M=2.5.

The measurements were focused on the following three issues: (1) change of the shock wave structure of supersonic flow within the compression ramp of the model; (2) pressure redistribution in vicinity of forebody wedges and cowl depending on plasma power and the test geometry; and (3) the flow parameters modification behind the interaction area. In accordance with these plan the electrical probing, schlieren visualization, camera capturing, and pressure measurements were performed in each test. The mass flow ratio of air through the model inlet was determined by means of measurements of static pressure in the throat measuring nozzles of flowmeter and total pressure at the exit of the model (not shown in Fig.2).

3. Experimental Data

The flow pattern in the inlet entrance, acquired by visualization technique, reveals that plasma generation forestream of the compression ramp leads to significant modification of the flow structure and location of oblique shock waves in respect of external compression surfaces. It was considered the shock wave angle and position accurate regulation due to electrical discharge power in wide range of parameters. Figures 5 and 6 demonstrate the schlieren images without plasma and at plasma “on” at Mach number $M=2.5$ and $M=3.0$ correspondingly. In the second image in Fig.5 the shock structure is close to design mode and excludes boundary layer separation on the cowl. At increasing of the kinetic power of the flow (Mach number in this particular case) the system requires more plasma power to be restored close to design mode. As it is shown in Fig.6 the shock structure can be properly regulated by means of the plasma power variation. Of course, if the discharge power exceeds some level the oblique shock is placed above the leading edge of the cowl.

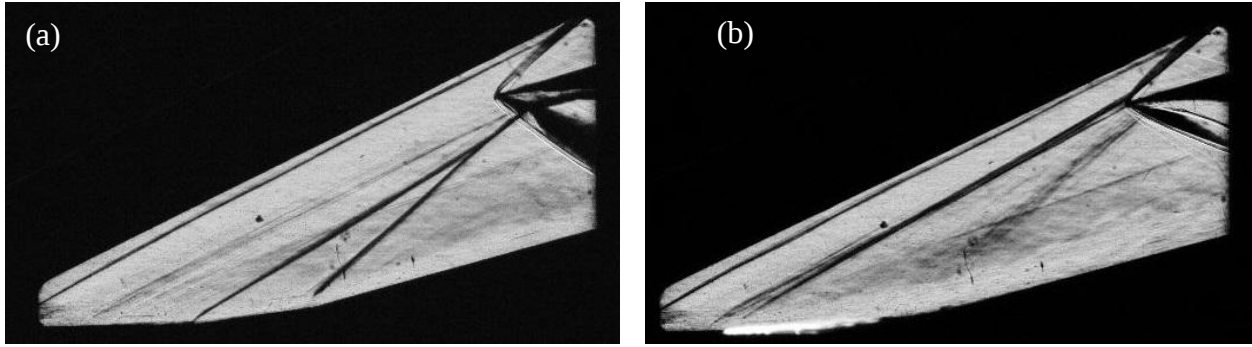


Fig.5. Schlieren visualization of shock structure at $M=2.5$, $AoA=0$
a – plasma off; b – plasma on, $W_{pl}=3.3kW$

