2. AERODYNAMIC FLOW CONTROL AT HIGH SPEED USING ENERGY DEPOSITION

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Abstract. A selective survey of research in aerodynamic flow control at high speed using energy deposition is presented. Specific topics discussed include drag reduction, unsteady effects, modification of shock structure and MHD control.

Introduction
Flow control for aerodynamic applications is an extraordinarily broad topic which has received substantial research interest over the past one hundred years. In recent times, significant efforts have focused on the use of energy deposition for flow control particularly for high speed (i.e., supersonic and hypersonic) air vehicles. The objective of this paper is to provide a selective survey of research in aerodynamic flow control at high speed using energy deposition. The first section provides a brief summary of important physical effects associated with energy deposition in supersonic flow of a perfect gas. The second through fourth sections focus on three main topics: aerodynamic flow control (specifically, drag reduction and effects of unsteady energy addition), modification of shock structure and MHD control. The survey is necessarily brief, and is meant to provide an indication of the extensive level of research activity in a few selected areas rather than a comprehensive assessment of the field.

Fundamentals of Energy Deposition

One Dimensional Flow

The basic principles of one-dimensional, steady energy addition in supersonic flow of a perfect gas are well known [30]. The behavior is summarized in Table 1 where ↑ and ↓ imply increase and decrease, respectively, with the addition of energy. Of particular importance is behavior of the “dynamic pressure” $pu^2$ which is observed to decrease with energy addition at $M > 1$.

\[ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = 0 \]  
\[ \frac{\partial p}{\partial t} + \frac{\partial (pu)}{\partial x} = 0 \]  
\[ \frac{\partial T}{\partial t} + \frac{\partial (uT)}{\partial x} = \frac{Q}{\rho} \]  

where $\rho$ is the density, $v$ is the velocity, $p$ is the static pressure, $T$ is the static temperature and $Q$ is the energy added per unit volume per time. The total energy added per unit time is defined as

\[ Q_t = \int \int Q \, dV \]  

Two- and Three-Dimensional Flow

The governing equations for energy deposition in an inviscid perfect gas are

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \]  
\[ \frac{\partial \rho v}{\partial t} + \nabla \cdot (\rho v^2) = - \frac{1}{\rho} \nabla p \]  
\[ \frac{\partial T}{\partial t} + v \cdot \nabla T = -(\gamma - 1)T \nabla \cdot v + \frac{Q}{\rho c_v} \]  

where $\rho$ is the density, $v$ is the velocity, $p$ is the static pressure, $T$ is the static temperature and $Q$ is the energy added per unit volume per time. The total energy added per unit time is defined as

\[ Q_t = \iiint Q \, dV \]  

The general configuration is shown in Fig.1. For steady flow of an inviscid perfect gas (in the absence of any body) the flowfield depends on the dimension-less parameters (functions) shown in Table 2. The dimensionless energy deposition ratio $\varepsilon$ is defined as

\[ \varepsilon = \frac{M^2 Q_0 L}{\rho_0 U_\infty^3} \]
Table 2. Dimensionless Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$M_\infty$</td>
<td>Mach number</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Energy deposition ratio (see (5))</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Ratio of specific heats</td>
</tr>
<tr>
<td>$G$</td>
<td>Energy distribution function</td>
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</table>

where $Q_0$ is a characteristic value of $Q$ and $L$ is a characteristic length scale of the region of energy addition. Given the characteristic length $L$, the quantity $Q_0$ may be formally defined by

$$Q_0 = \frac{Q_t}{L^3}$$

(6)

The energy deposition ratio $\varepsilon$ may be interpreted as proportional to the ratio of the energy added per unit time to the static enthalpy flux through the region of energy addition. The dimensionless distribution function $G$ describes the energy deposition. An equivalent definition can be formed assuming the energy deposition is expressed as

$$Q = \rho q$$

(7)

where $q$ is the energy added per unit mass per time. The dimensionless energy deposition factor $\varepsilon$ becomes

$$\varepsilon = \frac{M_\infty^2 q_0 L}{U_\infty^3}$$

(8)

where $q_0$ can be formally defined by

$$q_0 = \frac{Q_t}{\rho \omega L^2}$$

(9)

Note, however, that both $q(x)$ and $p(x)$ must be specified to evaluate $q_0$, where $x = (x,y,z)$.

For two-dimensional (planar) energy deposition, the corresponding definitions are

$$Q_t = \int QdA$$

(10)

where $Q$ is the energy added per unit area per time for a unit depth, and

$$Q_0 = \frac{Q_t}{L^2} \quad \text{and} \quad q_0 = \frac{Q_t}{\rho \omega L^2}$$

(11)

An alternate definition of the energy deposition parameter can be made using the energy deposition per unit mass and time alone, viz.,

$$L^3 q_0 = \iiint qdV$$

(12)

with a corresponding definition for two-dimensional flows

$$L^2 q_0 = \int qdA$$

(13)

and thus

$$\varepsilon' = \frac{M_\infty^2 q_0 L}{U_\infty^3}$$

(14)

For unsteady periodic energy deposition, an additional parameter may be defined as

$$\tau = \frac{U_\infty t_0}{L}$$

(15)

where $t_0$ is the period of the energy deposition. This represents the ratio of the period of the energy pulse to the time required for the flow to traverse the region of energy deposition.

