CURRENT ISSUES IN UNSTEADY TURBOMACHINERY FLOWS

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Among the numerous causes for unsteadiness in turbo machinery flows are turbulence and flow environment, wakes from stationary and rotating vanes, boundary layer separation, boundary layer/shear layer instabilities, presence of shock waves and deliberate unsteadiness for flow control purposes. These unsteady phenomena may lead to flow-structure interactions such as flutter and forced vibration as well as system instabilities such as stall and surge.

A major issue of unsteadiness relates to the fact that a fundamental understanding of unsteady flow physics is lacking and requires continued attention. Accurate simulations and sufficient high fidelity experimental data are not available.

The Glenn Research Center plan for Engine Component Flow Physics Modeling is part of the NASA 21st Century Aircraft Program. The main components of the plan include Low Pressure Turbine experimental and computational databases and models for flow control, data for Reynolds Stress modeling and model development and combustor spectra measurement and an LES version of the National Combustor Code. The goals, technical output and benefits/impacts of each element are described in the presentation. The specific areas selected for discussion in this presentation are blade wake interactions, flow control, and combustor exit turbulence and modeling.

The results of the technical work lead us to the recognition that (1) it is critical to sort out the limitations of current models and determine the needed improvements for models of transition, separation and reattachment, (2) to understand both the surface properties as well as those within the boundary layer, (3) to understand the interaction of the force created by the control device on the boundary layer behavior and the excitation required, (4) an understanding of combustor exit flow field spectra and (5) an understanding of turbulent reacting flows. These phenomena hold the key to a more effective utilization of turbomachinery devices.

Keynote

Current Issues in Unsteady Turbomachinery Flows

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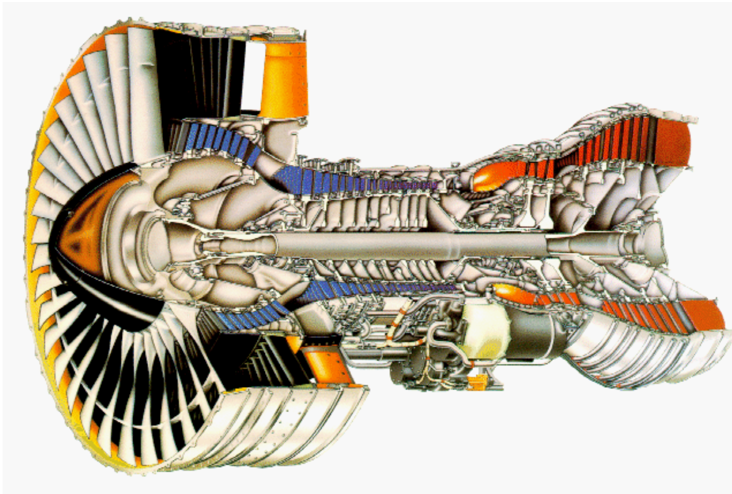
MINNOWBROOK IV
TRANSITION AND UNSTEADY ASPECTS OF TURBOMACHINERY FLOWS
17-20 AUGUST 2003

HIGH BYPASS RATIO ENGINE



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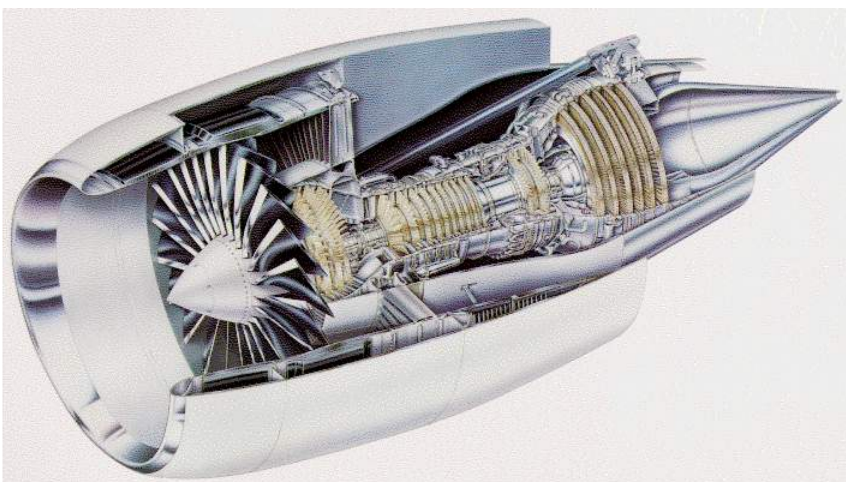
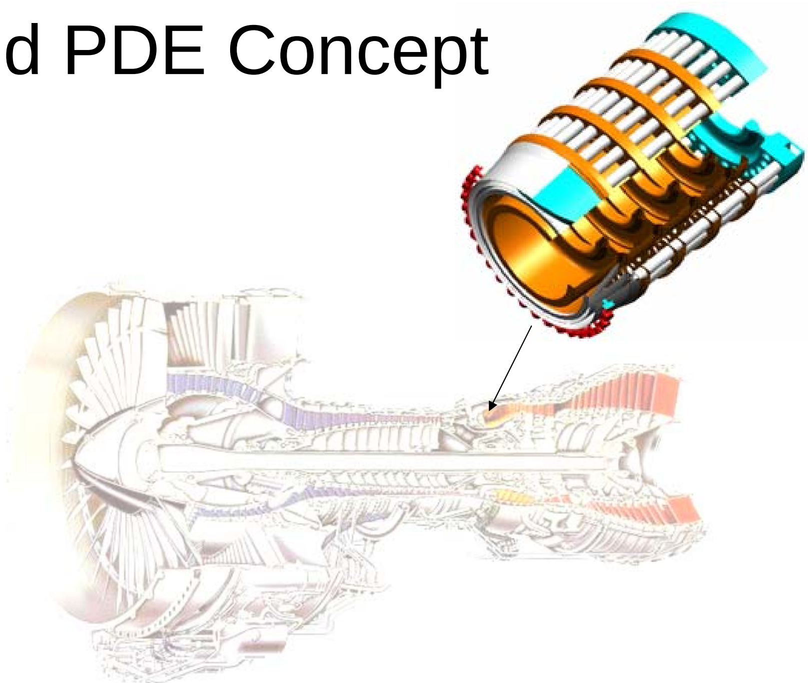


GE90

Hybrid PDE Concept



Sources of unsteadiness in turbomachinery flows

- Turbulence and flow environment
- Wakes - stationary & rotating vanes
- Boundary layer separation
- Boundary layer / shear layer instabilities
- Presence of shock waves
- Deliberate unsteadiness – flow control

- Flow-structure interactions-flutter & forced vibration
- System instabilities-stall, surge
- Turbofan hybrid cycle-PDE

