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Weakly ionized plasmas in aerospace applications

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Abstract

This paper is an overview of the activity and state-of-the-art in the field of plasma aerospace applications. Both experimental results and theoretical ideas are analysed. Principal attention is focused on understanding the physical mechanisms of the plasma effect on hypersonic aerodynamics. In particular, it is shown that drag reduction can be achieved using a proper distribution of heat sources around a flying body. Estimates of the energetic efficiency of the thermal mechanism of aerodynamic drag reduction are presented. The non-thermal effect caused by the interaction of a plasma flow with a magnetic field is also analysed. Specifically, it is shown that appropriate spatial distribution of volumetric forces around a hypersonic body allows for complete elimination of shock wave generation. It should be noted that in an ideal case, shock waves could be eliminated without energy consumption.

1. Introduction

The main problems of hypersonic flight in an atmosphere are associated with generation of shock waves resulting in high mechanical and thermal load on elements of an aircraft construction, sharp growth of drag force, and reduction of ramjet efficiency. To reduce loads on the main components of supersonic objects (aircrafts and rockets) and their aerodynamic drag, these components are shaped as cones or wedges with small apex angles. Nevertheless, at high flight velocities the drag of separate aircraft components and the loads on them becomes too high. This leads to fuel overrun, limits aircraft velocity, and restricts commercial capacity of modern aircrafts. Progress in aviation made in the recent decades resulted in the impossibility to further reduce this drag using traditional methods of aircraft shape optimization. Therefore, active search of basically new ways to fight the shock-wave drag of hypersonic aircraft was undertaken in the last two decades, first in the Soviet Union and then in the United States of America. Within this search, particular attention was paid to possible modification of media surrounding an aircraft.

Specifically, it has been found in experiments that gas-discharge plasma can modify propagation of shock waves considerably. A reduction of aerodynamic drag has also been detected, which stimulated active discussion among researchers of the nature of the observed effects. Numerous experiments have been carried out in different gases and using different sources of plasma such as beams of fast electrons, DC, RF, microwave and optical discharges. Besides ionization, an external magnetic field was applied to systems in order to control a hypersonic flow using volumetric Ampère forces and thereby to optimize shocks configuration in an air inlet of a ramjet. Recently, intense discussion of the use of gas discharges for fast ignition of fuel mixture in the ramjet combustion chamber was also initiated in the research community.

This paper presents an overview of the activity and state-of-the-art in the field of plasma aerospace applications. All directions of the research are analysed, including reduction of aerodynamic drag, optimization of ramjet operation, and mitigation of sonic boom. The main attention is given to understanding the physical mechanisms of the plasma effect on hypersonic aerodynamics. In particular, drag reduction is shown to be possible if a gas flow is properly heated ahead of a flying body. The energetic efficiency of such a thermal mechanism of aerodynamic drag reduction is estimated and conditions of possible energy gain are determined. The non-thermal effect, caused by the interaction of a plasma flow with a magnetic field, is analysed in the context of both possible ramjet optimization and complete elimination of shock generation at hypersonic flight. Problems of plasma aerospace applications and their prospects are discussed.

2. Abnormal aerodynamic effects in a quasi-homogeneous plasma

Experimental study of aerodynamics in weakly ionized plasma was started in 1959 when a special ballistic stand was installed at the Ioffe Physico-Technical Institute, USSR Academy of Science, St. Petersburg [1]. Configuration of shocks generated by a body moving with supersonic velocity through a large volume of gas-discharge plasma was investigated in early experiments. The shock shape was found to differ in plasma and neutral gas at the same temperature and velocity of the body. In principle, the observed difference could be ascribed to a higher sonic velocity in plasma, but the physical mechanism of the effect was unclear. The interest in these experiments increased considerably in the 1980s [2–16] and has not weakened until today [17–32]. Along with the ballistic experiments [3, 5], an intense study of shock tube experiments where a planar shock wave was propagated through a discharge plasma was undertaken [6–20]. The main effects observed in these experiments can be summarized as follows. As the shock is moving through the plasma, its velocity and thickness increase whereas its amplitude decreases. Similar effects were observed in air, different molecular (H_2, N_2, CO_2) and rare (Ar, Ne, Xe, He) gases, in plasma of DC and RF discharges, independent of the direction of discharge electric current with respect to the direction of shock propagation.