Linear, weakly- and strongly nonlinear solutions of (1) to (3) have been obtained for steady two- and three-dimensional energy deposition in supersonic flow. We summarize several of the key results below. Linearized solutions are based on an expansion in $\varepsilon$ with $\varepsilon<<1$.

Belokon et al [6] considered a two dimensional energy source of the form

$$q = Q_0 \exp[-((x^2+z^2)/r_0^2)] \quad \text{for} \quad x^2+z^2\geq0$$

(16)
The linearized farfield solution on the streamwise z-axis yielded positive and negative perturbations for the static pressure and density, respectively, with an exponential decay in z. Krasnobaev and Syunyaev [35] considered a three dimensional energy source of the form

$$q = \frac{U_0^3}{x^2 + y^2 + z^2} \text{ for } x^2 + y^2 + z^2 \geq 0$$

(17)

The farfield linearized solution on the axis of symmetry yields a decrease in the streamwise velocity and an increase in static pressure compared to the freestream. The velocity and pressure perturbations decay proportional to $z^{-1}$.

Krasnobaev [34] extended the linearized supersonic solution to an arbitrary planar or axisymmetric confined energy source $q(r,z)$ and showed that the effect of the energy source was analogous to flow past a slender body. Krasnobaev developed the weakly nonlinear extension of the theory using the characteristic variable method of Whitham [75] to find the shape of the shock wave which forms away from the energy source.

Terent’eva [68] further extended the linearized super-sonic solution to an arbitrary confined three dimensional energy source $q(r)$. Terent’eva derived solutions for the specific case of a finite size uniform cylindrical energy source aligned with the freestream flow given

$$q = \begin{cases} Q_0 & 0 \leq z \leq l \text{ and } x^2 + y^2 \leq \eta_0^2 \\ 0 & \text{otherwise} \end{cases}$$

(18)

The farfield solution on the axis of symmetry yields an increase in streamwise velocity and decrease in static pressure compared to the freestream. The dynamic pressure is decreased provided $M_\infty > \sqrt{2}$. The perturbations decay proportional to $z^{-2}$.

Vlasov et al [72] performed two dimensional computations in the nonlinear regime for a energy source of the form (16). Three qualitatively different regimes were observed, namely, 1) shock wave forms away from the energy source and the flow through the energy source is supersonic (weakly nonlinear) at $\varepsilon' = 9.5$ and $M_\infty = 3$, 2) shock wave intersects the energy source region for $\varepsilon' = 114$ and $M_\infty = 3$, and 3) shock wave forms up-stream of the energy source and intersects the axis (strongly nonlinear) at $\varepsilon' = 190$ and $M_\infty = 5$. The complete parametric description of these two regimes in terms of the dimensionless parameters $M_\infty, \varepsilon'$ and $\eta$ was not given, however.

Georgievskii and Levin [24] performed a series of Euler computations at $M_\infty = 3$ for a cylindrically symmetric time-dependent energy deposition

$$Q = \rho Q_0 \sigma(t) \exp \left[ -\frac{r^2 + z^2}{\eta_0^2} \right]$$

(19)

where $r^2 = x^2 + y^2$ and $\sigma(t)$ is a function with period $t_0$. Three different forms of $\sigma(t)$ were considered with the property

$$t_0 \int_0^\infty \sigma(t) dt = t_0$$

(20)

For a steady source ($\sigma(t) = 1$) the flowfield was observed to be subcritical (i.e., supersonic everywhere) for $\varepsilon' = 5.6$ and supercritical (i.e., a shock forms and hence a subsonic region exists) for $\varepsilon' = 11.2$. For an unsteady source, three general types of flows were observed in the supercritical regime. quasi-steady, transitional, and unsteady. In the quasi-steady case, the shock structure was observed to be quasi-steady. In the transitional case, the head of the shock was ob-served to be quasi-steady, but an oscillatory shock structure occurred downstream. In the unsteady case, every energy pulse was accompanied by a blast wave. The parameter defining the regimes (for fixed $\varepsilon$) is the dimensionless period $\tau$ defined by (15) with $L = 2r_0$. The quasi-steady regime was observed for $\tau = 1.8$ and the unsteady regime for $\tau = 7.1$.

**Aerodynamic Flow Control**

Energy deposition has been investigated as a method for controlling the aerodynamic forces and moments on air vehicles. In this paper, we focus on drag reduction. Significant additional research has been performed on use of energy deposition for controlling lift and moments.

