An Overview of the National Center for Hypersonic Combined Cycle Propulsion

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Overview of Presentation

• Introduction
  – Motivation
  – Objective and approach
  – Organization
• Flow regimes: experiments and modeling
  – Dual-inlet mode transition
  – Dual-mode transition
  – Hypervelocity
• Advanced modeling
  – LES – FDF
  – DNS
• Chemistry modeling
• Conclusions
Turbine-Based Combined Cycle Concept
Combined Cycle Flow Regimes and Center Facilities
Center Objective

The primary objective of the center is to advance the understanding of the critical mode transitions and supersonic/hypervelocity flow regimes of combined cycle propulsion by:

1. Developing an advanced suite of computational modeling and simulation tools for predicting combined cycle flow physics

2. Utilizing the unique facilities available to the Center and advanced flowfield diagnostics to conduct experiments that will:
   a. Provide insight into the fundamental physics of the complex flow in combined cycle hypersonic propulsion systems,
   b. Provide detailed data sets for the development and validation of models of combined cycle flow physics, and,

3. Bringing together the modelers and experimentalists in a synergistic way to work on common problems in hypersonic combined cycle propulsion
Research Approach

1. Develop and implement a hierarchy of novel methodologies for high fidelity simulations of various flow paths. These methodologies range from:
   
a. Current production-level *Generation I* RANS simulations, to  
b. New *Generation II* hybrid LES/RANS methods, to  
c. The most sophisticated envisioned form of LES/FDF for *Generation III* prediction of hypervelocity reacting flows, and  
d. Detailed/reduced *kinetics models* for thermal decomposition/oxidation of relevant hydrocarbon fuels.

2. Conduct experiments that will:
   
a. Elucidate the *fundamental flow physics* of compressible, turbulent reacting flows in combined cycle systems,  
b. Measure reacting flow *turbulent statistics and novel fuel-air mixing and flameholding* approaches through the development and application of *advanced diagnostics*,  
c. Develop *benchmark data sets* with quantified experimental uncertainty for the purposes of developing accurate *Generation I, II and III* models and,  
d. Generate *performance improvements* of combined cycle systems and develop methods for controlling combined cycle mode-transition.
Dual-Inlet Mode Transition

Matt Sexton, Marty Bradley, Kevin Bowcutt
The Boeing Company

Dave Saunders, John Slater, Vance Dippold
NASA Glenn Research Center

Jack Edwards, Santanu Ghosh
North Carolina State University
NASA Glenn LIMX in (10x10) Wind-Tunnel

High-speed inlet

Low-speed inlet
Boeing Generation I LIMX (10x10) CFD Results

Supercritical Simulation

Backpressured Simulation

Mach Number

Recovery

Mach Number

Recovery

x = 110 in.

x = 120 in.

x = 130 in.

x = 140 in.

x = 150 in.

x = 160 in.

x = 170 in.

x = 180 in.

x = 190 in.

x = 200 in.

x = 210 in.

x = 220 in.

x = 230 in.

x = 240 in.

x = 250 in.

x = 260 in.

x = 270 in.

x = 280 in.

x = 290 in.

National Center for Hypersonic Combined Cycle Propulsion
NCSU Generation II IMX (1x1) CFD Results

- Immersed Boundary Methodology simulating bleed flow through individual bleed holes in bleed surfaces from CAD file definition
- Sidewall treatment as immersed boundary and its effect on the sidewall boundary-layer and sidewall bleed-flow rates current focus of research

![CAD file rendition of IMX bleed region R1 with CFD results](image)
Dual-Mode Transition

Chris Goyne (experimental lead), Jim McDaniel
University of Virginia

Jack Edwards (computational lead), Hassan Hassan, Jesse Fulton
NCSU

Ron Hanson, Jay Jeffries
Stanford

Andrew Cutler
GWU
UVa Dual-Mode Combustion Facility

Capabilities:
- Electrically heated
- Continuous flow
- $T_0 = 1200$ K
- $\text{H}_2\text{O}, \text{CO}_2$ & $\text{O}_2$ addition
New Dual-Mode Combustion Facility

