Aerothermodynamics & Turbulence

8 March 2013

Dr. John D. Schmisseur
Program Officer
AFOSR/RTE

Air Force Research Laboratory

Integrity ★ Service ★ Excellence
Aerothermodynamics and Turbulence

Presented at the AFOSR Spring Review 2013, 4-8 March, Arlington, VA.

Security Classification: Unclassified

Limitation of Abstract: Same as Report (SAR)

Number of Pages: 30

Approved for public release; distribution unlimited.
A&T portfolio exists at the intersection of gasdynamics, thermophysics and chemistry

Goal: Understand and predict energy transfer between the kinetic, internal and chemical modes - Exploit this knowledge to shape macroscopic flow behavior
Essential Science for Future High-Speed Capabilities

Strategic Priorities Require Efficient Area Coverage

“Pivot to the Pacific”

High-Speed Capabilities Are Potential Game-Changers in response to an Anti-Access/Area Denial threat

- Survivable
- Responsive
- Efficient – greatly increased area coverage per asset

23 min at Mach 6

15 min at Mach 9
~120X area

15 min at Mach 6
~50X area

Advanced Simulation Tools Provide Insight, Reduce Uncertainty

Reduced Uncertainty in Complex Flows

Surface Heat Transfer and Detailed Flow Structure

Fuel Injection in a Scramjet Combustor

Addressing Future Testing Challenges

- Planned systems expected to be too large for ground test facilities
- Reliable simulations will help “connect the dots”

NASA Langley High-Temp Tunnel
Leadership and Collaborations

Past

First hypersonic flight data to capture shock interaction unsteadiness

National Hypersonic Foundational Research Plan

Joint Technology Office – Hypersonics
Basic Science Roadmap

Assessment of SOA and Future Research Directions

Ongoing

Jointly-Sponsored National Hypersonic Science Centers

Future

Basic Research for Understanding and Controlling Noise from High-Speed Jets

Driving a new scientific paradigm for high-speed flows
Transforming Scope Reflective of Evolving Air Force Responsibilities

Legacy Strength
Focus on
Energy Transfer Mechanisms in Fluids

Aerodynamics-
Driven Focus


Facilitated by FY13 BRI topic: Foundations of Energy Transfer in Multi-Physics Flow Phenomena

Other Portfolios

Natural Opportunities for cross-discipline collaboration - MURI, BRI
Strategic Vision

Goal: Understand, Predict & Exploit Energy Dynamics

Innovation from other disciplines

Facilities
- Ludwig Tubes: Mach 6 at low cost
- Quiet Tunnels
- Expansion Tubes – Study Noneq. Flows
- FLEET
- VENOM

Diagnostics
- Accel. MD
- GSI

Simulations

Sustainable Infrastructure for High Mach Science

New Insight into Critical Fine-Scale Phenomena

Towards Model-Free Simulations

Unprecedented Insight into Critical Molecular- and Micro-Scale Phenomena

Tech Transition

Innovation from other disciplines
Stanford Researchers Run First Million-Core Simulation at LLNL

AFOSR project investigating jet noise hits milestone with breakthrough simulation

Parviz Moin and Joseph Nichols, Stanford – running CharLES on LLNL Sequoia
Portfolio Snapshot

Laminar-Turbulent Transition
• Major investment area
• Significant progress as result
• Challenge to maintain momentum while balancing investment with other areas

Nonequilibrium Flows
• Emphasis on energy dynamics major new thrust area
• Significant portion of recent investments

It’s all connected

Turbulent Physics:
• Roughness and Jet Noise
• Significant investment from other agencies
• OSR investment targets fundamental physics not emphasized elsewhere
• Kinetic energy dynamics is important here

Shock Interactions
• Critical to planned HS weapons
• Ripe for a hard challenge to inspire innovation
• Aspiring to push this community to the brink soon
Future Portfolio Structure

