Energy Addition into Hypersonic Flow for Drag Reduction and Steering

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Atmospheric Pressure Weakly Ionized Plasmas for Energy Technologies, Flow Control and Materials Processing

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Outline

• Shock wave front at power deposition into hypersonic flow

• The effect of a plasma air spike in supersonic/hypersonic flows for drag reduction and effective blunt body geometry modification: *virtual shapes*

• Another examples of applications in hypersonics:
  – Scramjet inlets control at off-design Mach numbers: “Virtual cowl” in scramjet inlets at Mach numbers below the design value
  – Steering by the aerodynamic forces created by off-axis heat addition upstream of a body

Remote Power Delivery

• Guiding microwave

• Hybrid schemes:
  – fs laser + microwave
  – fs laser + ns laser

• Conclusions
Mechanical example of aerodynamic shaping

Trident I (1977)

changing in the effective aerodynamic shape made it possible to launch missiles from under water without surfacing submarine

The aerospike, a telescoping outward extension that reduces aerodynamic drag, is then deployed, and the boost phase begins.

\[ c_D/c_{D0} < 0.3 \]

Just, after the underwater launch

Later, in atmosphere

Instead of mechanical aerospike – plasma (Myrabo, 1993)

J.P. Reding and D.M. Jecmen, 1983
Plasma air spike: similarity analysis

The shape of the axi-symmetric shock wave front in the system of coordinates that is stationary with respect to the heat addition region – parabola:

\[ R = \alpha \left( \frac{P}{\rho_0 u_0^3} \right)^{1/4} z^{1/2} = \alpha b^{1/2} z^{1/2} , \quad b = \left( \frac{P}{\rho_0 u_0^3} \right)^{1/2} \]

Similarity law: \( r/b \sim (z/b)^{1/2} \)

The universal shape of the shock wave surface in relative units

Lines of flow. \( P \) – power (W); \( \rho_0, u_0 \) – free-stream density and velocity

Myrabo, Raizer, 94;
Myrabo, Raizer, Shneider, 97; 04
Schlieren picture of the flow with 62 kW arc and computed density plot (15 kW) overlay. Bracken, Myrabo et al, 2001

Experiment: Rensselaer Polytechnic Institute

RPI Hypersonic Shock Tunnel (RPHST): $T_0 = 37.7$ K, $p_0 = 38.6$ Pa; $M_0 = 10.1$
“Near Field” of Intensive Power Source in Hypersonic Flow

In parabolic SW solution: \[ R \sim |z|^{1/2}; \quad R \to 0 \text{ at } z \to 0 \]

→ “Near field” needs in a separate description

It is impossible make a “sharp nose” with Intensive heat deposition

The minimum curvature radius is limited by:

\[ R_F \propto \left( \frac{P}{\rho_0} \right)^{1/2} \frac{1}{u_0^{3/2}} \]

M.N.Shneider, MURI Report, July 2008; Shneider, Gimelshein, Raizer, Shock Waves, 2010
“Classic” DEAS RPI M=10 experiments

DEAS model with plasma torch

Front view

Outline

Studied in 1995-99 by authors: Marsh, Minucci, Myrabo, Nagamatsu, Toro, et all
Schematic of the RPI M=10 experiments

Twin-electrodes and nylon ring assembly, showing location of ‘on-axis’ electric arc. Hyper-sonic flow is directed to the left.

Schematic diagram of wire-suspended lightcraft model, indicating location of accelerometer

Plasma Air Spike

Bow shock wave in the case of no heat addition in the flow

Experiment (RPI HPST, M=10.1)  Euler 2D numerical modeling
Plasma Air Spike

Bow shock wave modification in the case of heat addition in the flow

Experiment (RPI HPST, M=10.1):
P=27 kW; L=0.6D

Computed shock wave structure (isobars) and flow streamlines at
P=7.5 kW, L=0.6 D

Myrabo, Raizer, Shneider, High Temperature, 2004
Plasma Air Spike

Drag reduction

$P = 7.5 \text{ kW}$

Drag force:

$$F = 2\pi \int_{0}^{a} p_s r dr$$

Propulsive power

$$P_{\text{total}} = Fu_0 + P$$

$P_{\text{total}} = 84 \text{ kW}$

$P_{\text{total}} = 55.8 \text{ kW}$

Significant reduction in propulsive power by adding energy in front of a body

Myrabo, Raizer, Shneider, High Temperature, 2004
Propulsion Power And Drag Force For RPI Experimental Conditions:

\[ p_0 = 38.6 \text{ Pa}; \quad T_0 = 37.7 \text{ K}; \quad M=10.1 \]

Drag force:

\[
F_D = \int_0^{R_b} p_s \cos \alpha \cdot 2\pi (r / \cos \alpha) dr = 2\pi \int_0^{R_b} p_s r dr
\]

- power of the heat source

\[ P_h \]

- drag power

\[ P_D = F_D \cdot u_0 = F_D \cdot c_0 \cdot M_0 \]

- propulsion power

\[ P_t = P_h + P_D \]

Optimal position distance >> blunt body radius!!!
Alternative to the Air-spike?

