Influence of Energy Input on the Flow Past Hypersonic Aircraft X-43

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Abstract. This paper deals with a numerical study of the influence of energy sources on the flow past hypersonic aircraft X-43. Flight mode with M = 6 and angle of attack α = 0°, 4° with energy deposition in areas around various parts of HA was considered. It is shown that energy input in front of the bow of the HA leads to a significant weakening of the bow shock wave and an increase in aerodynamic efficiency of the vehicle. The results of studies on the impact of energy input in the scramjet intake are also presented.

1. Introduction
In recent decades, research on development of hypersonic aircrafts (HA) using scramjets (supersonic combusting ramjet) for prolonged flight in the atmosphere has greatly intensified. Operating principle of scramjet is similar to that of a conventional ramjet, in which air flow entering through the intake is compressed due to the special shape of the aircraft and is decelerated to subsonic speed. In the ramjet for M > 6, deceleration of the incoming air flow to subsonic speeds leads to the values of temperature and pressure that are problematic because of the restrictions imposed by the thermal strength of the engine combustion chamber structural materials. The airflow in a scramjet is only partially decelerated and remains supersonic throughout the entire engine, therefore temperatures within are kept at a tolerable level and the engine can be used at flight speeds of M > 6. The positive results obtained during the testing of unmanned aircraft X-43A (figure 1) in 2004 within the framework of NASA Hyper-X program [1-4] show promise in the use of scramjet at flight speeds of M > 6.

![Figure 1. Experimental unmanned hypersonic flying vehicle X-43](image_url)
The development of modern aircrafts requires the search and development of new effective tools to manage the characteristics of the gas flow in the vicinity of the aircraft’s surface, control the transfer of heat and mass transfer in the boundary layer, reduce surface friction, delay the laminar-turbulent transition, control flow separation, reduce the ignition time and manage the process of combustion of fuel in a ramjet and scramjet engines.

One of the methods for improving the aerodynamic characteristics of prospective aircraft is a controlled action on the oncoming flow. It can be performed in various ways, in particular by using energy input localized in a small closed region. The possibility of remote energy input into a supersonic flow is confirmed in many experiments [5–10]. The high-temperature wake with reduced values of Mach number, total pressure, and velocity is formed behind the energy source, which enables us to vary the flow regime. If the energy source and body are of comparable sizes then the flow around the body is quasi-uniform and drag can be reduced by changing straightforwardly the parameters of the oncoming flow. This oncoming flow requires large energy expense and is impractical. However, energy input even in a relatively small space region can lead to restructure of the bow shock-wave ahead of the body. This method of drag reduction is rather efficient. Power expenses on this energy influence are substantially smaller than the gain in propulsion power from lower drag.

To date, a large amount of numerical research in this field has been performed [11-14]. However, in most of these works considered flow regimes are for moderate Mach numbers. This work is focused on numerical study of the impact of energy input on the flow past hypersonic aircraft X-43 at M = 6, characteristic for long atmospheric flight hypersonic aircrafts.

2. Problem Statement

The results presented below were obtained in the framework of the unsteady Reynolds averaged Navier–Stokes equations (URANS) for a viscous compressible gas with the Spalart–Allmaras turbulence model. For the simulation of energy input URANS system was supplemented with a source term in the conservation-of-energy equation. A detailed description of the mathematical model, numerical methods and program complex used in this work, is given in [15, 16].

The problem considered is the hypersonic flow past hypersonic aircraft X-43. Conditions of the incoming flow were consistent with the height h = 30 km [17]. Calculations were performed for the Mach number M = 6 and angles of attack $\alpha = 0^\circ$ and $4^\circ$. The Reynolds number was $Re = 2.0 \times 10^6 \text{ m}^{-1}$, pressure and density of the incoming flow $p_\infty = 1200 \text{ Pa}$ and $\rho_\infty = 1.84 \times 10^{-3} \text{ kg/m}^3$, respectively.