It is important to note that all these abnormal properties were observed under conditions of a very weak degree of gas ionization (of about 10^{-6} or less). The thermal mechanism of discharge influence on shocks seems reasonable in this case. Actually, strong inhomogeneous heating of gas is possible even for weak ionization in the discharge. At the same time, shock wave propagation is known to be sensitive to gas temperature and its spatial non-uniformity. Nevertheless, from the very beginning there were a lot of controversial speculations around the problem. A variety of hypotheses spread, starting with the influence of atom and molecules excitation in a discharge up to a specific influence of charge species on the gas equation of state. A great number of recent publications are concerned with analysis and numerical simulation of shock propagation through the gas-discharge plasma [18–28]. Detailed calculations showed [19–23] that complicated structures of shocks in a gas-discharge plasma are associated with spatial inhomogeneity of energy deposition more probably than with any other effects mentioned above. This conclusion has eventually been confirmed in recent experiments carried out at the Ohio State University [18] where independent control of gas temperature and plasma density was provided.

More detailed study of ballistic experiments allowed also for revealing a reduction of aerodynamic drag force $F_{\rm d}$ for bodies moving in plasma [3, 5]. It was found that not only the drag force but also the specific drag coefficient $C_{\rm d} = 2F_{\rm d}/(\rho U^2 S_{\perp})$ changes in plasma (here ρ is gas density, U is the velocity of a moving body, $S_{\perp}$ is the area of the body cross-section). Therefore, the results could not be attributed solely to the reduction in gas density caused by its isobaric heating in a discharge. Again, the effect was observed in different gases and in different types of discharge. However, depending on experimental conditions, the authors stated both an increase and a decrease in the value of the drag coefficient. There was even more uncertainty with the physical mechanism of the observed drag modification as compared to the phenomenon of shock modification. Numerical simulations demonstrated that an enhanced rate of V–T relaxation process at the front of the bow shock could decrease the drag coefficient [4, 33] at supersonic and transonic velocity of a moving body. However, this effect can occur in molecular (not in rare) gas only and it is completely impossible in the case of essentially subsonic velocity of a body. At the same time, pronounced reduction of the drag coefficient was observed at subsonic velocity, whereas at high velocities in air an increase in the drag coefficients was detected in some experiments [5]. It seems that a more probable factor here is the influence of the moving body on the parameters of the gas-discharge plasma itself (i.e. distribution of the intensity of the electric field and the current density in it). The result of this influence may be redistribution of the Ohmic heating power around the body. The consequences of such a redistribution depend on a multitude of factors, such as body shape and velocity, and configuration of discharge system. This can explain to some extent a variety of experimental results obtained in this field.

The latter hypothesis has been confirmed in recent experiments for both subsonic [34] and supersonic [32] velocities. Actually, at the subsonic velocity, the phenomenon of flow separation from the body surface is known to determine mainly the drag force. It was shown in experiments [34] that local energy deposition influences the formed vortex structure of the flow, thus reducing the drag coefficient. On the other hand, at supersonic velocity the shocks are known to contribute to the drag considerably. Detailed experimental investigations [32] demonstrated that the modification of bow shock reported earlier is caused by temperature rise in the boundary layers heated by the discharge.

3. Aerodynamics of supersonic flight under local ionization and heating of the surrounding air

From a practical point of view, an important question is energy cost of drag reduction that can be achieved using ionization of the surrounding air. This cost was too high in the ballistic experiments described in the previous section, since the gas-discharge plasma was produced in very large volumes. Obviously, the energy gain (if any) is possible only in the case of using local ionization of the air surrounding the moving body. This consideration stimulated a series of wind tunnel experiments [25, 34–45] where different plasma generators were tested. Most experiments were carried out using different types of plasmatrons generating a counter plasma jet (with respect to the outside gas flow) [35–40] or an electric discharge between the electrodes placed at the nose part of a body [41, 42]. But in a few experiments a microwave

[25, 45] or an optical [43, 44] discharge was used to produce plasma ahead of a body. Typically, the test models were shaped as a truncated cone (in the nose part) combined with a cylinder. However, models with more complicated shapes containing different combinations of cone, semi-sphere, ellipsoid, and cylinder were also under investigation. A joint team from Russia and the USA carried out their experiments with an exact 1/6-scale model of the nose part of the F-15 flight test laboratory and with various on-board plasma generators. In the majority of the experiments, particular attention was paid not only to measurements of the aerodynamic drag variation caused by operation of a plasma generator but also to determination of energy efficiency of the drag reduction observed. By definition the following expression was used to calculate the energy efficiency: $\eta = V_0 \Delta F_\mathrm{d}/W_\mathrm{p}$, where V_0 is the velocity of an unperturbed gas flow in a wind tunnel, ΔF_d denotes reduction of the drag force, and W_p stands for the power of the plasma generator. The main results of this experimental investigation can be summarized as follows:

(a) The reduction of drag is possible in the case of local ionization of the air surrounding the model.
(b) The drag reduction can be achieved with energy gain ($\eta > 1$).
(c) There are optimal conditions for the drag reduction (optimal power of the plasma generator for a given model shape and the Mach number M_0 of an unperturbed external flow, or an optimal value of the Mach number for a given model shape and a power of the plasma generator).
(d) The effect of drag reduction and respective energy gain is more pronounced in the case of a relatively high value of the model drag coefficient.