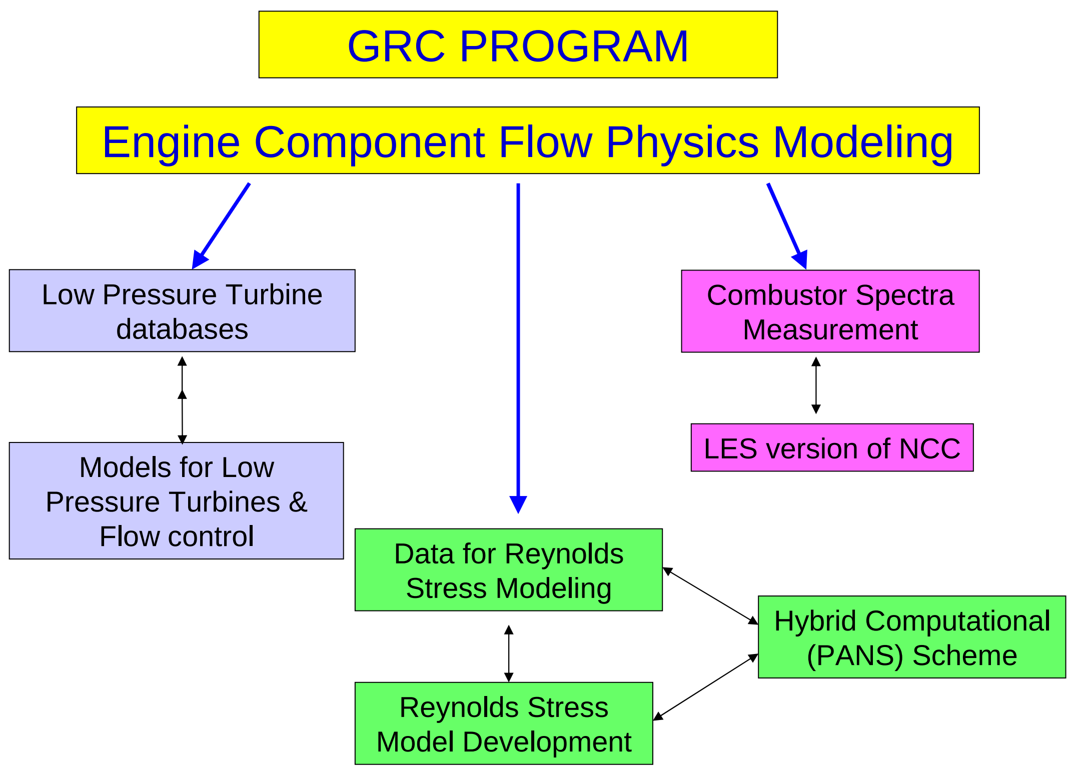
Other Cause for Unsteadiness

FOD damage and the fix !

Another cause of unsteadiness

Major Issues

- Fundamental understanding of unsteady flow physics is lacking and requires continued attention.
- Accurate simulations and sufficient high fidelity experimental data are not available.



Engine Component Flow Physics Modeling

MS#	MS Lvl	EASI MILESTONE/DP (Short Phrase)	OUTPUT (Performance Metric/Exit Criteria)	OUTCOME (Benefits & Impact)
11-04-2-01	L3	Data for Reynolds Stress Modeling	Measurements for validation of Reynolds stress modeling.	Provide measured cross term correlations needed for validation of 2nd order modeling.
11-04-2-02	L3	Reynolds Stress Model Development	Improved turbulence modeling for unsteady turbulent flows in engine and airframe components.	Enables improved accuracy for flow field simulation, providing increased confidence in design and analysis of engine and airframe components
11-04-3-03	L3	Hybrid Computational (PANS) Scheme	Demonstrated scheme for Partially Averaged Navier Stokes (PANS) flow simulation and demonstration of test cases for steady and unsteady turbulent wall and jet flow fields.	Verified robust, reliable computational method that will compute turbulent flow fields with a higher level of accuracy
11-04-3-04	L3	Combustor Spectra Measurement	Measurements of combustor turbulence	Provides for accurate boundary conditions for turbine heat transfer requirements and reduced cooling flow reqts
11-04-3-05	L3	LES version of NCC	Large Eddy Simulation (LES) version of National Combustor Code (NCC)	Provides accurate numerical data sets for improved modeling for combustor CFD design tools.
11-04-3-06	L3	Low PressureTurbine databases	Experimental and numerical data sets of unsteady low pressure turbine flows.	Provides validation data and physical understanding for CFD and modelling for more fuel efficienr engine performance.
11-04-2-07	L3	Models for Low Pressure Turbines	Improved transition and turbulence modeling for unsteady separated low pressure turbine flows.	Provides accurate models for design tools for prediction of high lift low pressure turbine airfoils to increase loading and avoid flow separation..
11-04-3-08	L3	Low Pressure Turbine Flow Control	Demonstration and CFD development for active and passive flow control techniques for effective control of boundary layer separation.	Provides high efficiency, low weight, reduced part count, as well as increased loading over entire flight envelope.

Selected areas for discussion

1. Blade wake interactions
2. Flow control
3. Combustor exit turbulence & modeling
4. Pulse detonation hybrid cycles

1. Blade Wake Interactions

- This topic has been an active research area,.
- Major recent contributions by Hodson et al, Halstead et al, Solomon et al, and others, mostly originating in Europe
- Has been a major topic in prior Minnowbrook workshops
- Research is particularly applicable for LPT flows

Characteristics of flow in LPT airfoil passages:

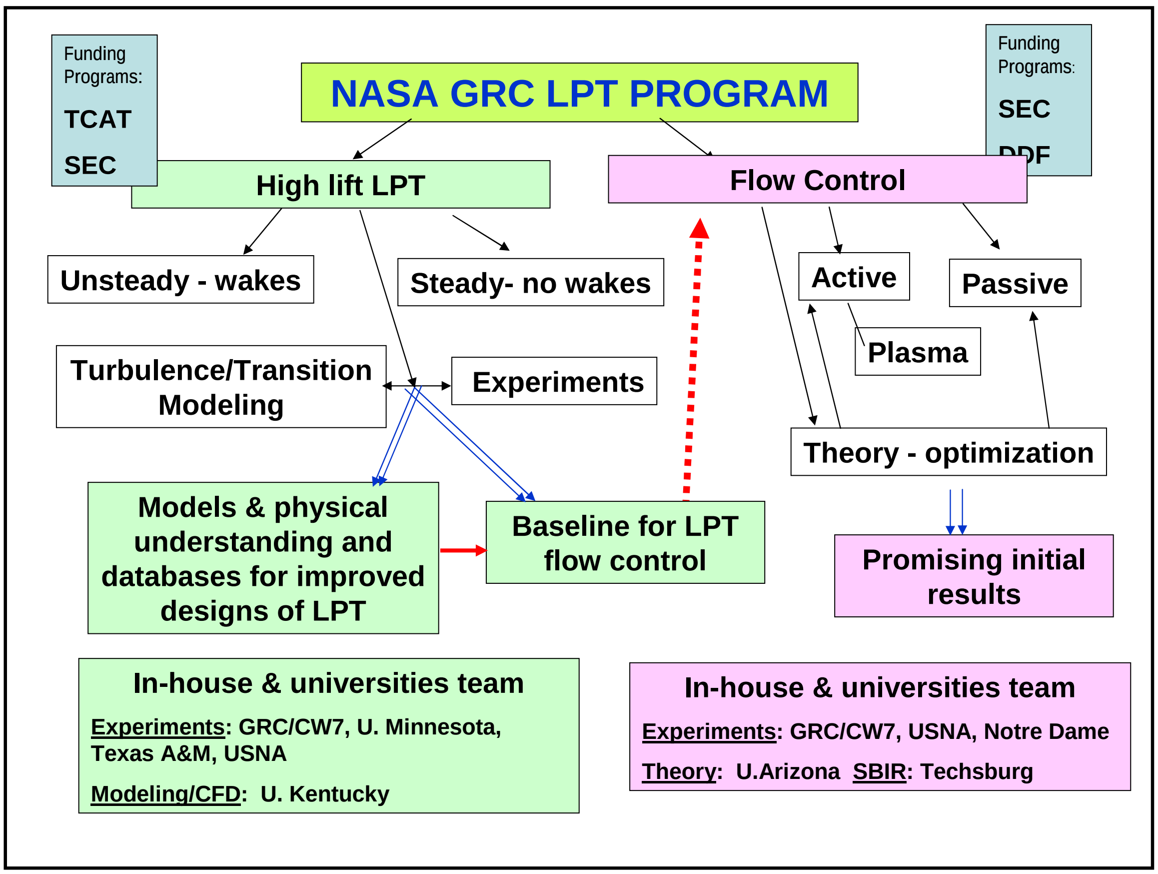
- Flow in LPT is unique compared to gas turbine components
- Low Reynolds number 25,000 - 300,000, Exit M ~0.5
- High free stream turbulence 0.5 % to 10 %
- Complex flow : transition, wakes, separation
- Unsteadiness
- Additional complexity in 3D flow at endwalls
- Cause of efficiency loss due to laminar separation on airfoil suction surface

