Numerical Modeling of Flow Control with Electrical Discharges

November 2014

Dr. Jonathan Poggie
Senior Aerospace Engineer
Air Force Research Laboratory
High-Speed Flow Research Group

• AFRL/RQ Computational Sciences Center
• Collaboration with experimental groups
• Plasma flow control since late 1990s
• Interesting challenges
  – Applications
  – Plasma physics, chemistry, fluid dynamics
  – Resolution of disparate scales
  – Computational techniques
  – Very large, multidisciplinary simulations
Reentry MHD

MHD Generator Configurations

- Resler & Sears (1958)
- Kranc, Porter & Cambel (1967)
- Donaldson & Brunner (1964)

Kantrowitz (1955): If reentry flows are going to be ionized, why not try to control them using electromagnetic effects?

Stagnation Point Heat Transfer Mitigation

- Mach 3 argon flow
- Wilkinson (1964)
AYAKS (AJAX) Hypersonic Vehicle Concept

- Design developed in Soviet Union in 1980s under Vladimir Fraishtadt, Leninetz Co.
- Weight tradeoff

AYAKS Features
- MHD energy bypass in engine
- Directed energy beam for bow shock control
- Endothermic fuels
Plasma Actuators

Corona Discharge for Drag Reduction

ns-DBD Actuators

Freestream speed 60 m/s
Little et al. AIAA J., 2012

Actuators produce greatest benefit where they can drive a flow instability

Malik et al., AIAA Paper 1983-0231
Plasma Aerodynamics: Current Status of Field

• Long history: where are we now?
• AIAA Plasma Aerodynamics Discussion Group
  – Plasma-based flow control
  – Plasma-enhanced combustion
• White paper,
  http://www.aiaa.org/PlasmaAeroWhitePaper_June2014/
• Aerospace America, November 2014, http://www.aerospaceamerica.org/Pages/Archives.aspx
Higher-Order Plasma Solver

Thermochemical Nonequilibrium

Viscous Flow

Maxwell’s Equations

Electrical Discharges

High-order numerics implemented in a multi-fluid context

Cleared for public release; distribution unlimited
Acknowledgements

• Funding
  – AFRL In-House Applied Research Funding
  – AFOSR: J. Schmisseur / I. Leyva, Aerothermodynamics
  – AFOSR: F. Fahroo, Computational Mathematics

• DoD HPCMP Computer Time
  – Frontier Project (90M cpu-hr/FY14)
  – AFRL (17M cpu-hr/FY14)

• Codes: G. Candler (US3D), M. Visbal (FDL3DI), I. Boyd (LeMANS)

• Organization
  – Computational Sciences Center: J. Benek
  – High-Speed Systems Division: T. Jackson, R. Kimmel
  – High-Speed Flow Research Group: N. Bisek, R. Gosse, T. Leger

• Helpful discussions: D. Gaitonde, A. Smits, I. Adamovich, I. Boyd, many others
DoD HPCMP Frontier Project

<table>
<thead>
<tr>
<th>Year</th>
<th>CPU-Hrs (millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>90</td>
</tr>
<tr>
<td>2015</td>
<td>150</td>
</tr>
<tr>
<td>2016</td>
<td>211</td>
</tr>
<tr>
<td>2017</td>
<td>890</td>
</tr>
<tr>
<td>2018</td>
<td>890</td>
</tr>
</tbody>
</table>

Garnet / ERDC: 150k cores

DoD supercomputer resources address stiff, multi-disciplinary physics

Top 500 List (July 2014)
24. Spirit
31. Garnet
114. Pershing

http://www.top500.org

Title: Unsteady Pressure and Heating Environment on High-Speed Vehicles with Responding Structures
PI: Dr. Ryan Gosse, AFRL/RQHV
Outline

1. Reentry MHD
2. Plasma actuators
3. Control of separation unsteadiness
4. Turbulence
Reentry Magnetohydrodynamics

Magnetic Field

Recirculating Current

MHD Drag

Flight Path

Temperature Contours

Shock Wave

IR Photographs Show Reduced Heating

Gülhan et al., J. Spacecraft & Rockets (2009)

Magnetic Force
- Decelerates flow
- Slows vehicle
- Reduces reentry heating
Physical Model