**Drag**

A simple one-dimensional analysis provides a simple approximate result regarding the effect of energy addition upstream of a body (Fig.1). Assume an incremental energy $\delta Q = \rho_0 u_0 A_0 \delta q$ is added per unit time in a finite interval.

\[ \text{ii} \] For the parameter $\varepsilon'$, the length $L$ is taken to be $r_0$. The dimensionless parameter $W_0$ introduced by Vlasov et al is $W_0 = M_\infty \sqrt{2/\pi} \cdot \varepsilon'$.

\[ \text{iii} \] The values of $\varepsilon$ are estimated using the computed result for $\rho/\rho_0$ in the region of energy deposition and choosing $L = r_0$. 
region with cross-sectional area $A_f$ and neglecting the variation of drag coefficient $C_D$ with Mach numberiv. The power $P$ required to overcome the drag on the vehicle is

$$P = DU_{\infty} = \frac{1}{2} \rho u^2 U_{\infty} C_D A$$  \hspace{1cm} (21)$$

Thus, the relative change in power $dP/dQ$ is

$$\frac{dP}{dQ} = - \frac{1}{2} \frac{1}{C_D} \frac{A}{A_0} \frac{M_{\infty}^2 - 1}{M_{\infty}^2 - 1}$$  \hspace{1cm} (22)$$

A net reduction in power requires $dP/dQ < -1$. The sign of $dP/dQ$ is negative for supersonic flow due to the behavior of $\rho u^2$ as indicated in Table 1.

Georgievskii and Levin [21] considered the effect of a steady energy deposition upstream of a body of revolution in supersonic flow at zero angle of attack for two different cases. In the first case, the energy deposition was assumed to occur on an infinitesimally thin line parallel to the flow and upstream of the body as shown in Fig.2. The linearized problem was solved and a general expression for the drag coefficient was obtained. Specific results were presented for a shape consisting of conical forebody and afterbody of equal length. It was shown that a net thrust can be achieved. The shape of the body of revolution of given volume and minimum resistance was determined analytically.

In the second case, a Gaussian energy deposition was assumed upstream of the body of the form

$$q = \frac{Q_0}{R_0} \left( \frac{p_\infty}{p_0} \right)^{\gamma/2} \exp \left[ - \frac{r^2 + (z-z_0)^2}{r_0^2} \right]$$  \hspace{1cm} (23)$$

where $r_0$ is the effective scale of the energy deposition, $R_0$ is the characteristic dimension of the body, and $r^2 = x^2 + y^2$. For a sufficiently large

iv This is reasonable for bluff bodies. For example, the drag coefficient for a sphere 15 at subcritical Reynolds numbers varies by less than 10% from Mach 1.5 to 4.

energy deposition, a recirculation region forms in front of the body as shown in Fig.3. The formation of a recirculation region in front of a bluff body in the presence of intense upstream energy deposition was also observed by Artem'ev et al. [4], Borzov et al. [9], and Georgievskii and Levin [20,23]. A reduction in drag (i.e., integrated frontal surface pressure) was observed for sufficiently high levels of energy deposition. The magnitude of the drag reduction was found to be insensitive to the location of energy deposition for sufficiently large distance from the body. This phenomenon was denoted “distance stabilization”. Also, the increment in drag reduction diminished with increasing energy addition.

Levin and Terent’eva [46] considered steady symmetric energy deposition upstream of a cone in supersonic flow at zero angle of attack. The energy release was assumed to be Gaussian (23). Numerical simulations of the Euler equations were performed for $M_{\infty} = 3$ to 4.25 and a range of cone half-angles $\mu$ from 10 to 25, energy deposition $q$ and energy locations $z_0$. The frontal drag was reduced for the range of cone angles studied by up to 45%. However, for sufficiently long cones the shock generated by the energy release interacted with the cone shock and an increased drag occurred. The position of the energy release for minimum drag with a fixed energy deposition $q$ and $M_{\infty}$ was determined.

Levin and Terent’eva [47] considered steady asymmetric energy deposition upstream of a cone in supersonic flow at small angles of attack. The configuration is shown in Fig.4. The energy release is Gaussian with the form

$$q = Q_0 \exp \left[ - \frac{(x-x_0)^2 + (z-z_0)^2}{l^2} \right]$$  \hspace{1cm} (24)$$

Euler simulations were performed for supersonic flow at cone half-angles $\mu$ from 5 to 15° and
angles of attack from $0^\circ$ to $10^\circ$. It was observed that the energy deposition located upstream and above the cone centerline both reduced the drag and increased the lift at positive $\alpha$.

![Fig.4. Flow configuration](image)

Yuriev et al [76] considered steady energy deposition near the surface of an NACA 0012 airfoil for $0.8 \leq M_\infty \leq 0.9$. Euler simulations indicated that energy deposition can reduce profile drag up to 25%, depending on the location of the energy deposition.

Riggins et al [63] and Riggins and Nelson [62] performed a series of laminar viscous computations of steady energy deposition upstream of a 2-D/axisymmetric semicircle/hemisphere cylinder at $M_\infty = 6.5$ and 10. The formation of two counter-rotating vortices (2-D) or an annular vortex (axisymmetric) was observed (i.e., recirculation region(s)). They defined a power effectiveness according to

\[ E = \frac{(D_{q=0} - D_{q>0})U_\infty}{Q} \]  

(25)

where $D_{q=0}$ is the drag in the absence of energy deposition, $D_{q>0}$ is the drag in the presence of energy deposition, and $Q$ is the total energy added per unit time. The computed $E$ exceeded one for all cases considered. Wave drag reduction of up to 50% was observed.