Maximum relative reduction in the drag coefficient (up to 45%) was found in experiments with a counter plasma jet [36, 37] for the Mach number $M_0 = 2$. In these experiments the model comprised a truncated cone with apex angle 60˚ and a cylinder with diameter 60 mm; the power of the plasma generator was 4–6 kW. However, the energy efficiency of the drag reduction was not measured in these experiments. This parameter was measured in similar experiments with erosive plasma jet generator [35] where the maximum value of $\eta = 200\%$ was found at $M_0 \approx 1.5$, with the corresponding reduction in the drag equal to 14%. It should be noted that the force of jet response was not taken into account in these experiments. In experiments with ionization of the external airflow, the maximum value of the drag reduction achieved 13% with energy efficiency 150% at $M_0 = 4$ and input discharge power 0.43 kW [41]. The highest value of energy gain (up to 320%) was found in experiments with the model of F-15 at $M_0 = 2$ [42]. However, the total drag reduction was relatively small (about 5–6%) in this case.

The above encouraging results of experiments stimulated intensive theoretical consideration of the problem [33, 38–40, 48–54]. Airflow perturbations caused by a counter gas jet were simulated numerically in [38–40]. By analysing the simulation results, one can come to a conclusion that there is no specific plasma effect in the observed drag reduction. The latter is determined exclusively by the airflow perturbations. The conclusion was also confirmed in experiments with the injection of a cold (nonionized) counter gas jet [46, 47]. Direct simulation of the discharge effect on the aerodynamic drag is still a distant prospect since it demands allowance for a lot of phenomena involved in the process, e.g. heating of electrons, ionization, plasma influence on electromagnetic field, energy exchange between electrons and molecules, gas flow around a body of complex shape, etc. Therefore, the key theoretical issue is getting an insight into the main physical mechanism responsible for the drag reduction in this case. There is no controversy in this field of research today. All the authors agree that the observed effects are thermal in nature and are caused by reduction of gas density during its heating in discharge. Consequently, they simulated the airflow perturbations caused by a given source of heat [33, 48–54].

Results of such simulations allow one to explain the main experimental peculiarities listed above, including the possibility of energy gain and existence of optimal conditions. Specifically, the authors of [50] have shown that even in the case of a complicated shape of the model (the nose part of F-15), it is possible to achieve quantitative agreement with the experimental results. The numerical simulations have also given additional information about optimal position [48] and configuration [49] of the heat source. Special attention was focused on the energy efficiency of reducing the aerodynamic drag by the methods of heat effect on an incident flow of gas [33, 51–54]. The authors of the majority of these papers (excluding [33]) conclude that gas heating is reasonable in terms of consumed energy only at high values of the Mach number ($M_0 > M_{\rm min}$, which depends on the shape of the body in the flow) or in the case of poorly streamlined bodies. This conclusion is most clearly formulated in [52] where a supersonic flow around a cone and a wedge was studied and, for optimal configuration of the heat source the energy efficiency, was found to be

$$\eta \approx \frac{\alpha^2 M_0^2}{4}, \tag{1}$$

where α is a total apex angle of the cone or wedge in the flow. This means that the use of gas heating is energetically reasonable only under the conditions, when the motion of the body is accompanied with generation of strong shock waves (with the pressure shock at the front exceeding the unperturbed pressure of the gas). In [54] it was shown also that under these conditions ($\alpha = 20^\circ \cong 0.35$, $M_0 = 10$) one can not only achieve the values of $\eta \sim 5$ while reducing the drag force by 50%, but also reduce the heat loads on the body by lowering the gas temperature at the body surface using the drop in SW intensity. The authors of [33] simulated the flows around the NASA-0012 numerically and found that the energy efficiency of local heat sources situated directly at the body surface can reach 4 in the transonic flow regime ($M_0 = 0.8$–0.9). Such a high efficiency is achieved when the distribution of heat sources over the body surface is optimized relative to the local supersonic regions of the flow. When such an optimal distribution of heat sources is disturbed, the opposite effect, i.e. augmentation of the drag force, can take place.