- Mach 2 nozzle
- Isolator
- Combustor
- TDLAT section
- Extender
- Modular walls
Assembly of New Dual-mode Combustor
New Dual-Mode Combustion Facility
Pressure Distributions – Run 2

Lean flameout: $\phi \sim 0.13$

Pref = Average Pressure at Nozzle Exit = 39.8 kPa
H = 0.25 inches = Fuel Injector Ramp Height
Maximum 95% Confidence Interval = 1.135 kPa (scan 1)

Data Taken 11/08/10
UVA combustor: Generation I simulations

Nonreacting – Mach number

Reacting – Mach number

Reacting - temperature

Mach: 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5

V25: 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3

V8: 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400
k-ζ Results: Static Temperatures

k-ζ model

M-SST model

Temperature (K): 0 500 1000 1500 2000 2500
k-ζ Results: OH Mass Fraction

k-ζ model

M-SST model
Measurement Locations and Measurement Techniques

1. SPIV, CARS, Rayleigh, TDLAS
2. SPIV, CARS, Rayleigh, TDLAS, PLIF
3. SPIV, CARS, Rayleigh, TDLAS, PLIF, TDLAT, combustion efficiency
4. CARS, TDLAS
5. SPIV, CARS, Rayleigh, TDLAS, PLIF, TDLAT, combustion efficiency
Experimental Collaboration: UVa Dual-Mode Combustion Facility

UVa Dual-Mode Combustion Tunnel

Optical table

TDLAT/GWU Lab

GWU CARS/IRS/PLIF

UVa TDLAT

Stanford TDLAS

UVa SPIV

PIV/TDLAS Lab

Tunnel Room

Tunnel Control Room

Tunnel Setup Area
Stanford TDLAS, March 2010

Laser Controller

DAQ

Pitch optics and housing

Polarization maintaining fiber

2x2 Multiplexer

λ = 1391 or 1338 nm

Detector

Multi-mode fiber

Tunnel exhaust flow 700 - 2000 K

Catch optics and housing

N₂ purged

Fabry-Perot Etalon

Combustor

Stanford Optics Tunnel Mount

λ = 1343 nm

H₂O Cooling

N₂ Purge

Pitch Optics

H₂O Cooling

Cooling

N₂ Purge

Pitch Optics

Tunnel exhaust flow 700 - 2000 K

Catch optics and housing

N₂ purged

Fabry-Perot Etalon

Combustor

Stanford Optics Tunnel Mount

λ = 1391 or 1338 nm

Detector

Multi-mode fiber
Stanford TDLAS, November 2010

Control Room

Translation stages

Tunnel Room

Pitch optics & purge tube

Combustor window
CARS Setup at UVa

Schematic showing beam paths

5'x8' optical table

Dual mode combustor

Measurement point

Beams from laser cart

Signal to spectrometer

5'x8' optical table

Dual mode combustor

Measurement point

Beams from laser cart

Signal to spectrometer

Linear bearings/rails*

*Horizontal motions are motor driven (not shown)

Combustor window standoff

Mobile laser cart

Setting up the beam relay system

National Center for Hypersonic Combined Cycle Propulsion
SPIV Experimental Set-up

CCD Camera

Cavity Flame-holder/Ramp Fuel Injector (Recirculation)

Combustor

YAG Laser Sheet

Isolator

Shock Train/Boundary Layer Interaction
Stereoscopic Particle Image Velocimetry: Effect of combustion on mixing

Fuel/Air mixing, No combustion
Averaged Velocity Field (708 measurements)

Fuel/Air combustion
Averaged Velocity Field (775 measurements)
Tunable Diode Laser Absorption Tomography

Flat flame burner laboratory calibration
TDLAT Dual-Mode Water Measurement

\[ \phi = 0.17 \]
SPIV Measurement of Velocity Vectors at Tunnel Exit (Φ = 0.17)
Combustion Efficiency
\( \phi = 0.17, \eta = .88 \)