Kolesnichenko et al [31] considered both quasi-steady and unsteady energy deposition upstream of a 2-D rectangular body. Euler simulations were performed for a series of energy pulses at $M_\infty = 1.9$ defined by a finite rectangular region initial condition upstream of the body with $\rho < \rho_\infty$ but $p = p_\infty$ and $u = U_\infty$, as shown in Fig.5. They observed that quasi-static energy deposition was more efficient than unsteady energy deposition in reducing the time integrated frontal drag. The strongest effect on drag reduction was the magnitude of the density “well” (i.e., the magnitude of $\rho_r - \rho_\infty$ in the initial energy pulse). They noted that the interaction of the density “well” with the bow shock produced a vortex pair which is associated with the reduced pressure on the front surface (and hence reduced drag). This is consistent with previous investigations which showed recirculation regions in front of blunt bodies in the presence of energy deposition. They also noted that the integrated effect of the density well was independent of its transverse dimension.

![Fig.5. Initial condition for energy pulse](image)

Girgis et al [25] considered steady energy deposition upstream of a cone-cylinder (Fig.6). Euler simulations were performed for a 15° half-angle cone at $M_\infty = 2.4$ to 5 and zero angle of attack and sideslip. The energy deposition was assumed Gaussian of the form

\[ Q = Q_0 \exp \left[ -\frac{(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2}{r_0^2} \right] \]  

(26)

Two studies were conducted to assess the effect of the size and location of the energy deposition on drag. In both studies, the energy source was located on the axis ($\theta = 0$ in Fig.6), and the dimensionless ratio $\sigma = Q/\frac{1}{2} \rho_\infty U_\infty^2 A = 1$ where $Q_t$ is the total energy added per unit time (4) and $A = \pi D^2/4$ is the
cross sectional area of the cylinder. In the first study, the effect of the location of the energy deposition was examined. The effective radius of the energy deposition was assumed to be \( r_0 = 0.2D \) where \( D \) is the diameter of the cylinder. The location of the center of the energy deposition was varied from \( R/D = 0.04 \) to 1.75. The energy deposition ratio \( \varepsilon = 31.7 \). The minimum drag occurred at \( R/D = 0.4 \). At this location a drag reduction of 35% was achieved. In the second study, the effective radius \( r_0 \) of the energy source was varied from \( r_0/D = 0.15 \) to 0.4 corresponding to \( \varepsilon = 56.4 \) to 7.9. Since \( \varepsilon = 1 \), the value of \( \varepsilon \propto \alpha (r_0/D)^2 \), i.e., the energy deposition is more intense as \( r_0/D \) decreases. The minimum drag corresponds to \( r_0/D = 0.15 \); however, this may not represent the global minimal drag under the conditions of this study since computation at smaller \( r_0/D \) was infeasible due to the limitations of the computational grid utilized. A drag reduction of 35% was obtained.

Shang et al [66] considered a plasma counter-jet issuing from a hemisphere-cylinder at \( M_\infty = 5.8 \). Both experiments and computations were performed. The configuration is shown in Fig.7. At a constant counterjet mass flow rate, a decrease in drag was observed with increasing counter-jet temperature. A maximum drag reduction of 13% was achieved. The possible plasmadynamic contribution to the drag reduction was not quantified.

Toro et al [69] performed a series of experiments for a “Directed Air Energy Spike” based on the concepts of Myrabo and Raizer [59]. The experimental model is shown in Fig.8. The model body is a double 15.2cm disk whose surfaces are scaled directly from the Apollo command module’s lower heat shield. A 15.2 cm long plasma torch with 0.635cm external diameter is attached on the model centerline. Experiments were performed at \( M_\infty = 10 \). Operation of the plasma torch at arc powers up to 70kW resulted in a reduced frontal drag compared to the power-off drag with the torch body attached. Additional experiments and axisymmetric Euler computations were performed for this configuration by Bracken et al. [10,11].

**Unsteady Effects**

Georgievskii and Levin [22] performed a series of Euler simulations for the unsteady interaction of a spherical or elliptical region of low density fluid with a sphere at \( M_\infty = 3 \) as displayed in Fig.9. The initial density within the elliptical region was \( \rho_0(1-\delta \rho) \), while the initial velocity and pressure within the elliptical region were freestream. Computations were performed for a series of shapes. For \( \delta \rho > 0 \) and an initial spherical shaped density region, the surface pressure on the centerline displayed a sharp peak (significantly above its undisturbed value) following the initial expansion attributable to the impingement of the low density region. The sharp peak is associated with the formation of a recirculation region (toroidal vortex).