Design needs

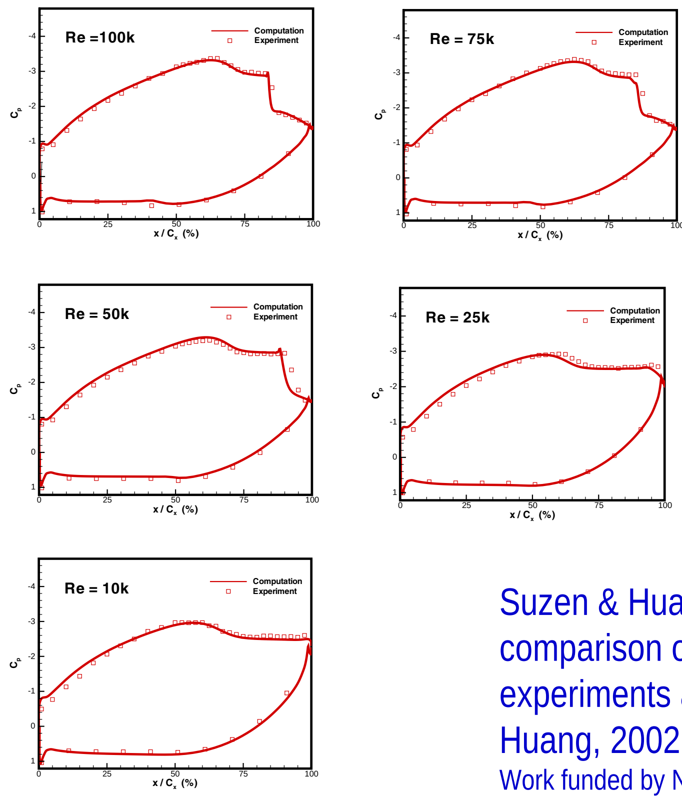
- Increase airfoil loading – reduce part count, weight, cost
- Reduce takeoff-to-cruise efficiency degradation.

Wake interaction in LPT - Background

- Much of the experimental work was based on surface measurements.
- Effort at GRC focus on high fidelity measurements inside the boundary layer -essential for successful CFD and model development.
- The goal is accurate simulation and validation of BL transition, separation and reattachment locations
- Common blade geometry (P&W PAK B) used
- Cascade simulations have yielded excellent agreement with experiment data.
- Simulation of cascade experiments with unsteady wakes are underway.



PAK B Blade Cascade Experiments of Corke et al. (2002)



Suzen & Huang (U. Kentucky) 2003: comparison of CFD with PAK B cascade experiments at U. Notre Dame by Corke & Huang, 2002,

Work funded by NASA GRC

Unsteady LPT flows with wakes:

• Focus on experiments with low speed <u>simulated</u> wake generators

Advantages:

• Enables detailed hot wire anemometry providing details of boundary layer behavior; transition, separation, reattachment, vortex formation, etc

•There is some criticism on use of cylindrical bars – however they are good for model validation – models that work for the turbulent wakes generated by cylindrical bars will work for airfoil wake.

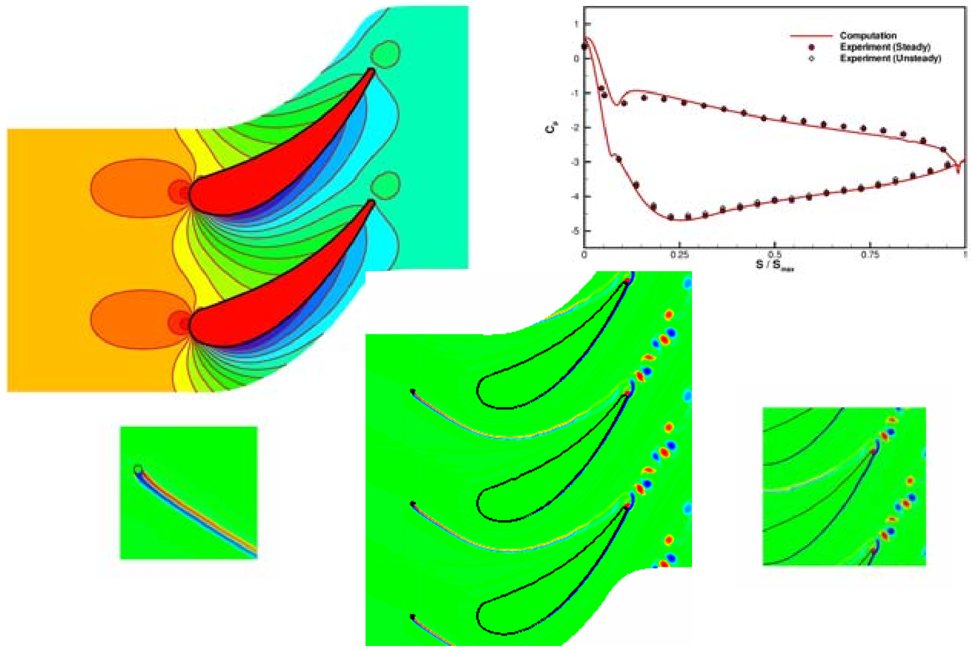
Recent Studies sponsored by GRC:

• U. Minnesota – Simon et al

• Texas A&M – Schobeiri et al

• Univ. Notre Dame – Corke et al development of a solid state wake generator.

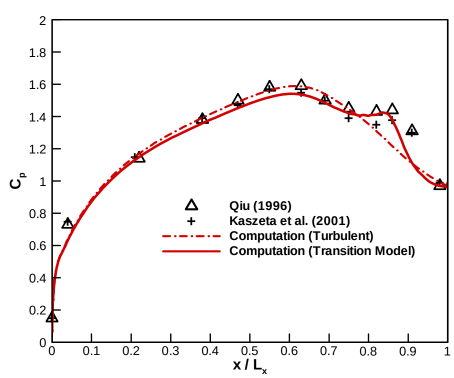
Suzen & Huang Simulation of the Experiments of Schobeiri and Pappu (1997) SSME Airfoil

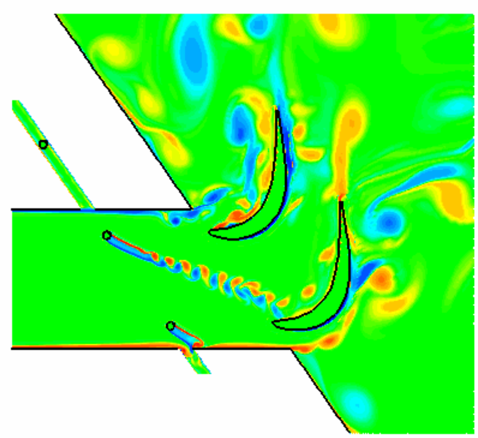


Suzen & Huang (U. Kentucky) 2003: Comparison of CFD with experiments at U. Minnesota by Simon & Kaszeta (2001)