Velocity (m/s)

Water Vapor Concentration (mols/m\(^3\))

SPIV Results

TDLAT Results

3/29/2011
Parallel Beam Tomography in Combustor

CFD solution of UVa combustor at X/H=25

Reconstructed image

First attempt at reconstruction from two orthogonal viewing angles with 10 beam paths each using Maximum Likelihood-Expectation Maximization (ML-EM)
Hypervelocity Regime

Dan Cresci, Ching-Yi Tsai
ATK GASL

Ron Hanson, Jay Jeffries
Stanford

Jack Edwards, Hassan Hassan
NCSU
Hypervelocity Regime
Test Hardware in ATK/GASL HyPulse Tunnel

Capabilities:
- Mach 5 to Mach 25
- Nozzle exit diam. approx. 26”
- Test time 10-15 ms.
Experiments in HYPULSE at ATK/GASL

Figure 1. The scramjet experiment in HYPULSE is adapted from an existing test article and includes advanced instream diagnostics such as TDLAS. Scramjet test article installed in HYPULSE for (a) Mach 5 conditions and (b) Mach 7 & 10 conditions.

Model Scramjet in the Test Cabin at HYPULSE

Supersonic Air

H₂ Fuel Injector
Behind Ramp

9 Beam Paths

Optical Fibers

Exhaust
Advanced Modeling

Peyman Givi (lead)
University of Pittsburgh

Farhad Jaberi
Michigan State University

Cyrus Madnia
SUNY at Buffalo

Steve Pope
Cornell University
DNS Iso-vorticity Surface in a Compressible Mixing Layer
LES-FDF Prediction of Product Formation in a Compressible Layer
DNS and LES of Homogeneous Turbulence-Shock Interactions
Chemistry Modeling

Harsha Chelliah (lead)
University of Virginia

Steve Pope
Cornell University

Wing Tsang
NIST
Detailed and Simplified Kinetic Models

• Rate parameters of detailed kinetic models are associated with uncertainty factors ranging from 1.2 to 5!

• Must understand higher-order coupling between parameters in order to reduce the uncertainties – accomplished via Monte Carlo simulations

• Reduction approaches must include ignition, propagation, and extinction – accomplished via PCA and QSSA
  - Demonstrated by applying to an optimized ethylene-air kinetic model containing 111 species in 784 reversible reactions
  - Skeletal model with 37-38 species can predict ethylene-air extinction within 2-3% of the detailed model (ignition less than 1%)
  - QSSA model with 20-24 species can achieve similar accuracy
Implementation of Models in LES/PDF

- ISAT tabulation error less than 1%
- ISAT/Skeletal
  - 38 species
  - 3% error
  - 21 μs/query
- ISAT/Reduced:
  - 24 species
  - 7% error
  - 17 μs/query
- ISAT+RCCE:
  - 7% and 3% error with just 18 and 25 (or more) represented species, respectively.
  - 25 μs/query (relatively large table build times)
- LES/PDF
  - $10^{11}$ queries at 30 μs/query = 834 hours
  - 4,000x speed-up compared to DE
  - Reduction in number of variables 111 to 30 (70% reduction)
- Future work
  - Implementation in LES/PDF
  - Parallel strategies

Reduction-Tabulation (top) and ISAT query-time (bottom) using (i) ISAT (with 111-species detailed mechanism);
(ii) ISAT+SKELETAL (38-species); (iii)ISAT+REDUCED (24-species);and (iv) ISAT+RCCE with $n_{rs}$ represented species
Conclusions

• Center has been in operation about 1.5 years

• Modeling and experiments have been initiated for all three flow regimes: dual-inlet, dual-mode and hypervelocity

• New FDF models have been developed and validated by DNS

• Chemistry models have been developed for a range of H-C fuels

• Research will continue to emphasize the fundamentals of hypersonic airbreathing propulsion and synergy between modeling and experiments