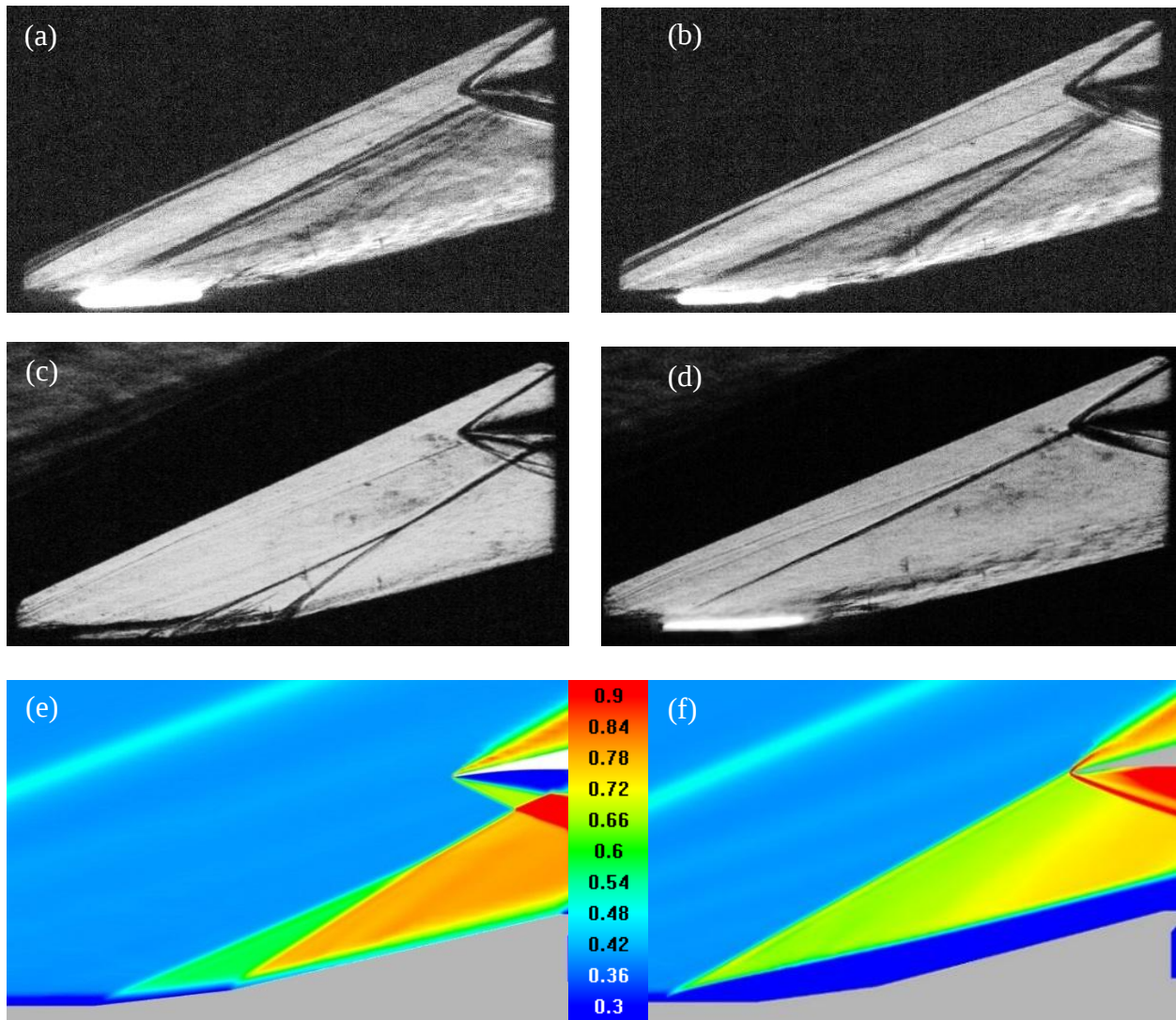


Fig.6. Schlieren visualization (a-d) and CFD results (e-f) at $M=3.0$, $AoA=0$
a – $W_{pl}=3.5kW$, b – $W_{pl}=6.5kW$, c – $W_{pl}=0$, d – $W_{pl}=8.5kW$;
e-f: density, kg/m^3 : e – $W_{heat}=0$, f – $W_{heat}=8.5kW$

An example of pressure record is shown in Fig.7a. Comparing to baseline the experiment under the plasma generation demonstrates a significant raise of static pressure right below the discharge area and decrease of the pressure on the ramp surfaces. At the same time the pressure recovery coefficient (PRC), measured in the inlet throat, has been modified weakly, typically increasing in a few per cent as it is shown in Fig.7b.