Work funded by NASA GRC

- Re = 21,000
- FSTI = 2.5%
- PAK-B blade passage
- $U_{rod} / U_{axial} = 0.7$





Future Work

- New blade configurations with higher loading to be used in common study
- Blade coordinates will be made available to researchers as done with PAK B
- Evaluation of current modeling to be carried out with new blade
- Extend work to 3D
- Design high lift LPT airfoil and test in new GRC dual spool rig (under construction)

2. Flow Control

Motivation

• There is limit to what can be accomplished with airfoil design and optimization
• Flow control provides a leap to new enabling technologies
• However; unsteadiness is challenge for experiments, simulation and physical understanding

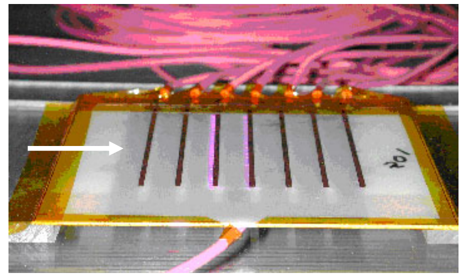
Classification

- Passive Flow Control – trips, dimples, vortex generators, bumps
  - unsteadiness caused by shedding, transition
- Active Flow Control
  - Steady - aspiration – suction-blowing
    - Unsteadiness may be caused by separation (shedding, instabilities) or transition
  - Oscillatory/Pulsed – Synthetic jets, pulse jets, plasma actuators
    - unsteady by definition

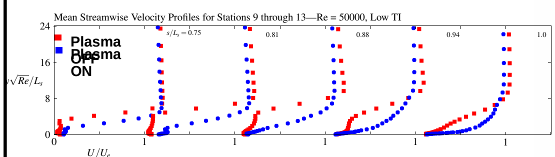
NASA GRC

Hultgren & Ashpis (2001)

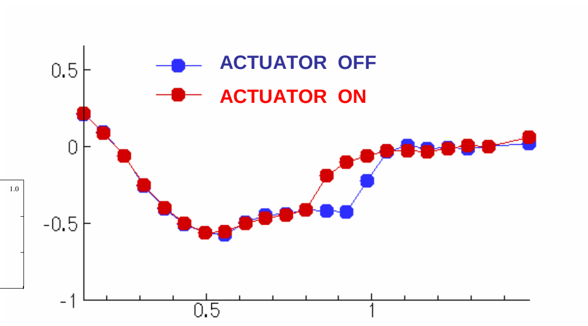
CW-7 TRANSITION WIND TUNNEL



Phased Array - Oscillating wall jet configuration



VELOCITY PROFILES



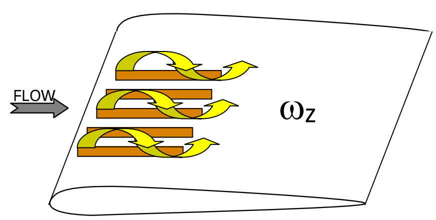
PRESSURE DISTRIBUTION ALONG THE SURFACE

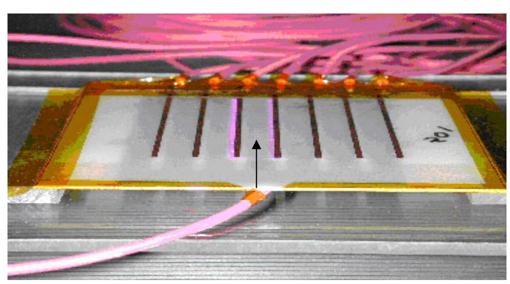
Separation control via generation of streamwise vortices

DIMPLES -Passive

Lake et al , 2000

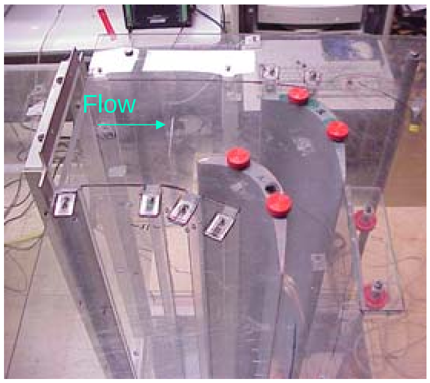
STREAMWISE ORIENTED GLOW DISCHARGE PLASMA ACTUATORS





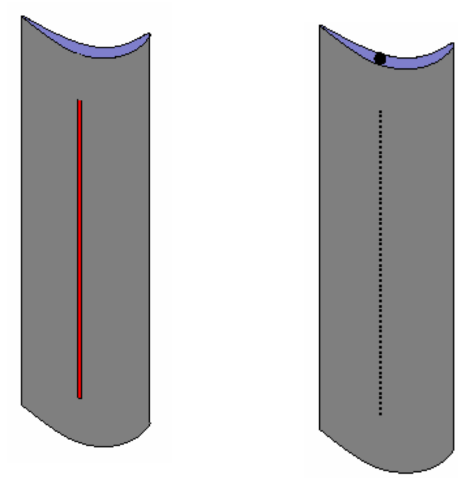
Corke et al 2002, Hultgren & Ashpis , 2002

Volino, USNA, 2002

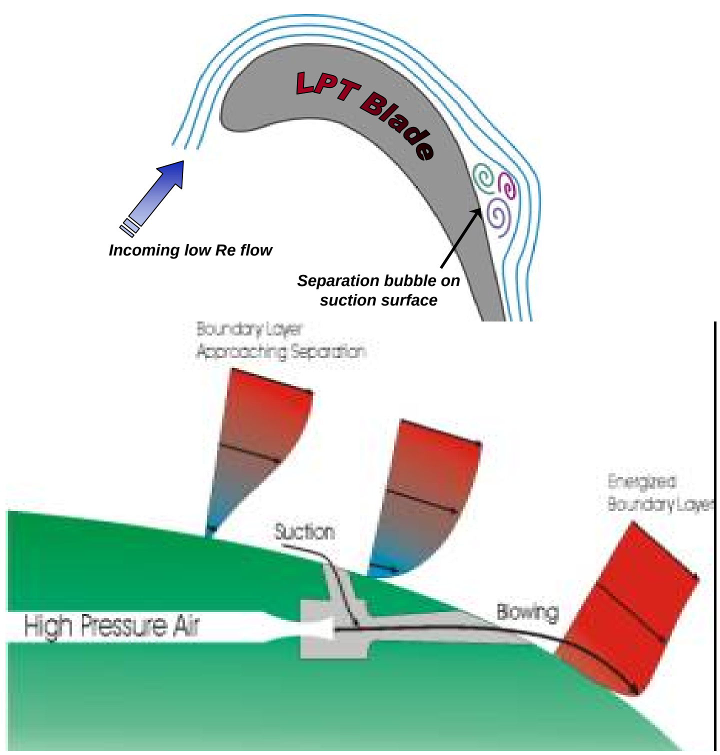


2D tripping strip

Vortex generator jets

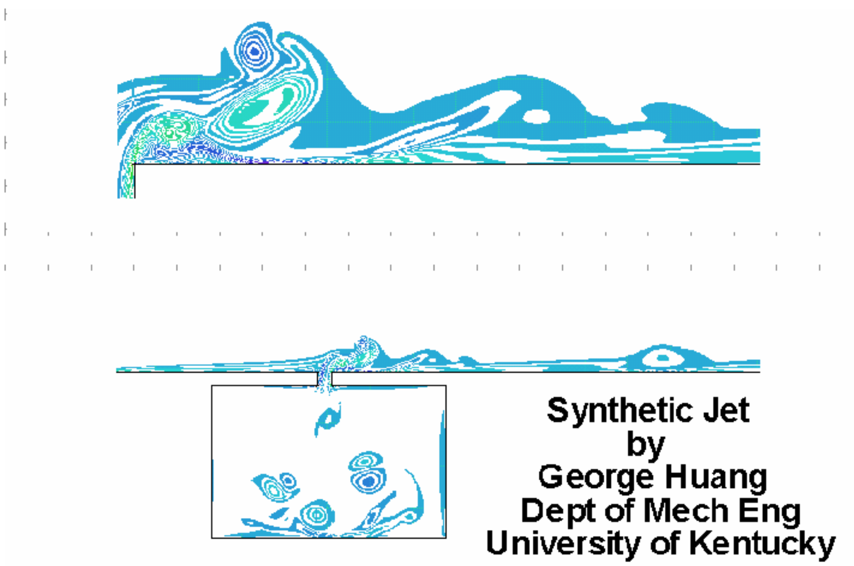


Ejector jet – SBIR – Technology in Blacksburg Inc.