Portfolio will be split as a result of the New AFOSR Organization

**Aerothermodynamics**  
PO: J. Schmisseur

- Intermodal Energy dynamics  
  - Kinetic, Internal, Chemical  
  - Gas-Surface Interactions  
- Excitation Mechanisms  
  - Shock Interactions  
  - Finite-Rate Processes

**Turbulence & Transition**  
PO: TBD

- Kinetic Energy dynamics  
  - Instability growth and competition  
  - Physics of Turbulence  
- Impact of Boundary and Initial Conditions  
  - Surface Roughness  
  - Inflow Disturbance Effects

In Energy, Power & Propulsion

In Dynamical Systems & Controls:
Accomplishments & Transitions

Current PI Accomplishments
- Members of the NAE (6)
- NSSEFF Fellow
- DoD Advisory Boards
  - AF SAB
  - JASON
  - Def. Studies Group
- PECASE (2)
- NSF CAREER (4)
- OSR Young Investigator (4)

Our Alumni
- AIAA Past President (2)
- AF Chief Scientists (2)
- Prior PM: Dr. S. Walker

Examples of Recent Tech Transitions
- 6 Students working at AFRL
- Purdue M6 Quiet Tunnel named critical national T&E resource
- Lead SME Consultants for HTV-2, CPGS
- Performed critical analysis for X-51 post-flight 2 investigation
- Transitioned STABL code to 25 org.
- T&E version funded by TRMC
- Transitioned US3D CFD to 14 org.
- AFRL, NASA, Boeing, LM, UTRC …
- Provided algorithm for accelerated chemistry sims in CFD to AFRL/RV
- Supported DARPA, MDA, Sandia, …
Outline

• Objectives, Challenges, Opportunities and Impact

• Portfolio Description

• Research Highlights
  • Laminar-Turbulent Transition
  • Energy Transfer Mechanisms

• Research Directions

• Summary

Innovative approach to evolving AF needs
Extensively coordinated with other agencies
Exciting Science
  • Leveraging advancements in numerics and diagnostics
  • Importing expertise from other disciplines
  • Unprecedented insight into fundamental processes
**Challenges** – understand K.E. Dynamics

- Dynamics occur at the microscale
  - Key instability dynamics occur at $10^{-6}$ of mean
- Process is a “race” between competing growing instabilities
- Nonlinear interactions play critical role

**Key Capability Advancements**

**Quiet Tunnels at Purdue and Texas A&M**
- Radiated Acoustic Waves
- Turbulent Flow
- Laminar Flow
- "Quiet" Flow
  - Flight-like disturbance environment

**Conventional tunnels:** noise corrupts transition experiments

**Quiet tunnels:** allow natural disturbance growth – “flight-like”

**Advanced Numerical Methods**
- Stability analysis – Texas A&M, Minnesota
- High Resolution @ Scale - Minnesota

---

**Design Driver for High-Speed Systems**

- **Boost-Glide Trajectory**
- **Heating Rate**
  - Laminar
  - Turbulent
- ~6X difference!

**Image:** Modified from Original by Dan Reda, 1979

**Quiet Tunnels at Purdue and Texas A&M**

**Radiated Acoustic Waves**

**Turbulent Flow**

**Laminar Flow**

**“Quiet” Flow**

- Flight-like disturbance environment
National Hypersonic Science Center: Integrating the best and brightest to enhance physics-based understanding and prediction of transition

- Biorthogonal Theory
- Fast and Slow Solutions
- NPSE, DNS
- Quiet Tunnels
- Diagnostics
- Linear Growth
- Breakdown

- 3 NAE Members
- 16 Fellows
- 2 NRC, 3 NATO
- > 80 students
- > 140 publications
- 2 Annual Review Articles
- Many external meaningful collaborations
New Insight Into Critical Physics

Second-mode nonlinear interactions quantified

Texas A&M Mach 6 Quiet Tunnel
- New optical measurements via focused schlieren deflectometry (FSD)
- Non-intrusive
- Low-cost
- High bandwidth (1 MHz)