Based on results of the numerical simulations carried out in [48, 49] one can infer that the optimal regime of drag reduction corresponds to isobaric gas heating ahead of the body. Therefore, in the case of supersonic flight, one can estimate the energy efficiency of the drag reduction using very simple notions. Actually, the force of aerodynamic drag of the body with its transverse cross-section area $S_\perp$ can be written down in the following form $F_{\rm d} = C_{\rm d} S_\perp \rho_{\rm g} V_{\rm g}^2/2$, where $\rho_{\rm g}$ and $V_{\rm g}$ are the density and the velocity of the gas surrounding the body, respectively. Under conditions of isobaric heating there is no noticeable change in the velocity of the supersonic gas flow with respect to the body, i.e. $V_{\rm g} \cong V_0$. The reduction of the drag is determined mainly by the reduction in the gas density and by the increase both in gas temperature and cross-section of the gas current tube that goes through the heat source (the latter effects contribute to reduction of the drag coefficient):

$$\rho_0 c_p T_0 V_0 S_0 \frac{\rho_0 - \rho_{\rm g}}{\rho_{\rm g}} = \rho_0 c_p V_0 S_0 (T_{\rm g} - T_0) = Q, \qquad S_{\rm g} = S_0 \frac{\rho_0}{\rho_{\rm g}}, \tag{2}$$

where ρ, T stand for the density and temperature of the gas, the indices ‘0’ and ‘g’ correspond to unperturbed parameters of the gas and its parameters after passing through the heat source, respectively, c_p is the specific heat capacity of gas under constant pressure, S_0 is the cross-section area of the heat source, Q stands for total power of the latter, and $S_{\rm g}$ is the cross-section area of a hot gas flow. When $S_{\rm g} \gg S_\perp$, it is reasonable to assume that the drag coefficient of the body does not change considerably. Consequently, a reduction of the drag force can be estimated as follows:

$$\Delta F_{\mathrm{d}} = \frac{C_{\mathrm{d}}(\rho_0 - \rho_{\mathrm{g}})V_0^2 S_{\perp}}{2}. \tag{3}$$

Therefore, the energy efficiency η is determined by the expression

$$\eta = \frac{\Delta F_{\mathrm{d}} V_0}{Q} = \frac{C_{\mathrm{d}} V_0^2 S_{\perp}}{2c_p T_0 S_{\mathrm{g}}} = \frac{\gamma - 1}{2}\frac{C_{\mathrm{d}} M_0^2 S_{\perp}}{S_{\mathrm{g}}}, \tag{4}$$

where γ stands for the adiabatic exponent of gas. As is clear from equation (4), the energy gain is possible only when $C_{\mathrm{d}} M_0^2 > 1$, that is consistent with equation (1).

Within the above concept one can treat the other results of [49] (that are related to the optimal position of the heat source, its optimal configuration and the effect of saturation of drag reduction as the heating power grows) as the conditions of isobaric heating of the supersonic gas flow. Specifically, the conditions of optimal position and configuration of the heat source can be represented as $L_0 > M_0 R_{\perp}$, where L_0 is the characteristic size of the heat source in the longitudinal direction with respect to the gas flow, $R_{\perp}$ is the transverse dimension of the body. These are the conditions under which a sonic wave can exit from the heat release region while the gas is passing through this region. In turn, the limitation of the total heat power $Q < \gamma p_0 L_0^2 R_{\perp}/(\gamma - 1)V_0$ is dictated by the requirement of weak heating of gas during removal of sonic perturbations from the heat release region.

A more complicated issue is the energy efficiency of using local heating for reducing the drag at transonic and subsonic flight velocities. According to the above estimation by equation (4), reducing the density of the entire gas flow incident on the body is not energetically reasonable. However, using local heating in the direct neighbourhood of the body surface one can change the configuration of the flow around the body, thus reducing the aerodynamic drag coefficient C_{d}; that was demonstrated in experiments [34] and in the corresponding calculations [33]. High energy efficiency is possible in this case, but determination of optimal energy deposition regions requires detailed numerical simulation or experimental investigation for each specific shape of the body.

4. Flow control using volumetric forces in plasma

As was mentioned above, hypersonic velocities of flight in an atmosphere give rise to serious difficulties in operation of air jet engines. We can distinguish two types of such difficulties. The first of them are caused by very high specific energy of the gas flow that enters the engine. Strong braking of such a flow ahead of the combustion chamber is unacceptable because this results in a too high temperature of gas. At the same time, without strong braking, this flow brings the fuel out of the combustion chamber very rapidly. As a result, the fuel has no time to burn inside the engine. Problems of the second type are associated with the need to reduce losses of the free energy of the flow, which are determined by shock waves in the inlet part of the engine diffuser. Optimized configuration of the diffuser is specific for each Mach number of the incoming gas flow. The off-design regime of ramjet operation takes place outside a relatively narrow range around this Mach number, which means an appreciable drop in efficiency.