Conservation Equations

\[
\frac{\partial \rho_s}{\partial t} + \nabla \cdot (\rho_s \mathbf{u} + J_s) = \dot{\omega}_s
\]

\[
\frac{\partial \rho\mathbf{u}}{\partial t} + \nabla \cdot (\rho\mathbf{uu} - \tau) + \nabla p = \mathbf{j} \times \mathbf{B}
\]

\[
\frac{\partial E}{\partial t} + \nabla \cdot ((E + p)\mathbf{u} - \tau \cdot \mathbf{u} + \mathbf{q} + \Sigma(J_s h_s)) = \mathbf{j} \cdot \mathbf{E}
\]

\[
\frac{\partial E_{ve}}{\partial t} + \nabla \cdot ((E_{ve})\mathbf{u} + q_{ve} + \Sigma(J_s e_{v,s})) = \dot{\omega}_{ve} + \gamma(E + \mathbf{u} \times \mathbf{B}) \cdot \mathbf{j}
\]

Ohm’s Law

\[
\nabla \cdot \tilde{\sigma} \cdot [-\nabla \phi + \mathbf{u} \times \mathbf{B}] = 0
\]

\[
E = -\nabla \phi \quad j = \tilde{\sigma} \cdot (E + \mathbf{u} \times \mathbf{B})
\]

Model Features

- Nonequilibrium ionization
- Low magnetic Reynolds number
- Hall effect and ion slip
MHD Heat Shield

Change in Shock Standoff Distance

Experiment: Argon flow at Mach 4.75 (Kranc et al., 1969)

10% reduction in peak heating
Hall effect neglected

N. J. Bisek, I. D. Boyd, and J. Poggie,
Journal of Spacecraft and Rockets, 2010
Hall Effect

- Large Hall parameter for this experiment
- Hall effect inhibits effect of control

\[ \beta_e = \mu_e B = \sigma B / (e n_e) \]

\( B = 0.13 \, T \)
\( \beta_e \approx 18 \)
Nanosecond-Pulse DBD Experiments

Pulsed Heating Model Predicts Shock Speed

Baseline shock location (CFD)

Baseline shock location (Exp.)

Compression wave (~370 m/s)
(before interaction)

Bow-shock (~90 m/s)
(after interaction)

Time delay [micro sec]: 01

N. Bisek, J. Poggie, M. Nishihara, and I. Adamovich,
ns-DBD Model

Discharge Configuration
Cylinder Flow Stagnation Conditions

Governing Equations
- Overall mass-averaged conservation laws
- Neutrals: diffusion equation
- Charged particles: mass, momentum, and energy conservation equations
- Poisson equation

Rates: function of electron temperature

Air Plasma Kinetic Model
- 23 species, 50 processes
- Ground-state neutrals: N$_2$, O$_2$, O, N, NO, O$_3$
- Charged particles: e$^-$, N$_2^+$, O$_2^+$, O$^+$
- Electronically excited states: N$_2$(A$^3\Sigma$), N$_2$(B$^3\Pi$), N$_2$(a$^{1}\Sigma$), N$_2$(C$^3\Pi$), O(1D)
- Vibrationally excited states: N$_2$(v=1-8)

Discharge Profiles

Number Density and Electric Field

- Breakdown
- Left sheath formation
- Right sheath formation
- Recombination over longer time scale

Next: once quasi-neutral, switch to larger time step

$V_0 = 27$ kV
Wave Motion

Bulk Gas Velocity Profiles

$V_0 = 27 \text{ kV}$

Wave Speed

Measured: 375 m/s
Computed: 340-380 m/s

$\Delta t = 10 \text{ ns}$, $\Delta t = 0.5 \text{ ms}$
2D ns-DBD Simulations

Electron Number Density

Next step: compute wave motion due to rapid gas heating

Cleared for public release; distribution unlimited
Closed-Loop Stall Control Experiment

• Participants
  – J. Poggie, C. Tilmann, P. Flick - Air Force Research Laboratory
  – J. Silkey, B. Osborne - The Boeing Company
  – G. Ervin, D. Maric - FlexSys, Inc
  – S. Mangalam, A. Mangalam - Tao Systems, Inc

• Demonstrate closed-loop stall sense and control system for subsonic aircraft

• Integrate three technologies
  – Morphing structures (FlexSys)
  – Instantaneous flow topology sensing (Tao Systems)
  – DBD plasma actuators (Boeing Co.)