Quantified second-mode nonlinear interactions enable identification of critical modes in transition process

Three-stage breakdown model provides new insight into hypersonic transition

Initial rise in friction from large amplitude primary wave

Saturation of primary wave

Steeper rise as all higher modes grow nonlinearly

Hot streaks of limited extent observed in DNS, experiment, NPSE for 3 different geometries

Establish and Exploit A Fundamental Understanding of Energy Transfer in Flows

Predictions Fail as Chemical Complexity Increases

Control Energy Transfer to Tailor Macroscopic Flow

Key to Progress is the Understanding and Accurately Modeling the Rate-Dependent Energy Transfer Mechanisms

G. Candler, U. Minn.

Attenuation of Acoustic Wave Synchronous With CO₂ Vibrational Relaxation Time

For CO₂ internal energy and acoustic instability modes overlap Curves for 3 total enthalpy values

Acoustic Absorption

2nd Mode Instability (Acoustic)

No Injection Argon at 12 g/s CO₂ at 12 g/s

Ar injection promotes transition, CO₂ inhibits transition
Non-equilibrium effects on turbulent flows: Can turbulence be shaped via coupling with internal energy transitions?

Utilizing massively large-scale DNS, molecular dynamics simulations and novel laser based experiments

Laser-Generated Flow Perturbation

DNS: Velocity gradients from shock turbulence interactions
Joint experiments and simulations reveal new insight into gas chemistry effects

HET – Hypersonic Expansion Tube:
chemically clean, Mach 7 flow

Ability to vary gas composition

Simulated shock structure varies with surface chemistry model

Computed Peak varies with chemistry model

Joanna Austin
U. Illinois
• AFOSR YIP
• NSF CAREER

Deborah Levin
Penn State
• JTHT Assoc. Ed.

"Study of shock-shock interactions for the HET facility double wedge configuration using a particle approach", To be presented San Diego, June 2013, AIAA Fluid Dynamics
MURI addresses scale-up of knowledge from molecular potential to nonequilibrium flow over a full-scale body

- Integrates contributions from chemistry, material science, and aerothermodynamics
- Coordinated simulations and experiments

Quantum Chemistry

Accurate Hypersonic Simulations

PI - Graham Candler
Paul DesJardin, Matt MacLean
Debbie Levin
Erica Corral
Tim Minton
Tom Schwartzentruber
Adri van Duin
Dan Kelley
Don Truhlar

- 14 grad students
- 10 post-docs
- 2 undergrad
- 18 articles
- 18 conference papers
Quantum chemistry advances gas-phase and gas surface interaction simulations

Relevant N$_4$, O$_4$, N$_2$O$_2$ potential energy surfaces calculated from interatomic potential

First simulation of shock wave using only atomic potentials as model

New gas-surface interaction model consistent with physical chemistry

Microscale: Highly Oriented Pyrolitic Graphite Oxidation

Coordinated experiments and simulations: bridging computational chemistry to macroscopic ablation experiments

(2) Oxidation in furnace

AFTER OXIDATION

(3) MD at molecular beam conditions

Graphitic layers preferentially oxidize at edges due to open bond sites

HOPG is a well-characterized form of carbon: planar

Integrated Flight and Ground Test Data Provide Unique, Detailed, and Unequivocal Data for Model Validation

UV Radiation Measured in LENS XX – Expansion Tunnel

Model effectiveness assessed from comparison of spectra from tunnel measurements, flight data, CFD and theory

Parker, MacLean, Dufrene, Holden, Desjardin, Weisberger, Levin: AIAA-2013-1058
Outline

• Objectives, Challenges, Opportunities and Impact

• Portfolio Description

• Research Highlights
  • Laminar-Turbulent Transition
  • Energy Transfer Mechanisms

• Research Directions

• Where we’re going

• Summary
Establish the multidisciplinary scientific foundation for innovative approaches to inherent flow control

- Identify fundamental processes
- Exploit energy transfer in shaping macroscopic flow behavior