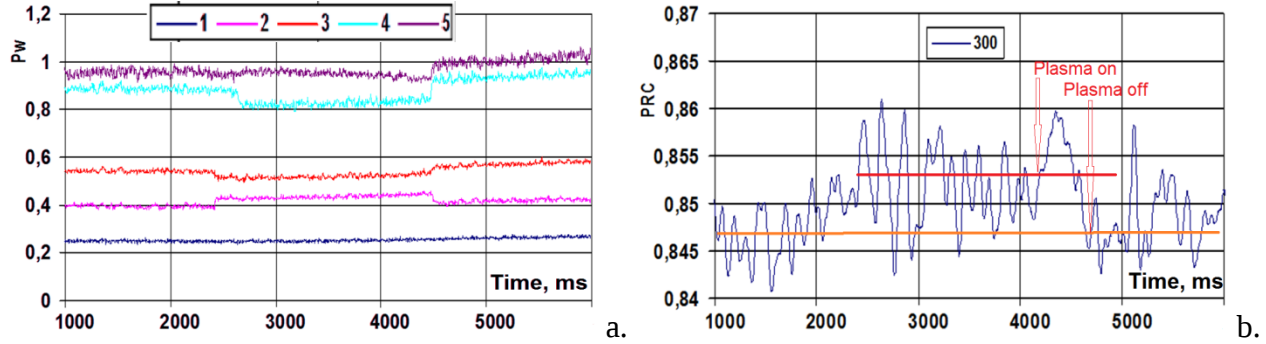


Fig.7. Pressure records(a) and pressure recovery coefficient (b).

Charts: 1 – upstream of the discharge, 2 – between the electrodes' row and the first wedge, 3 – on the first wedge, 4 – on the second wedge, 5 – in the throat.

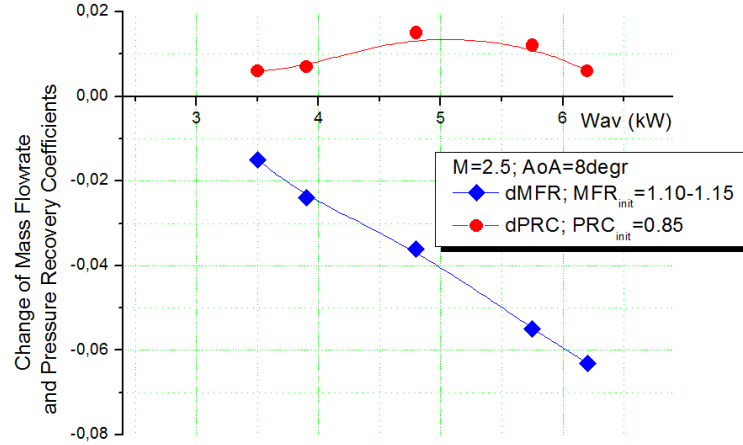


Fig.8. Modification of the mass flow ratio (MFR) and the pressure recovery coefficient (PRC) at $M=2.5$, $AoA=8\text{degr}$.

An influence of the discharge on the total pressure distribution in the model throat was examined to estimate an overall model inlet performance. It appeared in some rise of pressure values (up to 15%). The distribution of Pitot pressure obtained demonstrates that non-uniformity of the total pressure in the throat grows and weakly depends on discharge power that finally leads to some modification of the mass flow rate and growth of the total pressure recovery coefficient. Similar dependences have been obtained at variation of angle of attack from zero to $AoA=8\text{degr}$. As a result of shock-wave structure adjustment the 2-4% increasing of the total pressure recovery coefficient was typically observed. Figure 8 shows the result of measurements of mass flow ratio (MFR) and the pressure recovery coefficient (PRC) at $M=2.5$, $AoA=8\text{degr}$ as the function of the plasma power release. Such an operation mode was the closest to design regime among others tested. The decrease of the MFR is observed right because the main shock goes beside the cowl leading edge. It should be noted that the PRC increased in all tested operational modes. Appropriate data is presented in Table 1. Here all data is divided in three domains: design mode, near-design mode, and off-design mode, - in accordance with the Mach number, realized ahead of the discharge area (shown in Table as “local equivalent Mach number”). An “optimal” plasma power was chosen in each case, where the oblique shock was close to the cowl lip.

Table 1. Review of experimental data on MFR and PRC modification at plasma impact.