• Example of an AFRL technology demonstration program
Wind Tunnel Installation

AFRL SARL Wind Tunnel Facility

Mach 0.05-0.5
Test Section: 63.1 ft², 15 ft long
(5.86 m², 4.57 m)

Airfoil: 50 in span x 30 in chord
(1.27 m x 0.76 m)
Elliptical endplates: 45 in x 24 in
(1.14 m x 0.61 m)
Mach number: 0.05-0.10
Reynolds number: 0.9x10⁶ - 1.7x10⁶
AoA: up to 22 deg, Flap: +/- 10 deg
Turbulent boundary layer state

Poggie et al., J. Aircraft, 2010

Cleared for public release; distribution unlimited
Closed-Loop Control

- Flap hot-film array detects flap separation
- Fixed shear level triggers DBD panel
- Tested in real-time AoA sweeps

Lift vs. Angle of Attack

Sweeping 13-17 deg AoA

Created with Flip4Mac WMV Demo
www.Flip4Mac.com
Numerical Simulations: Interaction of Actuator and Flow

Specified Electric Body Force (Semi-Empirical Model)

Streamlines Colored with Mach Contours

Boeing CFD
3D RANS Computations
Code: BCFD-MHD
Body force: LENPAM

Streamwise vortex between actuators
Separation present between actuators

Cleared for public release; distribution unlimited
On to Higher Speeds: Closed-Loop Control with ns-DBD

NACA 0015

Hot Film Elements

Actuator

Schlieren Image of Pulse

Control to 93 m/s

Poggie - AFRL
Samimy, Adamovich, Little, et al. - OSU
A. Mangalam - Tao Systems

AIAA Paper 2011-487
Separation at High Speed: Large-Scale Unsteadiness

• Fatigue loading from unsteady SWBLI very serious design concern
• Typical for Mach 5 Cruise: 147 dB, 800 K (Zuchowski, AFRL TR, 2012)

Unsteady separation:
• Increases thermal loads
• Creates intense wall pressure fluctuations
• May drive resonant frequencies of flat aircraft panels
Separation Unsteadiness

• Plotkin (1975), Ganapathisubramani et al. (2006-2009), Touber and Sandham (2011)
• Low-frequency, large-scale disturbances selectively amplified by separation bubble

• These models are not mutually exclusive
• Frequency response depends on separation bubble properties

Cleared for public release; distribution unlimited
Plotkin (1975) Model

- Plotkin (AIAA J, 1975)
- Linearly-damped Brownian motion
- Time scales: $\tau_u << \tau_R$
- Frequency-selective amplifier
- Cut-off frequency set by separation bubble characteristics
- Input set by TBL

- Model ODE:
  $\dot{x} + x / \tau_R = u(t)$

- Fluctuation spectrum:
  $$G_p(f) = \frac{4}{p'^2 \tau_R} = \frac{4}{1 + (2\pi f \tau_R)^2}$$

- Autocorrelation:
  $$R_p(t) = \exp(-t / \tau_R)$$

- Fluctuation intensity:
  $$p'^2 = \left( \frac{\partial \bar{p}}{\partial x} \right)^2 u^2 \tau_u \tau_R$$
Wall Pressure Spectra

Blunt fin wall pressure spectra (M=3)
Poggie and Smits (2001, 2005)
Wind Tunnel Experiments

Blunt Fin at Mach 5
U. Texas, Austin Group

Wall Pressure Spectra

Shock Position Spectra

Gonzalez and Dolling (1993)

Brusniak and Dolling (1994)

- Model fits for different Mach number and tunnel
- Also fits for shock position spectrum
Flight Test Experiments

HIFiRE-1

- HIFiRE Flight 1: Woomera Range, March 22, 2010
- Documentation: Stanfield, Kimmel, and Adamczak, AIAA Papers (2012-2013)