Localized Heat Source

Power ~ Drag Power

Heating region – source of strong parabolic shock wave

Needle-like heat source in front of the blunt body causes bow shock wave reorganization with substantial drag reduction: $P_{\text{prop,heat}} \sim (d/D)P_{\text{prop,0}}$.

Heating power is relatively low

Kolesnichenko et al, 2001, 2002

Georgievsky and Levin, 2003
Steering

Fully three-dimensional inviscid numerical simulation (Girgis, et al, 2002)

Creation of Steering Force

Power deposition density

e-Beam plasma + Heat Addition by non-self sustained Microwave Discharge

Optimum Case: \( M_\infty = 3.0 \), \( P/P_D = 1.0 \), \( L_{\text{ext}}/D = 0.2 \), \( \theta = 60^\circ \), \( C_D/C_{D_0} = 0.37 \) and \( C_L/C_D = 0.42 \) \( (P_D = 0.5\rho_\infty u_\infty^3 A) \)

Pressure distribution

At \( M = 3; h = 20 \text{ km}; R = 0.25 \text{ m} \)

\( P_D = 6 \text{ MWatt} \)
March 27, 2004 successful test: 13 seconds of flight at M=7 in scramjet regime
Mass Capture Increase by Energy Addition Off The Cowl Lip at $M < M_{\text{design}}$ (VIRTUAL COWL)

Energy addition by
- Plasma-controlled external combustion
- Microwaves plus e-beam/laser guiding
- Gas or plasma jets
- Power can be generated by MHD in or downstream of combustor

Advantages:
- **Increases** mass capture
- **Increases** total pressure
- **Increases** L/D
- No B field required
- Required power - small fraction (~1%) of enthalpy flux into inlet

Issues:
- Substantial absolute power (several MW/m)
- Power delivery

First suggested: Shneider, Macheret and Miles, AIAA 2002-2251, May 2002
New Energy Bypass Concept

Energy addition for drag reduction, steering, and flow control

Plasma/MHD enhanced mixing and ignition control

MHD power extraction

Plasma generated virtual cowl for air capture increase

Combustor

Macheret, Shneider 2004
Problem:
how to deliver power into hypersonic flow far in front of vehicle?

Solutions:
E-beam + Microwave: (non-self-sustained MW discharge)

E-beam divergence → Magnet for e-beam focusing; E-beam: 100 keV - 1 MeV; membrane or windows

fs laser creates long thin weakly ionised non-equilibrium filament
L~1 – 10 m; $T_e$~ 1 eV; $n_e$~10^{16}-10^{17} m^{-3}; $T\approx T_0$: decays in ~ 10 ns (attachment)

fs laser filament + Microwave
fs laser filament + subsequent long (ns) laser pulse
Unguided Microwave Discharge in Air at $p=1$ Atm

$\lambda_{MW} = 8.9$ cm, a source of the focused radiation at the left, $E_a = 3$ kV/cm

(Khodataev K.V.: http://kir-khodataev.narod.ru/activity-e.htm)
Laser designated line pairs along the microwave polarization (a) and orthogonal to the microwave polarization (b). When all four lines are simultaneously written, a square is formed with relatively uniform energy deposition (c)

Edwards, Michael, Dogariu, Miles, AIAA 2011
Schlieren images of the temperature evolution of the laser designated microwave heated line. The microwave pulse lasts for 2 μsec and the laser pulse occurs 0.2 μsec after the microwave pulse begins. The line continues to grow due to thermal diffusion. The acoustic wave can be seen moving out of the region in the 4, 6 and 10 μsec images.

Centerline gas temperature for an initial ionization fraction of $10^{-3}$ for applied electric field values of 0.25, 0.50, and 0.75 times the breakdown electric field for air.
Microwave guiding in air by a laser induced waveguide


A sketch of a filament-array waveguides consisting of a nonionized air core and and one ring of laser induced filaments serving as a waveguide cladding.

Example:

Air: p=1 Atm, T=300 K, T_e=1 eV, n_e=10^{19} \text{ m}^{-3}; \text{MW wavelength 1 cm (30 GHz)}

for a waveguide with \textbf{core radius 6 cm made from 36 filaments of diameter 0.9 cm}, the attenuation (transmission) length, L\sim 4.9 \text{ m}

\textit{Plasma decaying was not considered!}
Microwave guiding in air by a laser induced waveguide


Microwave guiding was demonstrated over 16 cm in air using a large diameter hollow plasma waveguide. The waveguide was generated with the 100 TW femtosecond laser system. A deformable mirror was used to spatially shape the intense laser pulses in order to generate hundreds of filaments, creating a cylindrical plasma wall that acts as a microwave waveguide. The microwaves were confined for about 10 ns, which corresponds to the free electron plasma wall recombination time.