At first sight, the methods based on gas ionization are not applicable for solution of the ramjet problems because any additional heating seems to be undesirable. However, by applying an appropriate electromagnetic field it is possible not only to heat plasma, but also to affect it by means of volumetric (Ampère) forces. Such forces can be used for additional (non-thermal) control of gas flow. On the other hand, when a conducting medium moves in a magnetic field, an electromotive force is induced in it. This effect can be used to provide aircraft with electric energy required both to produce plasma and to generate electromagnetic fields. The above MHD principles for improving operation of a hypersonic jet engine are realized in two steps:

(a) take off a considerable share of the kinetic energy of the gas flow incident on the engine and convert it into the electric energy;
(b) bring the kinetic energy back to the gas after the flow has passed through the combustion chamber, thus counterbalancing the losses of the flow momentum that occurred at the previous stage.

These steps form the basis of the AJAX concept [55, 56]. Active research in this field has begun only recently. There are only a few publications presenting results of experimental investigations [57, 58]. An influence of the Ampère forces on a shock wave structure inside a diffuser was demonstrated in [57], whereas in [58] a considerable deceleration of a hypersonic flow of weakly ionized plasma was obtained with partial conversion of the kinetic energy of the flow into the electric energy. Nevertheless, there are a lot of papers claiming for the optimistic prospects on the basis of numerical simulations [55–57, 59–61].

A desirable regime of MHD interaction can be understood on an example of a simple model. The main contribution to the volumetric forces, under the conditions typical for aerodynamics, is determined by interaction of electric currents with a magnetic field (Ampère force): $\vec{f} = (1/c)[\vec{j} \times \vec{B}]$, where $\vec{f}$ is the vector of the force acting on a unit volume, $\vec{B}$ is the vector of magnetic field inductance, and $\vec{j}$ is the vector of the electric current density governed by the generalized Ohm law

$$\vec{j} = \sigma \cdot \left(\vec{E} + \frac{1}{c}[\vec{V} \times \vec{B}] \right).$$

Here, σ is the electric conductivity of the plasma, $\vec{V}$ is the velocity of the plasma flow, $\vec{E}$ is the vector of the electric field strength determined by load factor k within a simple model [61]: $\vec{E} = -(k/c)[\vec{V} \times \vec{B}]$. In this case, the volumetric power density of the Ampère forces in the plasma is equal to

$$W_{\mathrm{f}} = \vec{V} \cdot \vec{f} = -\frac{\sigma}{c^2}(1-k)[\vec{V} \times \vec{B}]^2. \tag{5}$$

When $k < 1$, the kinetic energy of the plasma flow decreases and part of it is converted into the electric energy with volumetric power density $W_{\mathrm{e}} = -kW_{\mathrm{f}}$. The process is accompanied with heat release whose power per unit volume is $q = \vec{j}^2/\sigma = -(1-k)W_{\mathrm{f}}$. The plasma flow is governed by gas dynamic equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0, \qquad \rho \frac{\partial \vec{V}}{\partial t} + \rho (\vec{V} \nabla) \vec{V} + \nabla \cdot p = \vec{f}, \tag{6}$$

$$\frac{\partial}{\partial t}\left[\rho \left(\frac{V^2}{2} + \varepsilon\right)\right] + \nabla \left[\rho \vec{V} \left(\frac{V^2}{2} + h\right)\right] = \vec{V}\vec{f} + q, \tag{7}$$

where p is the pressure of the plasma, $\varepsilon = c_v T = p/(\gamma - 1)\rho$ is its specific internal energy; c_v is specific heat capacity at constant volume, $h = c_p T = c_{\mathrm{s}}^2/(\gamma - 1)$ is specific enthalpy; c_p is specific heat capacity at fixed pressure; and c_{s} is sound velocity in the gas, $\gamma = c_p/c_v$.