Bridging Multiple Portfolios

- Aerothermodynamics and Turbulence
- Energy Conversion and Combustion Sciences
- Molecular Dynamics and Theoretical Chemistry
- Flow Interactions and Control
- Plasma and Electroenergetic Physics

Emphasized projects that bridged interests of at least two of the participating portfolios

Opportunity to Pick Up New Ideas from Other Disciplines
Upcoming Emphasis Area: Conjugate Gas-Surface Interactions

“...the crosshatch patterns degenerate to scallop patterns. For some materials, such as graphite, the degeneration process is so rapid that the initial crosshatch pattern is generally indiscernible.”

Grabow & White, AIAA J, 13, 5

- Pattern is material-dependent
- Kinetic effect – occurs at low temp

Does the 3-Stage Breakdown Model Developed by the NHSC – Transition Team Contribute to the Ablation Pattern Above?
- How do the flow structure and material response couple?

We now have the tools to take on the challenge of complex, coupled flow surface interactions.
Upcoming Emphasis Area:
Highly-Distorted Turbulence

**M = 5**  
High Kinetic Energy

Boundary Layer: Viscous diffusion of kinetic energy into heat

**M = 3**  
Shock/Boundary Layer Interaction: Extreme loads at separation and reattachment

If this is tough…  
Heat transfer prediction remains a challenge for high-speed boundary layers

Planned High-Speed Systems will have Highly-Distorted Boundary Layers

**… this should be a real challenge!**  
Significant flow distortion occurs in 3-D SBLIs

Utilize full-spectrum of diagnostic and simulation capabilities to explore energy dynamics in highly-distorted turbulent flows
Summary

• Objectives, Challenges, Opportunities and Impact

• Portfolio Description

• Research Highlights
  • Laminar-Turbulent Transition
  • Energy Transfer Mechanisms

• Research Directions

• Summary

• World-leading scientific research with game-changing impact

• Evolving with expanding AF areas of responsibility

• Leveraging contributions from other disciplines

• Unprecedented insight into fundamental processes

• Future directions are scientifically challenging while relevant
NAME: John D. Schmisseur

Aerothermodynamics & Turbulence

BRIEF DESCRIPTION OF PORTFOLIO:

Identify, Model and Exploit critical physical phenomena in turbulent and high-speed flows

• emphasis on energy transfer

Sole US basic research program in this area

SUB-AREAS IN PORTFOLIO:

• Boundary Layer Physics
• Shock-Dominated Flows
• Gas Thermophysics
  • Gas-Surface Interactions
• Turbulence and Transition

Partners

National Hypersonic Foundational Research Plan

Joint Technology Office - Hypersonics

Assessment of SOA and Future Research Directions

Jet Noise

Tech Transition

DISTRIBUTION STATEMENT A – Unclassified, Unlimited Distribution
Roughness Pattern Reduces Turbulence Near Surface: Unraveling energy redistribution improves understanding and control of hypersonic viscous heat transfer and drag

Experimental Observation 1: Roughness induced pressure field drives local turbulence

Cross-hatched roughness pattern similar to ablated surfaces

RANS Simulations: Tailored pressure gradient reduces local turbulence

Experimental Observation 2: 40\% reduction in local transverse stresses $\Rightarrow$ Reduced heat flux

$Q_{\text{wall}}$ is prop. to $T_{yy}$

40\%

- $T_{yy}$ – Transverse Reynolds Stress


New Control Strategies for Supersonic Combustion

Non-equilibrium effects on turbulence chemistry interaction

Can ro-vibrational non-equilibrium effectively transfer energy from thermal to mechanical or chemical modes in high speed turbulent flow?

Integrating advanced laser diagnostics with innovative computational chemistry

Potential Energy Surface – helps determine reaction rates

Detailed flow simulations of ethylene jet in cross flow using accurate rates


R. Burns, H. Koo, N. Clemens, V. Raman, AIAA paper 2011-3936, 2011