Due to the symmetry conditions the calculations were carried out for half of the X-43 model. Calculation area was the half of the cone, in the center of which the device was located. A hexagonal block-structured grid with 8 991 802 elements was used. Detailed description of the grid model used can be found in [18].

For $\alpha = 0^\circ$ the energy input location was $x \in [-3.74; -3.70], y \in [0.12; 0.13], z \in [0.; 0.2]$ (figure 2). The total power of energy input was $Q = 6.8\%N$ where $N = F_U$ – power necessary to overcome the drag for the undisturbed flow. We assume that energy input is stationary and spatially homogeneous in its area.

![Figure 2. Location of energy input area in front of the nose.](image-url)
For the purpose of modeling the fuel combustion process in the engine, calculations with the energy input inside the engine for the angle of attack $\alpha = 0^\circ$ were made (figure 3).

![Figure 3. Location of energy input area in the engine.](image)

The amount of energy deposited was determined by the following relationship:

$$q_{\text{max}} = \frac{I_\infty f_{O_2} H_U}{L V_{\text{energ}}}$$

where $I_\infty$ [kg/s] – air mass flow through the inlet, $f_{O_2} = 0.2315$ – ratio by mass of oxygen in the air, $H_U = 119.54$ MJ/kg – heat of combustion (hydrogen), $L = 34.5$ – stoichiometric air-to-fuel ratio (hydrogen), $V_{\text{energ}} = 0.00192$ m$^3$ – volume of the area of energy input. Thus $q_{\text{max}}$ is the highest possible (within the framework of this approach) amount of the energy released for this fuel.

3. **Numerical simulation results**

3.1. **The case of undisturbed flow, effect of angle of attack**
First, let’s consider an undisturbed flow (figures 4 and 5).

![Figure 4. Pressure distribution in the case of undisturbed flow, slice $z = 0.01$, $\alpha = 0^\circ$.](image)
As shown in figures 4 and 5, there is a bow shock and the shock wave from the wedge at the bottom of the fuselage in front of the air intake. X-43 uses the fuselage nose part to form the shock in front of the intake. The airflow in a scramjet is only partially decelerated and remains supersonic throughout the entire engine. The main flow features inside the engine are the multiple reflected shocks (figure 6). The rear surface of the body after the scramjet plays a role of a nozzle and is intended to accelerate a supersonic gas flow coming from the engine.

Let’s consider the effect of the angle of attack. Figure 7 shows pressure distribution with the angle of attack $\alpha = 4^\circ$. 

![Figure 5. Pressure distribution on the model surface, slice $z = 0.01$, $x = 1.65$, $\alpha = 0^\circ$.](image)

![Figure 6. Flow in the engine, pressure distribution in the case of undisturbed flow, slice $z = 0.01$, $\alpha = 0^\circ$.](image)
In general, the current structure remains the same. The differences lie in the fact that by increasing the angle of attack rarefaction occurs above the upper surface and pressure increases on the lower surface. The last point, in turn, increases the pressure of the flow entering the engine, see table 1.

Table 1. Parameters of the flow in the air intake in the case of undisturbed flow, $M = 6$, $P_{0,\infty} = 1578.88$, drag and lift coefficients $C_D$ and $C_L$, aerodynamic quality $K$.

| $\alpha$ | Air flow ($\rho u$) | $P_{0,\text{in}}$ | $P_{0,\text{out}}$ | $(P_{0,\text{in}} - P_{0,\text{out}})/P_{0,\text{in}}$ | $C_D$ | $C_L$ | $K$  |
|----------|---------------------|--------------------|--------------------|-------------------------------------------------|--------|--------|------|
| 0        | 0.239               | 422.11             | 317.88             | 24.69%                                          | 0.01633| 0.00407| 0.25 |
| 4        | 0.372               | 610.42             | 484.01             | 20.71%                                          | 0.02311| 0.05441| 2.353|

Also, due to the angle of attack, the shock wave comes closer to the front edge of the air intake, which allows it to capture a larger part of the flow. It is obvious that an increase in the angle of attack also increases lift.