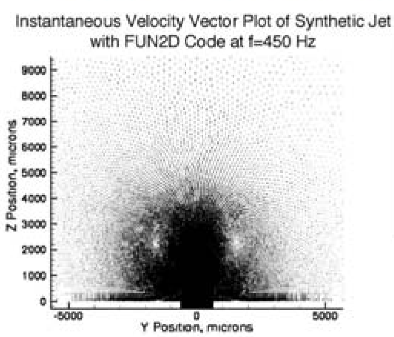


ZERO NET MASS DEVICE - SYNTHETIC JET

Laminar 2D simulation

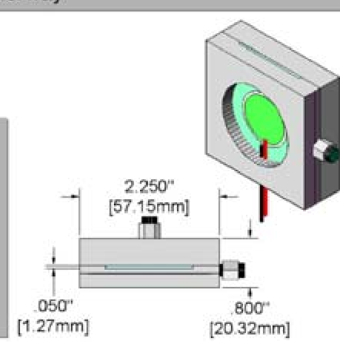


Synthetic Jet for CFD Validation and Modeling

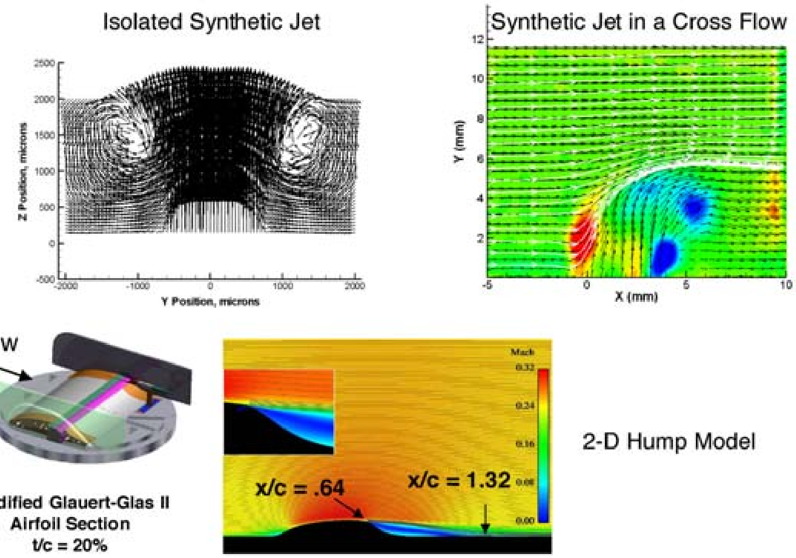


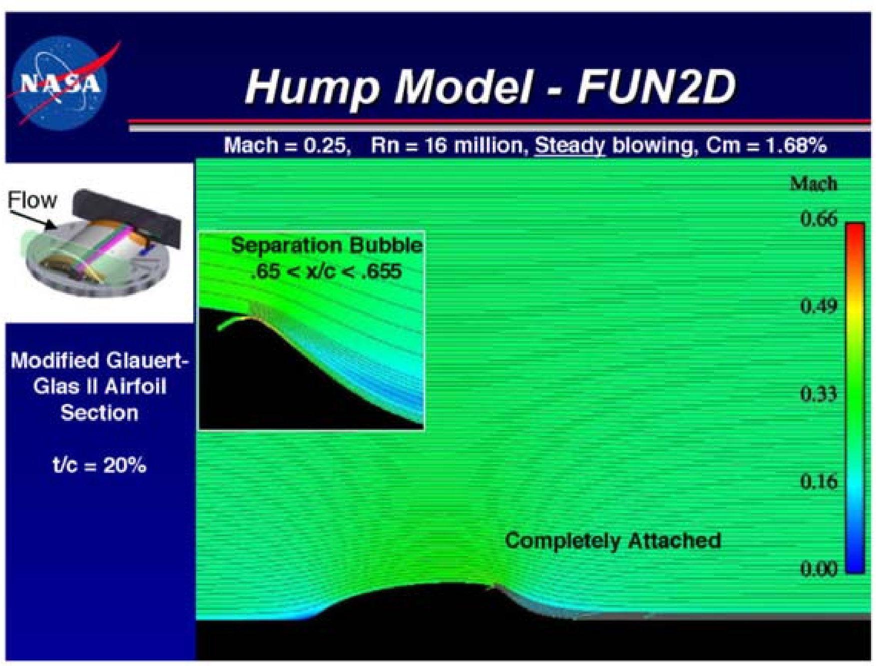
- Benchmark time-accurate codes, both unstructured and structured, against synthetic jet model
- Outcome will provide flow physics understanding of actuator interactions
- Calculations and experiments underway

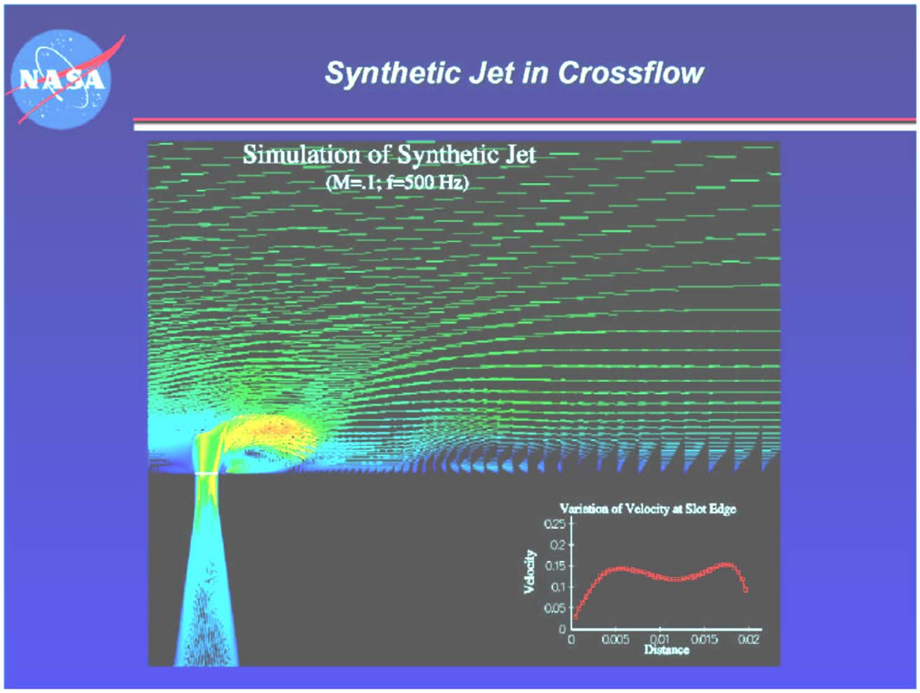
- **New actuator jointly designed by CFD modelers and experimentalists**
  - **Best performance not required**
    - **Single disk - easier B.C.**
    - **Wider 2D slot - better measurements**
  - **Redundant measurements**
    - **Hot-wire, LV, PIV, input signal, diaphragm displacement, cavity pressure**



Benchmarks for Validating CFD







FLOW CONTROL - Summary (Inspired by Sellers, NASA Langley)

- **Active Flow Control has the potential to revolutionize the gas turbine**

However ….