\[^{v}\text{This quantity is proportional to the ratio of the total energy added per unit time to the power required to overcome the drag on the cone-cylinder at fixed } M_\infty.\]
Tretyakov et al. [70] performed experiments to measure the drag on a cone-cylinder and hemisphere-cylinder at $M_f=2$ in argon in the presence of a high frequency CO$_2$ laser discharge upstream of the body. Results were obtained for focal locations at one and two diameters upstream of the body on the centerline. The dimensionless pulse period is defined by

$$\tau = \frac{U_f}{fl} \quad (27)$$

where $f$ is the pulse repetition frequency and $l$ is the distance of the laser focus to the leading edge of the body. The quantity $\tau$ represents the ratio of the elapsed time between pulses to the time required for the freestream flow to travel between the pulse location and the leading edge of the body. The time average drag is reduced by up to 45% for $\tau \approx 1$ as indicated in Fig.10 where $D$ is the diameter of the cylinder.

Adelgren et al. [2,3] performed a series of experiments using a laser energy pulse upstream of a sphere at $M_f=3.45$ for a total pressure $p_{re}=1.4$ MPa and total temperature $T_{re}=290$K. A Nd:YAG laser (532nm) pulse of 10ns duration was focused on the centerline at one diameter upstream of the sphere. Surface pressure was measured across the windward face using a pressure transducer. Three energy levels ranging from 150 to 200mJ were used. An instantaneous Schlieren image is shown in Fig.11. The surface pressure vs time at discrete angular positions on the sphere is shown for one energy level in Fig.12, and at the centerline of the sphere for all three energy levels in Fig.13. The initial pressure rise associated with the blast wave is evident in Fig.13. The subsequent decay in surface pressure is associated with the impingement of the high temperature region on the surface.

Adelgren et al. also performed experiments for laser energy pulse upstream of an Edney IV interaction (Fig.14) at the same freestream conditions. The objective of the experiment was to
ascertain the capability of a laser energy pulse to decrease the high stagnation pressure associate with the Edney IV interaction. [17] The basic concept is to deflect the supersonic jet (Fig.14) away from the surface, thereby decreasing the surface stagnation pressure. Fig.15 displays the experimental surface pressure vs time at discrete angular locations on the sphere for a laser pulse focused 0.67 diameter upstream of the cylinder and 0.28 diameter above the centerline. The laser pulse is effective in reducing the surface stagnation pressure.

![Fig.14. Edney IV interaction](image1.png)

![Fig.15. Laser energy pulse in Edney IV interaction](image2.png)

![Fig.16. Mach stem height vs t (22\(^\circ\times22\(^\circ\)))](image3.png)

Adelgren et al. extended their experiments on laser energy deposition to crossing shocks at the same freestream conditions. Symmetric wedges of 21\(^\circ\) and 22\(^\circ\) were used to generate crossing shocks within the regular and dual solution 73 domains, respectively. A Nd:YAG laser energy pulse (10ns) of 317mJ was focused to a 3mm 3 volume upstream of the crossing shocks on and off the centerline, respectively, for the 21\(^\circ\) and 22\(^\circ\) wedges. Schlieren images at 30\(\mu\)s and 90\(\mu\)s after the laser pulse are shown in Figs.17 and 18. The laser energy pulse was effective in significantly reducing the height of the Mach stem as indicated in Fig.16. This has potential important application in reducing the high total pressure loss associated with the Mach stem for a crossing shock inlet operating (perhaps momentarily) within the dual solution domain.

**Modification of Shock Structure**

**Sonic Boom Alleviation**

The sonic boom associated with the flight of supersonic aircraft has been a significant impediment to the establishment of supersonic commercial passenger service over inhabited regions. The basic theory of the sonic boom is...
presented in several references including Whitham [74] and Seebass [64]. The pressure signature at the surface of the earth is

\[ p - p_{\infty} = \frac{p_{\infty} K_s \gamma M_f^2 F(y)}{\sqrt{2} \beta h} \]

where \( p \) is the static pressure at the earth’s surface, \( p_{\infty} \) is the ambient static pressure, \( K_s \) is the reflection factor, \( \gamma \) is the ratio of specific heats, \( M_f \) is the freestream Mach number (with \( \beta = \sqrt{M_f^2 - 1} \)), \( h \) is the altitude of the aircraft and \( F(y) \) is the Whitham function

\[ F(y) = \frac{1}{2\pi^2} \int_0^\infty d\gamma A(x) (y - \gamma)^{-1/2} d\gamma \]

with \( x \) denoting the distance from the nose of the body, \( A(x) \) is the cross-sectional area and \( y \) is a quantity which is constant on characteristic surfaces.

The apparent principal objection to sonic boom is the short rise times associated with the leading and trailing signatures of the classical \( N \)-wave ((i.e., the leading and trailing shock waves [5]), rather than the absolute magnitude of the pressure changes. Consequently, this objectionable characteristic of sonic boom signature can be reduced or eliminated by increasing the rise time \( \tau \) for the pressure signature (both leading and trailing compressions of the \( N \)-wave). Batdorf estimates that a rise \( \tau = 10 \text{ms} \) is sufficient to reduce the acoustic power of a 2psf overpressure by 20dB within the principal frequency range of human hearing (1000 to 6000Hz).