	M	AoA	Local M, equivalent	Modification of MFR	Modification of PRC
Design	2.0	0	2.0	reduction	increase
Near-Design	2.5	8	2.17	reduction	increase
	2.5	5	2.3	reduction	increase
Off-Design	2.5	0	2.5	increase	increase
	3.0	5	2.76	increase	increase
	3.0	0	3.0	increase	increase

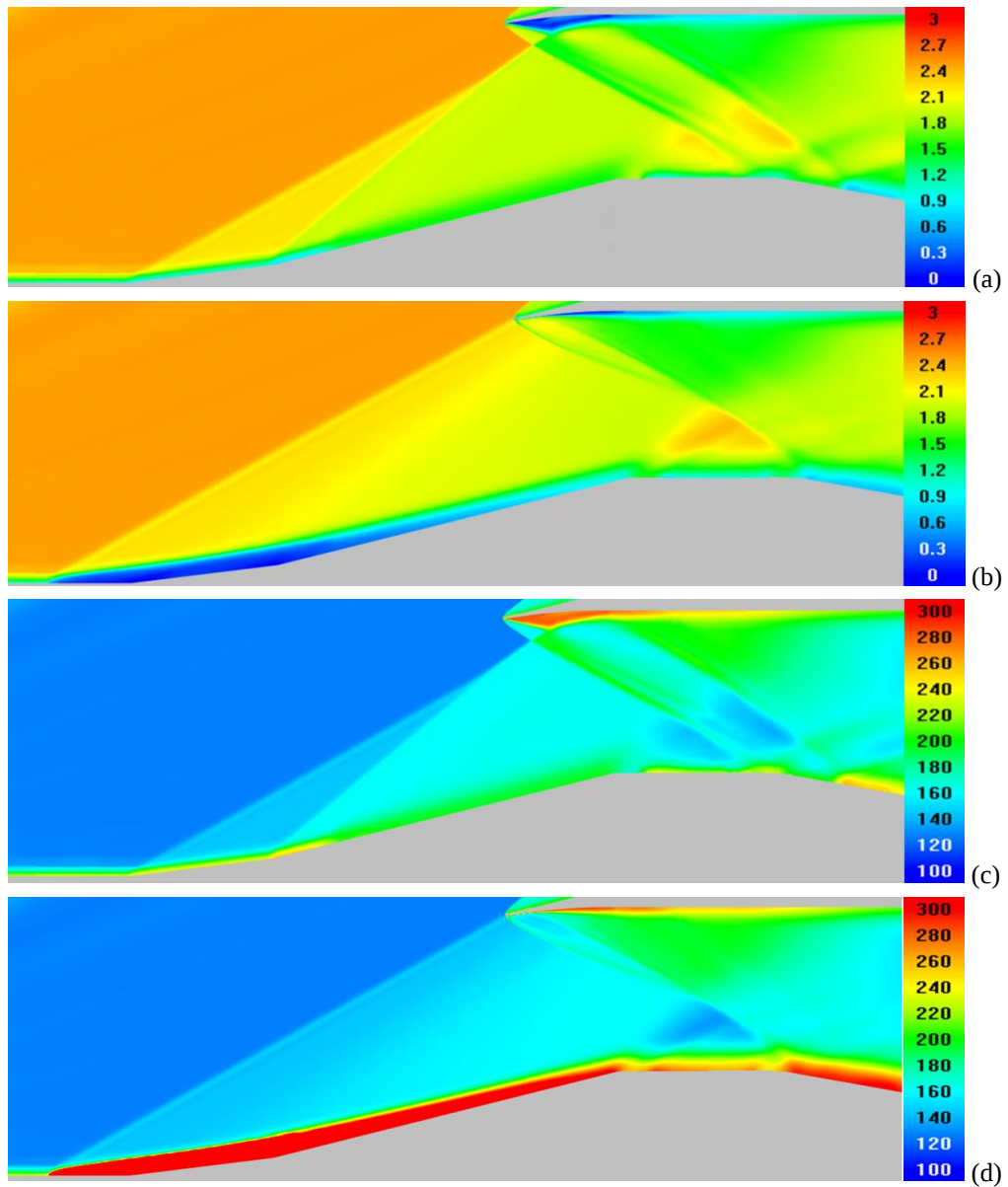


Fig. 9. Computational results for x2 enlarged model at $M=2.5$
Mach number – a, b; Temperature, (K) – c, d; heating off – a, c and heating on – b, d.