In order to remove a considerable share of energy from the hypersonic plasma flow along the path length L the product $W_{\mathrm{e}}L$ should be comparable in magnitude to $\rho V^3/2$. The dimensionless parameter, usually introduced as a characteristic measure of the MHD interaction is called the Stuart number $S = \sigma B^2 L/\rho V c^2$. A significant decrease in the energy of the hypersonic flow is possible at $2k(1-k)S \geqslant 1$ only. However, the structure of the supersonic flow can also be significantly perturbed at a smaller value of the Stuart number [59, 61]. The fact is that the structure of the supersonic flow is determined, to a great extent, by the value of a dimensionless parameter such as the Mach number $M = V/c_{\mathrm{s}}$. Under the conditions of the hypersonic flow, there is no need to change the flow velocity significantly to achieve a considerable change in the Mach number. It suffices to change the sound velocity in the gas (i.e. the temperature of the gas), which requires a significantly weaker effect in terms of energy and can be achieved when the inequality $(1-k)[\gamma+1+\gamma(\gamma-1)(1-k)M^2]S \geqslant 1$ is fulfilled. However, such a perturbation of the flow is accompanied with a considerable increase in its entropy, if the loading factor is not high enough. This results in undesirable loss of the ramjet thrust [60]. Analysis of the gas dynamic equations (6)–(7) shows that to avoid considerable loss of the thrust it is necessary to provide the following conditions

$$1-k \leqslant \frac{\gamma+1}{\gamma(\gamma-1)M^2}, \qquad S \geqslant \frac{1}{(\gamma+1)(1-k)}. \tag{8}$$

In principle, the Ampère forces can also be used to control the gas flow outside the aircraft. However, in current literature this effect is discussed only in the context of flow deceleration in front of separate protruding fragments of aircraft structures to reduce thermal and mechanical loads on such fragments [62]. At the same time, it seems rather attractive to consider the idea of using the MHD control of the external flow incident on the aircraft globally. As is shown below on the simplest example, control over the flow incident on the body by means of volumetric forces makes it possible not only to generate the thrust force, but also to reduce the drag and load forces, and even to eliminate formation of shock waves completely in the case of supersonic flowing around the body.

All the above effects can be illustrated by solving the two-dimensional problem of a stationary supersonic flow around a thin body analytically under the conditions of relative smallness of all gas-dynamic perturbations. In this case, the equations linearized relative to small gas-dynamic perturbations have the following form:

$$\begin{aligned} &\rho_0 \frac{\partial \tilde{U}}{\partial \tau} + \frac{\partial \tilde{p}}{\partial y} = f_y \\ &\frac{\partial \tilde{p}}{\partial \tau} + \rho_0 \tilde{C}^2 \frac{\partial \tilde{U}}{\partial y} = \tilde{q} \\ &\tilde{U}(V_0\tau, y = \pm\Phi(V_0\tau)) = \pm V_0 \alpha(V_0\tau) \end{aligned} \tag{9}$$

$$\rho_0 V_0 \frac{\partial \tilde{V}}{\partial x} = -\frac{\partial \tilde{p}}{\partial x} + f_x \tag{10}$$

$$V_0 c_{\mathrm{s}0}^2 \frac{\partial \tilde{\rho}}{\partial x} = V_0 \frac{\partial \tilde{p}}{\partial x} - (\gamma-1)q, \tag{11}$$

where $\tau = x/V_0$ is equivalent time, x and y are the co-ordinates along and transverse to the unperturbed gas flow, respectively; $\tilde{\rho}$ and $\tilde{p}$ are the perturbations of density and pressure of the gas; $\tilde{V}$ and $\tilde{U}$ are the perturbations of the longitudinal and transverse components of the gas velocity vector, respectively; f_x and f_y are the longitudinal and transverse components of the vector of the force that affects a unit volume of the gas; q is the volumetric density of heat source power;

$$\tilde{C} = \frac{c_{\mathrm{s}0} M_0}{\sqrt{M_0^2 - 1}}$$

is equivalent sonic velocity, c_{s0} is sound velocity in the unperturbed flow, and function Φ describes the surface of the body ($y = \pm\Phi(x)$), $\alpha(x) = \mathrm{d}\Phi/\mathrm{d}x$, $\tilde{q} = [(\gamma - 1)qM_0 - c_{s0} f_x]$ $M_0/(M_0^2 - 1)$.