Kulite Transducer Stations
Wind Tunnel vs. Flight Test

Pressure Fluctuations
Nondimensional Power Spectral Density

- Relatively good agreement for a variety of ramp and fin configurations, $M = 2-5$
- Flight data may roll off at a somewhat slower rate
- Motivates examination of pressure transducer frequency response
Large-Eddy Simulation

Compression Ramp Configuration

M = 2.3, Re_θ = 2000
24 deg ramp

High-Fidelity, Implicit LES
AFRL FDL3DI code
Simulations with 16-188 million cells
Body-force boundary layer trip

Incoming Boundary Layer Profile
van Driest Coordinates

u' = y'

FDL3DI
Comp. - Rai, et al.
Exp. - Shutts, et al.
Exp. - Elena and LaCharme

Incoming Boundary Layer Turbulence Kinetic Energy

Power Spectral Density of TKE

Normalized Frequency, fτ/u_∞

More energy resolved as grid refined

Cleared for public release; distribution unlimited
Wall Pressure Statistics

Experimental Results

Various configurations, M = 2-5

Poggi et al., AIAA Journal, 2014

Computational Results

LES captures large-scale unsteadiness

HIFiRE-1 Flight Data

Large-Scale Shock Motion

Boundary Layer Turbulence

x/δ₀ = 67.0

x/δ₀ = 68.0

x/δ₀ = 69.0

Plotkin (1975)

Cleared for public release; distribution unlimited
Plasma-Based Control of Unsteady SWBLI

Compression Ramp Configuration

Mach 2.3

24°


Magnetically-Driven Gliding Surface Discharge Actuator

- Explored experimentally by Princeton University group
- Plasma column moves faster than bulk flow
- Imparts momentum and heat
- Reduced order model for LES
Effect of Control

Reduced:
- Size of separation bubble
- Energy in low-frequency wall pressure fluctuations
- Fatigue loading

Baseline Case

Control Case

24° Ramp
Mach 2.3
Re_θ = 2500

Cleared for public release; distribution unlimited
Turbulent Boundary Layer

Density contours, $\rho/\rho_\infty$

Cleared for public release; distribution unlimited
Turbulent Boundary Layer: Comparison to Experiment

Velocity Fluctuations vs. Height

- Alving (1988), M = 0
- Elena and Lacharme (1988), M = 2.3
- Konrad (1993), M = 2.9
- LES, M = 2.3
- LES, M = 2.9

Side View: Density Contours

- M = 2.3, $\text{Re}_{\theta_i} = 2000$

Laser Scattering Experiments
- M = 2.9, $\text{Re}_{\theta_i} = 36000$
- Poggie et al., Experiments in Fluids, 2004
Turbulent Boundary Layer

$M = 2.3, \text{Re}_{\theta_i} = 2000$

DNS
$3.3 \times 10^{10}$ cells
Turbulent Boundary Layer: Effect of Resolution

Density Field – End View Looking Downstream

Large Eddy Simulation (LES)

\[ \Delta x^+ = 45 \]

1x10^7 cells

Direct Numerical Simulation (DNS)

\[ \Delta x^+ = 1 \]

3.3x10^{10} cells

LES is an approximation
High-Frequency Content: Effect of Resolution

Spectral convergence indicates full resolution

\[ \frac{x}{\delta_0} = 100 \]
\[ \frac{y}{\delta} = 0.5 \]

Virtual Probe

Power Spectral Density

Kolmogorov length scale \( \lambda = \eta \)

Theory: Isotropic Turbulence

Increasing Resolution

Pope (2000)

\[ \Delta z^* = 1 \]
\[ \Delta z^* = 2 \]
\[ \Delta z^* = 5 \]
\[ \Delta z^* = 10 \]
Low-Frequency Content: Effect of Domain Width

End View: Density

Downstream View
y-z-plane, x/δ₀ = 100

Increasing L_z

x/δ₀ = 100
y/δ = 0.5

Power Spectral Density

Spanwise Wavenumber

Low frequencies drive separation unsteadiness and structural loading

Cleared for public release; distribution unlimited
Summary and Conclusions

• Plasma aerodynamics has a long history, and an exciting future
• Necessary to understand both fluid mechanics and actuator physics
• Large computations compare well to experiment; draw together physics of plasmas and fluids