Comparison of the obtained drag and lift coefficients with experimental data [4] is shown in figure 8.

3.2. Impact of the energy input in front of the nose

Let’s consider results obtained for energy input in front of the nose part of the model.

Energy input ahead of the body substantially changes the flow structure (figure 9). Shock waves issue from the energy input region. The front of the bow shock wave is changed by the wake formed behind the energy input region. In the space between the energy input region and the nose there is formed an area with lower pressure in comparison with the oncoming flow. The weakening of the bow shock wave leads to a decrease in drag (table 2) which in turn raises the aerodynamic quality. The angle of the bow shock wave is also changed, so now it comes closer to the front edge of the air intake, which allows it to capture a larger part of the flow. Since energy input reduces the intensity of the bow shock wave, speed and, therefore, stagnation pressure, of the flow entering the air intake is higher than in the case without energy input.
Figure 8. Drag and lift coefficients, comparison with experimental data.

Figure 9. Pressure distribution with energy input in front of the bow, center, slice \( z = 0.01 \), \( \alpha = 0^\circ \).

Table 2. Parameters of the flow in the air intake with energy input in front of the bow, \( M = 6 \), \( P_0 = 1578.88 \), drag and lift coefficients \( C_D \) and \( C_L \), aerodynamic quality \( K \).

| \( Q \) | Air flow ( \( \rho u \) ) | \( P_{0,\text{in}} \) | \( P_{0,\text{out}} \) | \( (P_{0,\text{in}} - P_{0,\text{out}})/P_{0,\text{in}} \) | \( C_D \) | \( C_L \) | \( K \) |
|---|---|---|---|---|---|---|---|
| 0 | 0.239 | 422.11 | 317.88 | 24.69% | 0.01633 | 0.00407 | 0.25 |
| 6.8\%N | 0.294 | 627.95 | 421.25 | 32.92% | 0.01431 | 0.00382 | 0.266 |

Influence of the plasma region is not limited to a decrease in the bow shock wave intensity. The parameters of the boundary layer near the model surface are also changed (figure 10).
3.3. **Impact of the energy input inside the engine**

Let’s consider results obtained with energy input in the engine for $\alpha = 0^\circ$ and $q = q_{\text{max}}$.

As shown on Figures 11, 12 and Table 3, energy input in this way significantly affects the structure of the flow in the air intake. Shock-wave structure moves to the inlet cross-section due to the counter pressure created by energy input, thus increasing the intensity of the incident shock from the bottom wall of the intake. The area of separation located on the upper wall of the air intake significantly increases in size and under the influence of the counter pressure moves to the inlet section. Considering the integral characteristics of the flow in the engine (table. 3), it can be concluded that we get close to off-design operating mode of the air intake. Further research on this topic is scheduled to take place in subsequent papers.

| $q$   | $P_{o\text{in}}$ | $P_{o\text{out}}$ | $(P_{o\text{in}}- P_{o\text{out}})/P_{o\text{in}}$ | $C_D$   | $C_L$   |
|-------|------------------|-------------------|-----------------------------------------------|---------|---------|
| 0     | 422.11           | 317.88            | 24.69%                                        | 0.01633 | 0.00407 |
| $q_{\text{max}}$ | 330.84           | 130.18            | 60.65%                                        | 0.01457 | 0.01064 |
Figure 12. Flow in the engine, Mach number distribution in the case of undisturbed flow (left) and with energy input in the engine (right), slice $z = 0.01$, $\alpha = 0^\circ$.

4. Conclusions

The influence of energy input on the aerodynamic characteristics of the aircraft X-43A for various angles of attack was investigated. It is shown that energy input in front of the nose leads to a decrease in drag. For the purpose of modeling the fuel combustion process in the engine, calculations with the energy input inside the engine were made, off-design operating mode of the air intake was obtained.

Acknowledgments

This work was supported by the Russian Foundation for Basic Research project No. 16-31-00399.

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