Three different factors are sources of gas-dynamic perturbations within the equivalent acoustic problem (9). The first of them is equivalent to the motion of a gas-tight piston with velocity $V_0\alpha$. The second is the action of volumetric force f_y. The third one is equivalent to the action of a heat source with its volumetric power density $\tilde{q}$ (note that, within the equivalent acoustic problem, the power of the heat source, $\tilde{q}$, can be both negative and positive). In the absence of volumetric sources ($f_x, f_y = 0, q = 0$) the solution of the acoustic problem (9) is well known. In this case, the excess pressure $\tilde{p}$ at the body surface is equal to

$$\tilde{p}_0(x, y = \pm\Phi(x)) = \rho_0 V_0 \tilde{C}\alpha(x). \tag{12}$$

Correspondingly, the force of the aerodynamic drag, F_{d0} (per unit of body length transverse to the flow) is determined by the following integral over the longitudinal size of the body, L_x:

$$F_{d0} = 2\int_{L_x} \tilde{p}_0\alpha(x)\,\mathrm{d}x = 2\int_{L_x} \rho_0 V_0 \tilde{C}\alpha^2(x)\,\mathrm{d}x. \tag{13}$$

The formed gas-dynamic perturbations take off energy (per unit of transverse size):

$$W_0 = 2\int_{L_x} \tilde{p}_0(x, y = \Phi)\tilde{U}(x, y = \Phi)\,\mathrm{d}x = V_0 F_{d0}. \tag{14}$$

An engine that should develop a thrust equal to F_{d0} to provide a stationary flight compensates these energy losses.

A certain share of the required thrust force can be obtained as the recoil reaction, if the accelerating volumetric force $f_x > 0$ is applied to the flow around the body. Let this force be localized in the near-surface layer in the neighbourhood of the body, and let the thickness of this layer, l_y, be small: $l_y \ll L_x/M_0$. Then, according to the solution of the equivalent acoustic problem (9) the excess pressure $\tilde{p}$ on the surface of the body will become lower by $\Delta\tilde{p}_x$

$$\Delta\tilde{p}_x \cong \frac{1}{\sqrt{M_0^2 - 1}}\int_{l_y} f_x\,\mathrm{d}y, \tag{15}$$

where the integration is performed over the whole layer thickness l_y. If f_x is the same all over the surface of the body, the resulting force acting on the body from the gas will not change: $F_d = 2\int \tilde{p}_x\alpha(x)\,\mathrm{d}x = F_{d0}$. The additional thrust force will be $R = 2L_x\int_{l_y} f_x\,\mathrm{d}y$. In the ideal case, its generation will require the following power expenses (per unit of the transverse body length): $W_R = RV_0$. Note that, when the inequality $M_0^2\alpha^2 \ll M_0^2 - 1$ is valid, the additional thrust force can reach the values of the order of F_{d0} at $|\Delta\tilde{p}_x| \ll |\tilde{p}_0|$. However, generation of this additional force will require power W_0 equal to the power needed to fight the drag force.

Under the conditions of weak gas-dynamic perturbations, the action of the heat source q causes mainly an increase in the excess pressure at the surface of the body. Therefore, it can be used to reduce the aerodynamic drag only when the source is placed in the rear part of the body, where $\alpha(x) < 0$. If the heat source is localized in the thin near-surface layer in the neighbourhood of the body, the excess pressure produced by it is equal to

$$\Delta\tilde{p}_q \approx \frac{M_0}{\sqrt{M_0^2 - 1}}\frac{\gamma - 1}{c_{s0}}\int_{l_y} q\,\mathrm{d}y.$$

The energy efficiency of such a drag reduction under the considered conditions is low:

$$\eta = \frac{V_0\int_{L_x}\Delta\tilde{p}_q\alpha(x)\,\mathrm{d}x}{\int_{L_x}\int_{l_y} q\,\mathrm{d}y\,\mathrm{d}x} \ll 1. \tag{16}$$

An alternative way to reduce the drag may be the use of transverse forces f_y. When they are localized in the near-surface layer, they change the value of the excess pressure on the surface: $\Delta\tilde{p}_y = -\int_{l_y} f_y\,\mathrm{d}y$. By choosing the corresponding distribution of f_y at the surface of the body, one can provide the absence of the excess pressure on it: $\tilde{p} = \tilde{p}_0 + \Delta\tilde{p}_y = 0$. Then, the corresponding energy expenditures are equal to W_0, i.e. this way of drag elimination yields no energy gain.