Recently: more than 60 m (!) microwave guiding was reported by Zvorykin et al, JETP Letters, v.91 (5) 2010
Electron Losses in Weakly-ionized Plasma in Air

Typical parameters for plasma filaments, induced by fs-laser in air:
\[ n_e \approx 10^{13} - 10^{17} \text{ 1/cm}^3; \ T_e \approx 1 \text{ eV}; \ T = T_v = 300 \text{ K} \]

Main Losses:
\[ \frac{dn_e}{dt} = -\beta n_e n_+ - n_e / \tau_a \]

Dissociative recombination:
\[ e + AB^+ \rightarrow AB^* \rightarrow A + B \]
\[ \beta \approx 2 \cdot 10^{-7} \sqrt{300/T_e[K]} \text{ cm}^3 / s \]

Formation of negative ions in 3 body attachment:
\[ e + O_2 + M \Rightarrow e + O_2^- + M; \ M = O_2, N_2, H_2O \]
\[ \tau_a \propto 1/N_g; \text{ at } p = 1 \text{ Atm; } T_e = 300 \text{ K: } \tau_a \approx 10 \text{ ns} \]

In cold air: cluster ion formation \( O_4^+, N_4^+, \ldots \) with higher rate of dissociative recombination

Filament decays in time \( \sim 10 \text{ ns} \), therefore 2nd laser pulse is required to extend plasma lifetime
Organization of Double Laser Pulse ionization

Fig. 1. Experimental setup. The fs laser generates the plasma channel and the delayed ns laser revives it.

Figure taken from the paper: Mysyrovich et al, “Revival of femtosecond laser plasma filaments in air by a nanosecond laser”, Optics Express, 17, No 14, 2009
The rates of electron losses, recombination and attachment, are functions of $T_e$:

$$T_e \downarrow \Rightarrow \text{rates of losses} \uparrow \Rightarrow n_e \downarrow$$

If the second laser pulse of sub-breakdown intensity heats up electrons the plasma decaying suppresses.

Photodetachment:

$$\hbar \omega_L + O_2^{-} \rightarrow O_2 + e; \quad \hbar \omega_L \geq \varepsilon_a \approx 0.5 \text{ eV}$$

CO$_2$ can not induce photodetachment:

Nd: Yag, $\lambda = 1.06 \mu m: \hbar \omega_L = 1.17 \text{ eV} > \varepsilon_a \approx 0.5 \text{ eV}$

CO$_2$, $\lambda = 10.6 \mu m: \hbar \omega_L \approx 0.12 \text{ eV} < \varepsilon_a \approx 0.5 \text{ eV}$

Thermal detachment

$Detachment \ in \ result \ of \ collisions \ with \ vibrationally \ excited \ molecules \ (not \ considered \ yet)$
Long-lived microwave plasma guides in air sustained by a subsequent long laser pulse: 1D model results

Attenuation length of microwave radiation with a wavelength of 1 cm (30 GHz) in a plasma waveguide with a core radius of 5 cm in the wake of a laser-induced filament in the atmosphere without and with second laser pulse

Shneider, Zeltikov, Miles, JAP 108 (2010)
Refractive index and the attenuation parameter in atmospheric air plasma at STAP and different electron densities for infrared CO2-laser radiation at $\lambda = 10.6 \, \mu m$.
“Filament + second laser pulse” breakdown development
Formation of arc-like plasma

Second laser: CO$_2$ ($\lambda=10.6$ μm)

$\lambda=10.6$ μm; $I_L=6.5 \times 10^{13}$ W/m$^2$

Shneider, Zeltikov, Miles, Physics Plasmas (2011)
The eikonal equation

\[ \frac{d}{ds} \left[ n(r) \frac{dr}{ds} \right] = \nabla n(r) \]

Equation for the ray trajectory

\[ z(x) = \beta \int_{0}^{x} \frac{dx}{\left[ n^2(x) - \beta^2 \right]^{1/2}} \]

The ray invariant

\[ \beta = n(x) \cos \theta_z(x) = n(x) \frac{dz}{ds} \]

Example: CO\textsubscript{2} laser, $\lambda$=10.6 $\mu$m

Filament: $r$=50 $\mu$m, $n_e(r=0)$=9x10\textsuperscript{17} cm\textsuperscript{-3}; $\Delta n$≈5x10\textsuperscript{-2}

From eikonal equation, the beam divergence, $\theta$~1 rad at distance < 1 cm.

$n_e(r=0)$=9x10\textsuperscript{15} cm\textsuperscript{-3}; $\Delta n$≈5x10\textsuperscript{-5}

From eikonal equation, the beam divergence, $\theta$~1 rad at distance ~ 1 m.
Conclusions

• Combination of fs laser preionization with a subsequent sub-critical microwave or ns laser pulse - promising methods for energy delivery into gas for drag reduction in hypersonics

• Microwave radiation can be effectively transported in the plasma waveguide formed by the filaments created by fs laser

• In atmospheric air at certain levels of pre-ionization by fs laser pulse, the avalanche and essential Joule heating are possible in a MW-field at intensities below breakdown

• Near- and mid-IR long laser pulses can tailor plasma decay in the wake of a filament, thus substantially increasing the plasma-guide lifetime and facilitating long-distance transmission of microwaves

• The length for uniform filament heating and ionization by a subsequent ns laser pulse depends on plasma density and laser radiation frequency due to laser beam divergence on filament plasma
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