Several methods have been proposed for increasing the rise time \( \tau \) of the compression waves at the earth’s surface. The first approach is to change the actual shape of the aircraft (for a given cruise \( M_c \) and \( h \)). It can be shown [5] that the optimal body shape for this purpose is characterized by \( A(x) \propto x^{5/2} \) near the nose. For a notional supersonic commercial aircraft (272,000kg at Mach 2.7 and 18.2km altitude), the estimated vehicle length [55,64] to avoid shock formation at the earth’s surface is 305m. This is practically infeasible\(^{vi}\) given the characteristics of current airports. The Airports Council International [28] (ACI) recommended maximum commercial aircraft length is 80m.

\(^{vi}\) For comparison, the maximum takeoff mass of the TU-144 180,000kg and the length is 65.7m. The corresponding values for the Concorde are 185,000kg and 61.7m.

The second approach is to simulate a longer aircraft by energy addition ahead of the vehicle. Batdorf [5] estimates that the input power required to achieve a 10ms rise time for a notional supersonic commercial aircraft of 91.4m length and 272,000 kg is 220MW which is equivalent to 60% of the cruise power requirement for the aircraft. Miller and Carlson [57,58] performed a comparable study and estimated a significantly larger power requirement. Also, the vehicle is in the flowpath of the heated air resulting in a significant increase in recovery temperature and concomitant requirements for surface cooling. Marconi [54] analyzed energy addition upstream of a single element airfoil and determined both the optimum input power distribution and the effect of the heated flow on the wave drag of the airfoil at conditions corresponding to a supersonic commercial aircraft at Mach 2.4 with length of 91.4m. He observed a significant decrease in drag due to the thermal wake of the heated region and estimated the net power increase of 30% for elimination of the sonic boom.

The third approach is to modify the pressure signature by off-axis energy addition. Batdorf [5] describes two approaches, namely, a thermal spike and a thermal keel displaced below the vehicle, but limits discussion of energy addition to a brief description of the use of combustion of fuel. Miles et al [56] describe preliminary concept of off-axis energy addition by microwave radiation.

In summary, the alleviation of sonic boom for supersonic commercial aircraft by energy addition is an important aerodynamic application. Several key technical issues remain to be solved, however, to achieve a practical implementation. These include optimization of the input energy distribution and vehicle configuration for a given mission requirement, and design of an efficient power system for energy distribution.

**Effect on Shock Structure**

An important practical application of energy deposition is the reduction of aerodynamic drag or control of aerodynamic characteristics of air vehicles. The main idea of these studies is the use of energy deposition in air flow (with help of plasma, laser radiation, microwave-radiation, etc.) to improve the streamlining of the aerodynamic elements. Both the method of energy deposition and the physical mechanism by which energy influences the aerodynamic processes are important. The process determines the practical economy of the method. The results of many experiments have shown that the basic mechanism of influence on the shock system is gas dynamic (i.e., the effect of the increased static enthalpy due
to energy deposition) which is present in every means of energy deposition in air flow. The specific features of influence of individual methods of energy deposition is a complex question.

The problem of energy deposition on the structure of shock waves can divided into three basic tasks. Research on physical mechanisms which lead to energy release near the shock front, determination of modification of a shock wave under energy influence, and the analysis of the experimental methods and devices which are used to achieve energy deposition. These issues are discussed, for example, in Kuranov et al [42], Kuranov et al [40,41], Kolosov et al [32], Kuranov et al [39], Kuchinsky et al [37], Golyatin et al [27], Kuchinsky and Suhomlinov [36], Sukhomlinov et al [67], Ivanov and Suhomlinov [29], Adelgren et al [3], Ershov et al [18], and Sepman et al [65].

One of the possible mechanisms of appearance of the heat source initiating by shock and acoustic waves passing through plasma is suggested in Kuchinsky et al [37] and Golyatin et al [27]. According to these works, sharp density enhancement as a result of plasma compression leads to an increase of electrostatic intensity and as a consequence, the rise of heat release. The appearance of the heat source near the shock front leads to a visible modification of a shock wave. Golyatin et al [27] discusses this problem. In particular, this work shows the analytic expressions for the speed distribution, the pressure and the temperature, which are added up as a result of the heat source influence. In Fig.19 the example of the design of modification of shock wave density at the various values of power which is put in the center of shock structure is shown. In this figure the density is normalized by its unperturbed value, and the energy contribution is normalized by a limit value (from the point of view of the existence of the univariate stationary solution). The gradual increase of the specific peak in density distribution with increase in the energy contribution is evident.