It is possible to achieve energy gain while eliminating drag if one uses the longitudinal volumetric force f_x. Really, it follows from equation (15) that one can choose the corresponding distribution of f_x along the body and provide the excess pressure equal to zero: $\tilde{p}_0 - \Delta\tilde{p}_x = 0$, if $\int_{l_y} f_x\,\mathrm{d}y = \rho_0 V_0^2 \alpha(x)$. The most unexpected result here is the fact that in the ideal case (when $q = 0$) the required energy expenditures are zero because

$$\int_{L_x} V_0 \int_{l_y} f_x\,\mathrm{d}y\,\mathrm{d}x = \rho_0 V_0^3 \int_{L_x} \alpha(x)\,\mathrm{d}x = 0.$$

This result is not even a consequence of the used approximation of small gas-dynamic perturbations. Indeed, there is a well-known hydrodynamic phenomenon that is called the D'Alambere paradox and consists in the absence of drag when an incompressible liquid flows around a body potentially. This means that, in principle, there can be such spatial distribution of the velocity of the flow around the body for which neither momentum nor energy are transferred to this flow. Under usual conditions this regime cannot be realized in the case of a body moving in a gas at supersonic velocity, since this requires realization of two contradicting conditions. On one hand, in order to achieve the D'Alambere flow regime, the gas density along the current lines should remain constant. On the other hand, the current lines differ from the rectilinear ones, which is possible (in the absence of volumetric forces) only due to inhomogeneous distribution of gas pressure around the body. At the same time, under the conditions of the adiabatic flow the density and pressure of the gas are uniquely related to each other. This contradiction can be eliminated, if distributed volumetric forces, which can provide the required curvature of the streamlines, affect the gas in the neighbourhood of the body. Note that when such a field of volumetric forces around the body moving at supersonic velocity is realized, no shock waves will be generated. Generally, no energy will be transferred to the gas flow around the body, since the total mechanic power developed by the force field will be zero. The energy will be deposited in the gas in front of the body, but the same amount of energy will be removed from the gas behind it.

5. Conclusion

Plasma is a conducting medium, which gives a unique possibility to act on its flow by means of forces and heat sources produced volumetrically by an electromagnetic field. This fact makes it possible to control the flow of ionized gas using additional, electronic methods, independent of the traditional mechanical ones. The range of possible applications of such methods in aerodynamics is very wide. The list of such applications, which are currently discussed, includes

(a) reduction of aerodynamic drag;
(b) local redistribution of thermal and mechanical loads on structural elements of aircraft;
(c) mitigation of the sonic boom that accompanies all supersonic flights in an atmosphere;
(d) generation of additional rotational momenta to improve aircraft manoeuvrability;
(e) improvement of air jet efficiency.

However, detailed theoretical analysis of these problems shows that their realization is associated with considerable technical difficulties that are primarily connected with too strong electromagnetic fields required.

Actually, the energy efficiency of reducing the aerodynamic drag is not very high. Therefore, the use of plasma aerodynamics to reduce the total aerodynamic drag is associated with operation of electromagnetic systems, the power of which is almost as high as the power of aircraft engines. In order to generate the required electric energy and provide efficient gas heating using the generated energy, one has to place special equipment on board the aircraft; this equipment will not only weigh heavy, but will also generate strong electromagnetic interference into operation of navigation and flight control systems.

Calculations show that efficient drag reduction requires definite distribution of the power of heat sources in space. The possibility to realize the required spatial distribution under the conditions of the gas discharge is far from evident, since the discharge plasma is characterized by various instabilities and is usually beyond detailed quantitative calculations. This is why at the Workshop on Magneto-Plasma Aerodynamics (Moscow, 24–26 April 2001) one of the main results of the studies performed was the statement that the use of plasma methods to reduce the total aerodynamic drag can be justified only at very high hypersonic flight velocities. At transonic velocities it seems reasonable to apply such methods in the incident flow only locally, in order to reduce loads on separate structural elements of the aircraft.

The problems of the MHD effect on plasma are associated with gas ionization and generation of strong magnetic fields. Acceptable energy cost of ionization is achieved only by using beams of high-energy electrons [58, 63], which means that high-voltage equipment that contains voltage of the order of several hundreds of kilovolts should be placed on board. The problem of continuous injection of the electron beam into the gas has not been solved technically either. Electric conductivity of the plasma produced by electron beams in air is not too high. Therefore, to achieve the goals of MHD interaction (cf equation (8)) it is necessary to generate a very strong magnetic field (of order 1 T to modify shock wave structure in the off-design regime of the inlet diffuser, and of order 10 T to transfer the kinetic energy of the incident gas flow into the output nozzle without losses in the thrust force). Such a strong magnetic field has already been used in laboratory experiments [57, 58]. Generation of such fields on board an aircraft seems rather doubtful. Note that complete elimination of shock waves by the MHD methods described in the previous section requires even stronger magnetic fields.

Thus, at the current stage of technical development, the only realistic application of gas discharge in aviation is solution of the problem of complete fuel combustion in a hypersonic ramjet. The ways to stimulate combustion using various gas discharges are studied rather intensely in several research centres and promising experimental results have been obtained in this field [64–67].

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