4. Computational Results

Numerical modeling of the flow in the inlet was performed in FlowVision™ software at several values of Mach number for both the presence and in absence of energy input simulating the discharge plasma in order to obtain more information about the flow parameters and to verify the experimental results. Computational simulation of undisturbed flow in experimental configuration was based on solution of 3D time-dependent Reynolds averaged Navier-Stokes equations with the utilization of the wide used SST-model of turbulence. Model of perfect gas was used at modeling undisturbed flow in the computational domain. Logarithm law velocity profile and adiabatic conditions were specified on all walls of the inlet. Direct current electric was simulated by introducing the volumetric heat source. Calculations at Mach numbers $M=2-3$ provided for full basic inlet model show that flow parameters vary insignificantly along the Z-axis. Influence of 3D-geometry is important only near sidewalls and electrodes. It was found that the periodic electrodes system produces a wave-like periodic structure of flow parameters near the electrodes. Consequently if we neglect the influence of the side wall we can use only a thin layer with one plasma filament. It can significantly reduce the computational domain and time of calculation. This will allow decreasing the time of calculation and improving the spatial resolution. Typically, 2×10^6 cells grid was used for full model calculations and 3×10^5 cells grid was used for thin 3 mm computational domain.

The comparison of the experimental data and the simulation results at $M=3$, $AoA=0$ is presented in Fig.6. In the most cases the results obtained by CFD calculation are in good agreement with the experimental data. A soft plasma wedge interacts with the ramp producing one strong shock at high and moderate level of electrical power release or a system of shocks (strong one from the plasma edge and a few weak shocks within the affected area in case of small power $W < 3 \text{ kW}$). An overall flow structure in the ramp changes very fast and under some conditions a more-less optimal shock wave pattern may be realized. The simplest criterion of such an optimization is the main shock position coinciding with the cowl lip.

The set of simulations with using $\times 2$ enlarged model at $M = 2.5$ was provided for investigation of plasma control scaling. Thin 3 mm computational domain was used for simulation. Power release at recalculation for full $\times 2$ enlarged model was 10 kW. Mesh with 295 000 cells and local adaptation to the shock waves was used. Results of simulation for enlarged model are shown in Figure 9. It is clearly seen that the plasma control works well: flow separation on the cowl lip is reduced and shock structure is more regular.

5. Conclusions

Numerous potential applications may be forecasted for plasma-based flow control technique. However it should be considered that in spite of large interest to this scientific field, a prospective of practical implementation is still ambiguous. One of important purposes of this work is to highlight the benefits and penalties of plasma approach for high-speed flow steering in inlet-like geometrical configuration.

In terms of Plasma Aerodynamics one of the most promising ideas for a practical interest is the plasma steering effect in high-speed inlet configuration. The work, shortly described in this paper, aims at providing a first feasibility assessment for a supersonic air inlet control based on near-surface electrical discharge and at fulfillment a mid-scale experiment. This work examined several aspects of the problem, namely, the effect of discharge on supersonic flow structure and parameters; control of flow parameters in inlet's configuration; reduction of pressure losses; etc.

Main results of the performed test of the model inlet with the surface discharge are listed below.

1. Shock waves position on compression surfaces and structure of flowfield in front of the supersonic inlet are intensely affected by near-surface quasi-DC electrical discharge. The particular effect appears in two-shock wave structure transformation to single-shock configuration with consequent artificial "soft" curved surface of isentropic compression. Location of the first shock root links up with the electrodes system; its intensity is a rising function of electrical power deposition.
2. The near-surface discharge generation modifies the pressure distribution on compression surfaces significantly. These changes appear in pressure elevation behind the electrode's row on plane part of wall and in pressure reduction on inclined surfaces of compression ramp. The variation of static pressure inside the model might be considered as negligible in the most cases.
3. The electrical discharge influences the value of mass flow rate through the model. If the operation parameters are close to design mode, the plasma generation leads to decrease of mass flow rate due to main shock lifting above the

cowl leading edge. In off-design mode the plasma generation causes some increase of MFR at moderate power deposition. The effect observed is also in MFR reduction if the discharge power exceeds some value.

4. In the most cases the plasma deposition leads to some increase of the pressure recovery coefficient due to reduction of pressure loss in shock waves and replacement of them with a more isentropic compression.

5. At discharge power higher than $W=6\text{kW}$ the effect of unsteady separation takes place near inner corners of the compression ramp. It causes in increasing of the discharge length and in significant rising of boundary layer displacement thickness. Estimation, made by the data of schlieren visualization, gives thickness of this layer 2 and more times higher than the boundary layer without the discharge.

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