The main part of the work is devoted to passing a shock wave through plasma. The display of the specific plasma effects is shown in the conducted experimental research due to influence of the heat mechanism. The influence of the dissipative plasma properties is analyzed in Kolosov et al [32]. In Fig.20 it is shown a qualitative type of shock structure, which is described by the asymptotic expressions, obtained from the solution of the equation of Kortveg-deVris-Burgers [32]. The middle area fits to the values of the shock phase, where the obtained solutions are wrong. Here in the position data “density - the moment of density registration” density data, obtained by G.I.Mishin, Y.L.Serov and others on the ballistic route in “Physicotechnical Institute of A.F.Ioffe”. It is evident that on this graph a wave phase is proportional to time on the experimental graph. It is

![Fig.19. Distribution of density (relative to unperturbed value) near the shock front at various relative energy depositions](image1)

![Fig.20. The qualitative comparison of results of calculations according to equation of Kortveg-deVris-Burgers with experimental data](image2)
shown, that both these figures are qualitative similar. Some differences are caused by the difference between the actual distribution function and the Maxwell distribution in the experimental plasma in PTI. Besides, it is assumed during writing plasma equation it is considered that charged particles disappear as a result of ambipolar diffusion, while in the experimental conditions in PTI recombination has the main part in destruction of all particles.

The second important quantity, defined energy deposition in gas due to plasma, is length covered discharge of the part cathode surface l, as time is proportionate to l (Fig.22). This quantity doesn’t depend on the distance between electrodes, but it depends on air pressure (at the settled current). The derivative \( dl/di \) increases with decreasing pressure. The dependence changes \( l(i) \) with modification of the cathode geometric form. Therefore, it is possible to hope that the discharge of such type will have enough fastness and reliability in control.

For the more detailed analysis of influence of special plasma properties it is necessary to define data of dissipation parameters in the specific plasma installations. In the present time many plasma installations are tested, with help of which the influence on the shock distribution and formation are realized. Discharge, which has no walls, intended for creating artificial plasma shell near the surface of the flying vehicle is studied in Kuranov et al [40] and Ivanov and Suhomlinov [29]. Discharge (without walls) has some specific properties. Current density depends on an unique parameter, the pressure (Fig.21). The results of the determination \( j \) for all experimental tested cases (various currencies, cathode forms, electrode positional relationship, anode material and etc.) are shown. It is possible to consider that with the consideration of the mistake of the determination \( j \) all the points lay on the fluently growing dependence [40]

\[
|j| \approx \frac{5}{18} p^{3/2}
\]  

(28)

where \( j \) is in mA/cm\(^2\) and \( p \) is in Torr.
MHD Control

MHD control, in comparison with control by energy deposition as described above, provides not only an energy influence on flow parameters but also a force action on the flow. In principal, we can form a magnetic field distribution and choose a configuration and loading of electrodes in such a way that the Lorentz force will have the required direction. In some applications, is necessary to have the Lorentz force directed away from the vehicle (e.g., to decrease heat loading) and in other cases is necessary to have the Lorentz force directed towards the vehicle (e.g., to increase air capture in an inlet). The dimensionless MHD interaction parameter $S = \sigma B^2 L / \rho u$ is traditionally used to characterize the MHD effect, where $\sigma$ is flow conductivity, $B$ is the magnetic induction, $L$ is the length of the interaction, $\rho$ is the flow density and $u$ is the flow velocity. It is evident that a noticeable MHD effect can be achieved at high values of conductivity or magnetic induction.

Since the temperature in the shock layer at the nose of a hypersonic aircraft is extremely high, the equilibrium conductivity in this region is high too. Thus, in these conditions MHD control, in principle, can be realized. The influence of magnetic field on stream over blunt body is considered in Bityurin et al [8], Bityurin et al [7], Damevin and Hoffman [16], MacCormack [49], Lineberry et al [48], and Poggie and Gaitonde [61], where it is shown that MHD control allows the possibility to decrease wall heat flux and to increase the bow shock wave standoff distance from the body. Early studies in this direction emerged in the mid 1950s. An historical review of investigations of magnetic field influence on drag and wall heat fluxes of blunt body at atmospheric entry is presented in Poggie and Gaitonde [61].

Several years ago new possible applications of MHD control for hypersonic aircraft were proposed in the context of the AJAX concept schematically shown in Fig.23. At first it was proposed to use MHD systems in scramjet to improve the scramjet performance [19]. The proposed scramjet scheme located the MHD generator upstream of the combustion chamber and MHD accelerator located downstream. According to the concept the MHD generator transforms part of the flow enthalpy into the electric power which is transferred to the MHD accelerator for additional acceleration of combustion products. The use of MHD systems in the scramjet increases the effectiveness of thermodynamic cycle of the propulsion system, the specific impulse and thrust [38]. At the present time, two alternative titles are generally used in the special literature as a name for such an engine. Magneto-Plasma-Chemical Engine (MPCE) [19,38] and MHD bypass scramjet [60]. Typically the static temperature upstream of the scramjet combustion chamber does not exceed 2000K. In such conditions the equilibrium ionization fraction of the air flow, and hence its conductivity, are negligible. Thus the conditions are principally different from those in a shock layer. To realize an effective MHD interaction in the scramjet it is necessary to ensure nonequilibrium ionization of the flow. Therefore it is necessary to put additional energy into flow. The problem of ensuring nonequilibrium conductivity of a cold flow in MHD generator channel is discussed in Brichkin et al [12-14], Kuranov and Sheikin [43-45], and Macheret et al [50,51,53]. It is shown that at technically feasible parameters of the ionizer and magnetic system there is self-sustained operational mode for which the power spent on flow ionization does not exceed the power produced by MHD generator.