- **The dynamic environment that empowers flow control is not well understood,**

nor…

- **Can that dynamic environment be readily predicted with today's computational tools,**

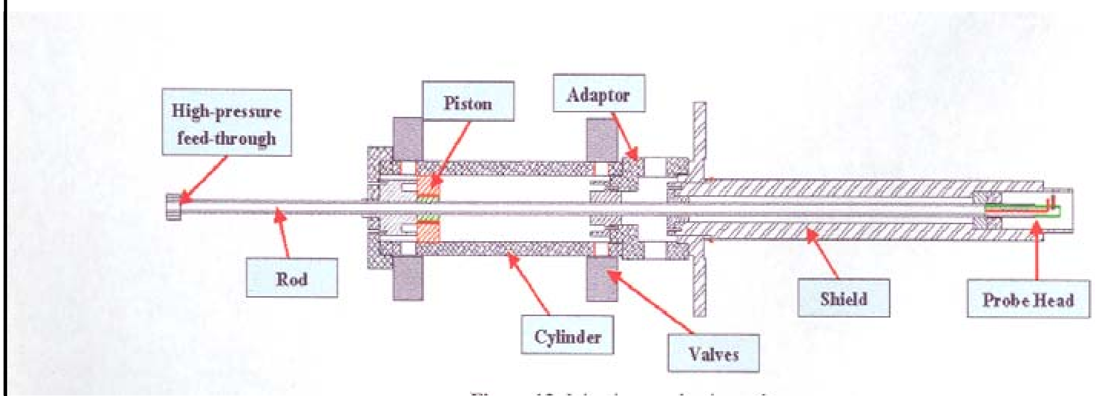
The challenge….

- **The engineering and integration needed to use and manufacture the necessary actuators, sensors and controls using advanced and smart materials needs to be demonstrated,**

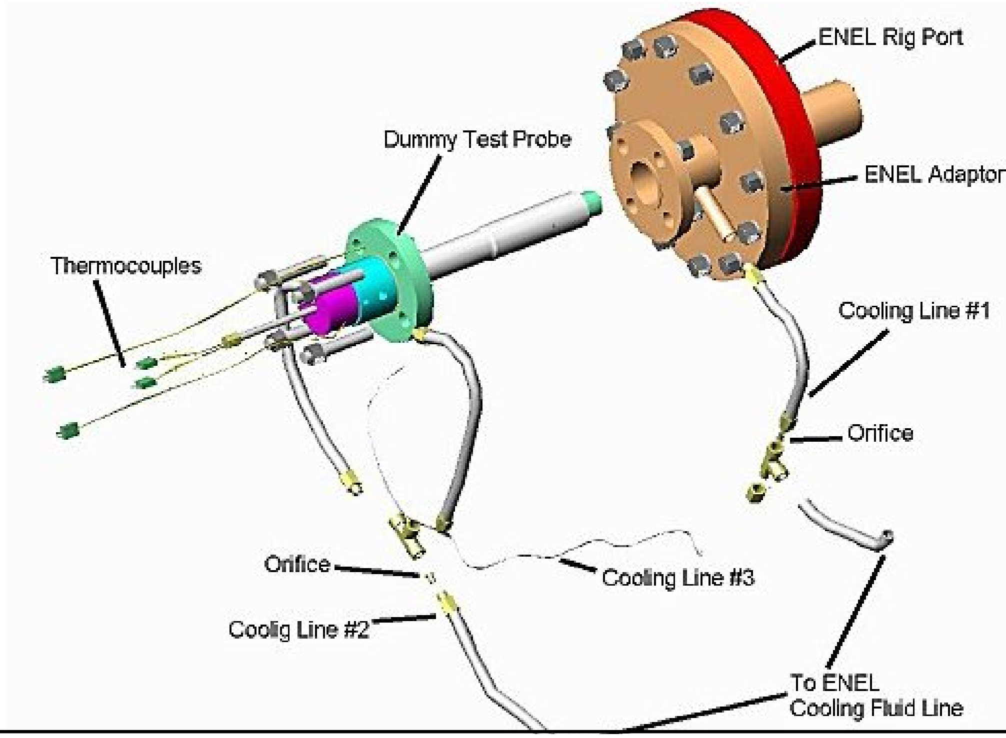
3. Combustor exit turbulence and combustor modeling

- *Combustor Spectra Measurement*
  - ***Attainment of turbulence intensity, scale and spectra at combustor exit plane in a full scale combustor facility***
- *LES version of NCC (National Combustor Code)*
  - ***Shih, Ohio Aerospace Institute***
  - ***Develop generalized wall function valid for adverse and favorable pressure gradient and validate with benchmark combustion datasets***
  - ***Develop LES version of the National Combustor Code with suitable modeling for turbulent, swirling, reacting flow***