The second possible application of MHD control in the hypersonic aircraft according to AJAX concept is realization of a MHD-controlled inlet. The potential of an external MHD generator to control the flowfield in the scramjet inlet is discussed in Brichkin et al [12,13], Kuranov and Sheikin [43,45], Kopchenov et al [33], Vatazhin et al [71], Golovachev and Suschikh [26] and Macheret et al [52]. It is shown that MHD control allows the modification of the inlet flowfield at off-design conditions. More overall results for MHD-controlled inlet in 2-D Euler approach are obtained in Kuranov and Sheikin [45] and are presented in Figs.24-31.

The following assumptions were used in the calculations. The magnetic induction vector is located in the plane of figure $B = (B_x, B_y, 0)$. The density of an induced current $J$ is connected to a magnetic induction vector $B$ and electrical field $E$ by a generalized Ohm’s law. An e-beam ionizer sustains the nonequilibrium conductivity. The power spent on flow ionization is less than the power produced by the MHD generator in all the presented cases. The Lorentz force $f = j \times B$ has two components. $f = (f_x, f_y, 0)$. An inlet with design Mach number $M_e = 10$ and total turning angle $\theta_o = 15^\circ$ was...
Fig. 24. Density contours in MHD controlled inlet 
$(M_e = M_f = 10; B = 0)$

Fig. 25. Density contours in MHD controlled inlet 
$(M_e = 12; M_f = 10; B = 0)$

Fig. 26. Density contours in MHD controlled inlet 
$(M_e = 12; M_f = 10; B = 5.3T)$

Fig. 27. Density contours in MHD controlled inlet 
$(M_e = 6; M_f = 10; B = 0)$

Fig. 28. Density contours in MHD controlled inlet 
$(M_e = 6; M_f = 10; B = 3T; |B_x/B_y| = 0, q_{ion} = 10^{-2} W/cm^3, x_i = 0, \Delta x = 5)$

Fig. 29. Density contours in MHD controlled inlet 
$(M_e = 6; M_f = 10; B = 3T; |B_x/B_y| = 1, q_{ion} = 1W/cm^3, x_i = 3.5, \Delta x = 1)$

Fig. 30. Relative mass flow-rate $(M_e = 6; q = 10^{-2} W/cm^3, x_i = 0, \Delta x = 5)$
assumed in the calculations. Fig.24 shows the density contours in the inlet with-out MHD interaction at design conditions. In this case oblique shocks are concentrated on the cowl lip. Fig.25 shows density contours in the inlet at off-design conditions \((M_f=12)\) without the MHD interaction. In this case the location of shock intersections are not on cowl lip. Fig.26 shows the density contours at \(M_f=12\) with the MHD interaction at \(B=5.3T\). It is evident that the flowfield at off-design conditions with the MHD interaction is quite similar to flowfield at design conditions. The same results were obtained in Golovachev and Suschikh [26] and Macheret et al [52].

\[\text{Fig.31. Relative mass flow-rate (} M_f=6; B=3T, |B_x/B_y|=1)\]

Figs.27 to 29 demonstrate the possibilities of MHD control in the situation where the flight Mach number is less than designed Mach number. In this situation the MHD interaction can increase the air mass flow-rate. Fig.27 shows the density contours in the inlet without MHD control. Figs.28 and 29 show density contours in the inlet with MHD control. The ionization regions in these cases are infinite bands which are enclosed in \(x_i < x < x_i + \Delta x\) region. Fig.28 displays the flowfield in the MHD-controlled inlet in the case where the magnetic induction has only a \(y\) component and the ionization region is a broad band. For Fig.29 the \(x\) and \(y\) components of the magnetic field are equal and the ionization region is a narrow band. Fig.30 shows the dependencies of the relative value of mass flow-rate upon magnetic induction for various configuration of magnetic field where \(\phi\) is the mass flow rate with the MHD interaction and \(\phi_0\) is without the MHD interaction. Fig.31 shows the dependencies of the relative value of air mass flow rate upon power density applied to ionization for various locations of the ionized region. The configuration and magnitude of the magnetic field, the location of the ionized region and the power density applied to the ionization noticeably influence the air mass flow rate. When the flight Mach number is less than designed Mach number the effect of MHD interaction depends upon many parameters. Therefore, both increasing and decreasing the air mass flow rate while increasing the MHD interaction can be obtained.

Conclusions

The paper presents a selective survey of research in energy deposition for high speed flows with specific focus on drag reduction, unsteady effects, modification of shock structure and MHD control. It is evident that energy deposition as a means of flow control is a area of widespread research interest and significant potential.

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