Injection Mechanism



COMBUSTOR SPECTRA MEASUREMENTS PROBE MECHANISM

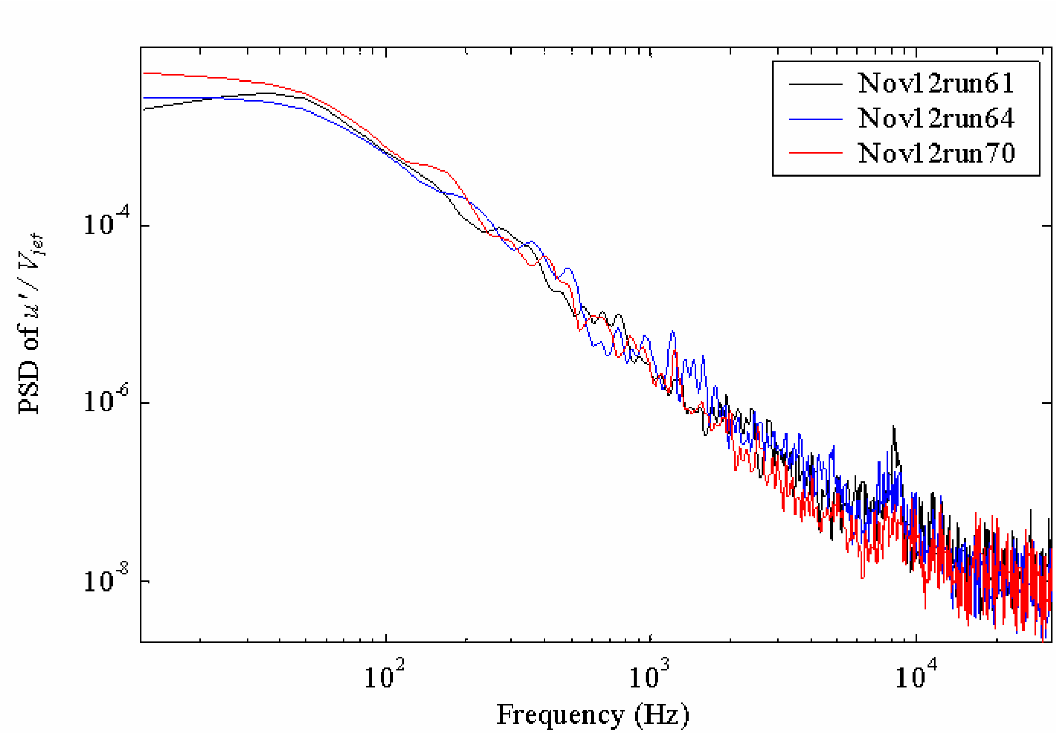


Combustor Spectra Measurement

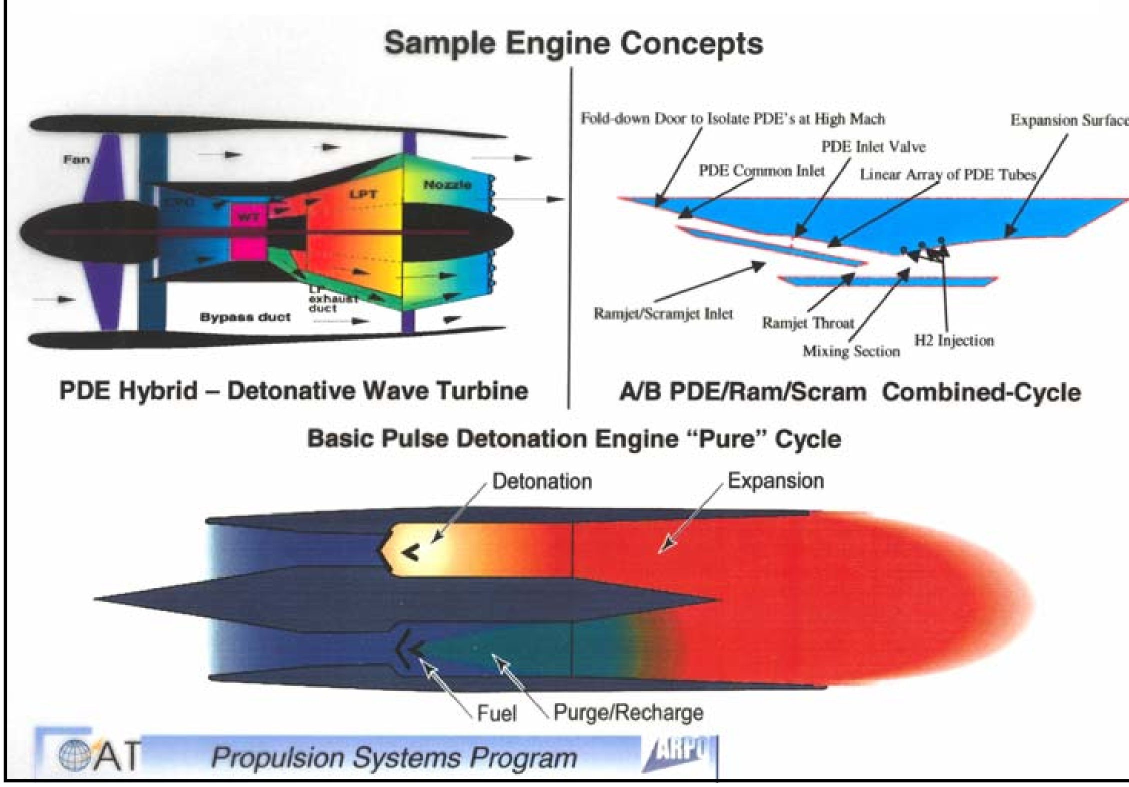
MEASUREMENT OF TURBULENT PRESSURE AND TEMPERATURE FLUCTUATIONS IN A GAS TURBINE

Injection Mechanism in ENEL Rig

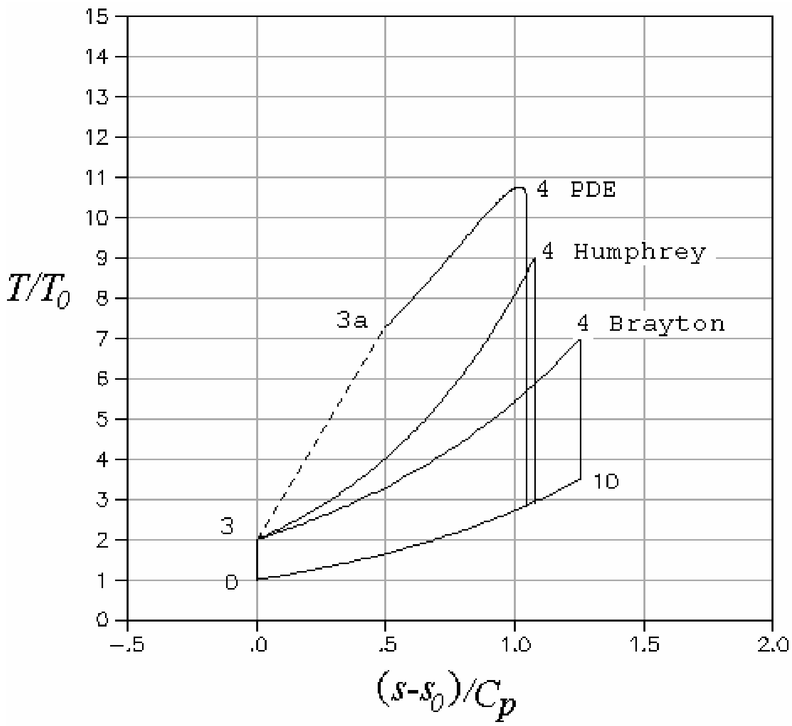
Power Spectral Density



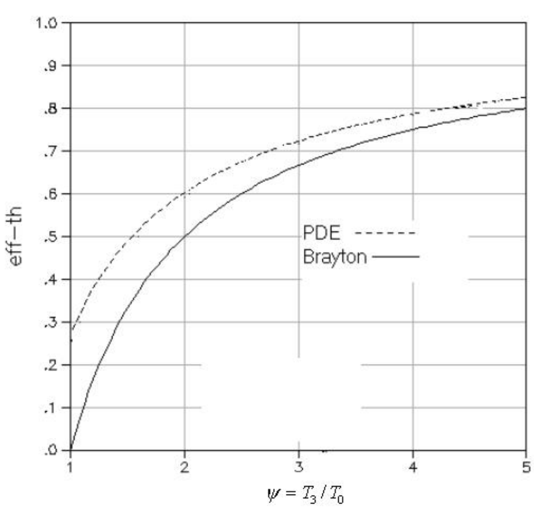
4. Pulse detonation hybrid cycles



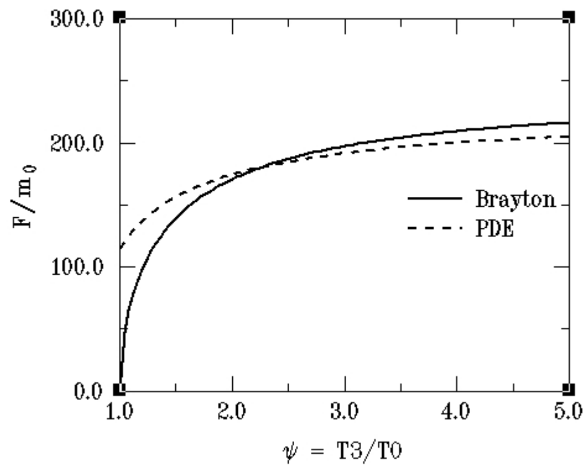
THERMO CYCLE ANALYSIS



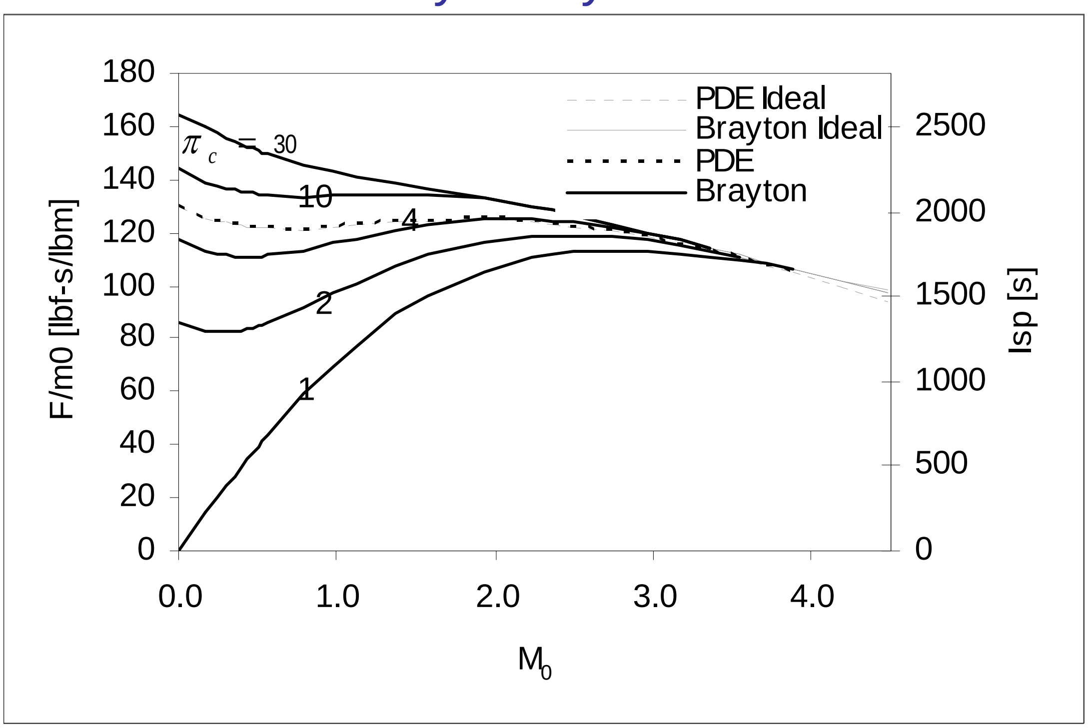
PDE & Brayton Thermal efficiencies



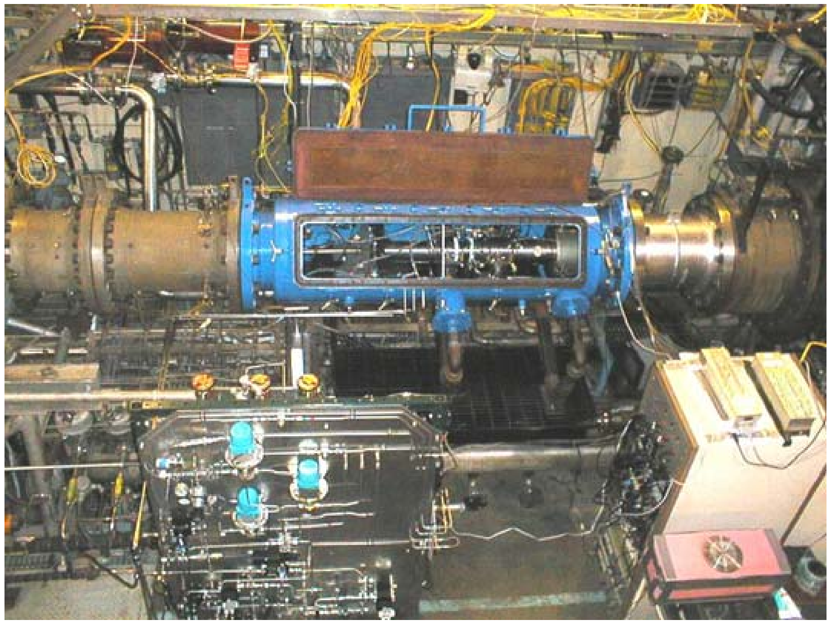
Specific thrust for the PDE and Brayton Cycles versus temperature ratio, stoichiometric propane-air



Specific Thrust and Impulse for the PDE and Brayton Cycles



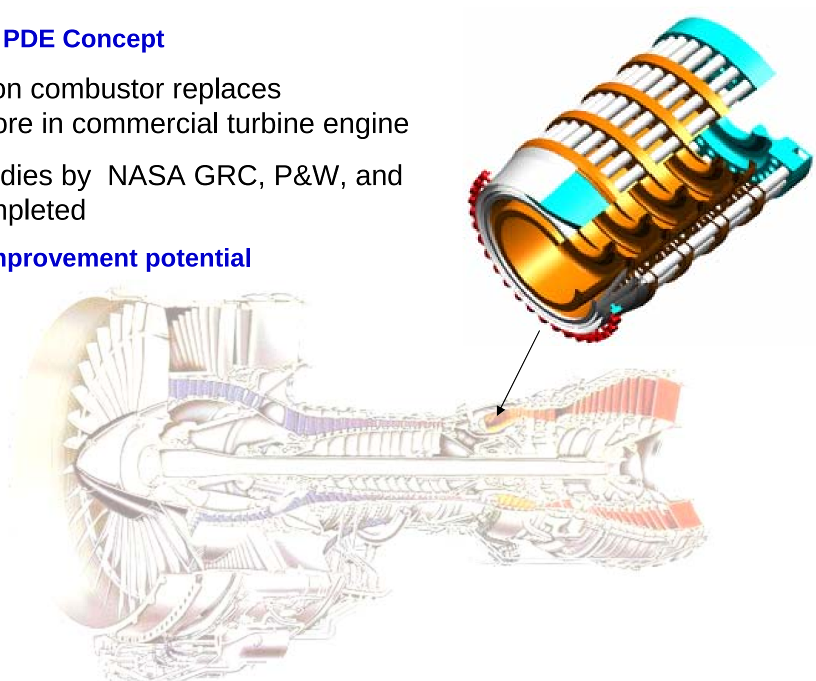
PDE Testing at Glenn



PDET Project – Hybrid PDE Application

Advanced Hybrid PDE Concept

- Pulse detonation combustor replaces conventional core in commercial turbine engine
- Conceptual studies by NASA GRC, P&W, and APRI were completed
- **10-15% TSFC improvement potential**



PDET Project - Summary

• Pulse detonation (PD)-based engine concept studies indicate significant performance improvements possible but----

- **Significant technology challenges remain**

• Future efforts will focus on **PDE-hybrid** systems

• Continue fundamental research in support of engine concept development

- Initiate proof-of-concept demonstrations (NASA/Industry)
- Hybrid engine single tube combustor test in process
- Combustor operability
- Combustor integration
- Develop a multi-PD tube - nozzle test rig

• Develop robust system analysis capability

- Requires accurate component loss models

Closing remarks

- Critical to sort out the limitations of current models and determine the needed improvements
- Necessary to understand both the surface properties as well as those within the boundary layer
- Knowledge of the interaction of the force created by the control device on the boundary layer behavior and excitation is needed
- BL transition, separation and reattachment remain as key issues for gas turbine flows
- Combustor exit flow field spectra need further resolution
- Turbulent reacting flow understanding has improved, but continues to be challenging

Closing remarks

- As scientists, researchers and engineers, we recognize the need to pursue improved understanding of the flow physics inherent in propulsion devices
- There is a recognized path (or scientific approach) to achieving this knowledge
- There is a need to sustain the activities started by this group some 8 –10 years ago
- Therefore, we must remain committed to our research activities in order to achieve significant improvements in propulsion systems

Closing remarks

- There is an increasing impatience with the “art of science”
- NASA is emphasizing a broader technology readiness level for IH research; Levels 1 through 6.
- NASA also emphasizing earlier application of S&T efforts
- NASA’s turbine engine research is focusing on emissions (fuel efficiency), noise and high speed accelerators.
- Commercial aircraft business undergoing severe reductions world-wide with some consequence on S & T funding.
- A persistent effort is needed on our part to accomplish our objectives.