Low Order Modeling Tools For Preliminary Pressure Gain Combustion Benefits Analyses

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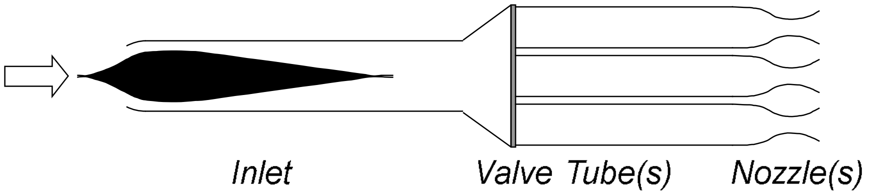
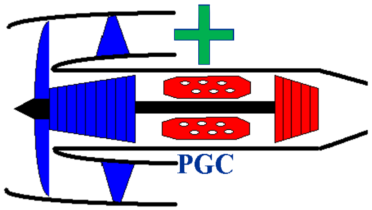
Outline

(NOTE: PGC≡Pressure Gain Combustion)

- Background/Motivation
- Model Description
- PGC/Turbine Interaction Assessment
- Example Results
- Concluding Remarks

Background





WORKING DEFINITION

PGC: *A combustion process whereby the appropriately averaged total pressure of the exit flow is above that of the inlet flow.*

Thermodynamically: Utilize Atkinson-Type Cycle Rather Than Brayton

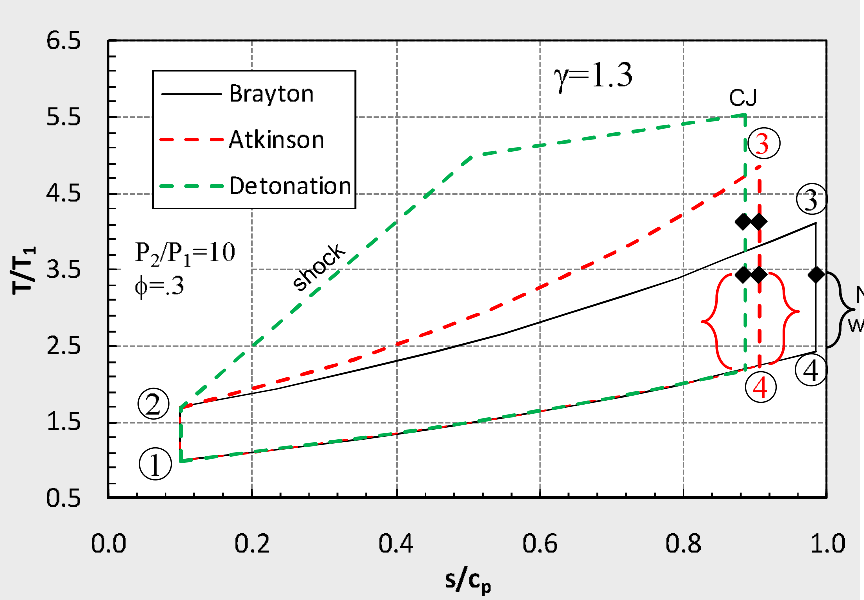
Brayton

1-2: Isentropic (adiabatic) Compression
2-3: Isobaric Heat Addition
3-4: Isentropic Expansion
4-1: Isobaric Heat Rejection

Atkinson (aka Humphrey)

1-2: Isentropic (adiabatic) Compression
2-3: Isochoric Heat Addition
3-4: Isentropic Expansion
4-1: Isobaric Heat Rejection

Identical Mechanical Compression,& Heat Input



Higher Thermodynamic Efficiency

Background

Pressure Gain Combustion Approaches

- Pulsed Resonant Combustion* (Lowest Pressure Gain, Lowest Risk)
  - Subsonic combustion wave combustor valved at intake end, open at exhaust end; gasdynamic waves generated by pulsed combustion are used to generate a moderate increase in total pressure in the exhaust flow
  - Common configuration is a derivative of a pulsejet (V-1 “Buzz-bomb” engine)
  - Lowest pressure rise with lowest pressure, temperature and velocity fluctuations in exhaust flow
- Constant Volume Combustion (High Pressure Gain, High Risk)
  - Subsonic combustion wave combustor valved at both intake and exhaust ends
  - Rotating tube configuration (wave-rotor derivative) has been demonstrated.
  - High pressure rise with high pressure, temperature and velocity fluctuations in exhaust flow
- Detonative Combustion* (Highest Pressure Gain, Highest Risk)
  - Supersonic combustion wave combustor valved at intake end, open at exhaust end; Leading shock wave provides high compression of combustor flow
  - Multiple straight tube, and so-called rotating detonation configurations demonstrated
  - Highest pressure rise with highest pressure, temperature and velocity fluctuations in exhaust flow

*Valveless versions of these combustors have been demonstrated, but with lower pressure gain

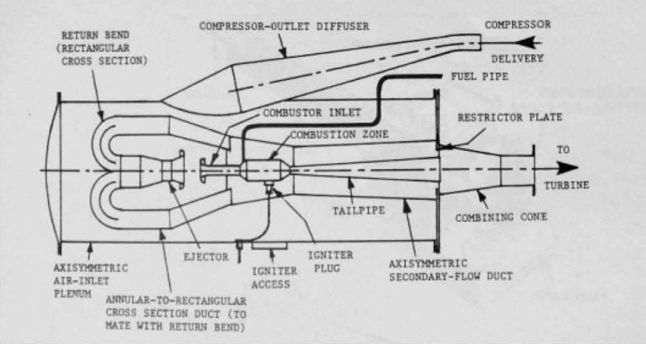
All Approaches Are Fundamentally Unsteady and Periodic

Background

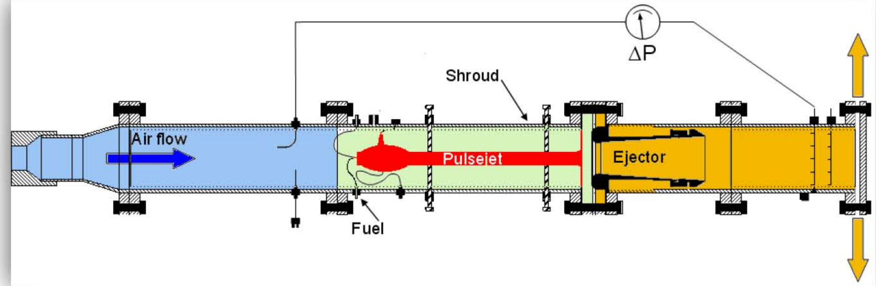
Recent Implementation Approaches

Resonant Pulsed Combustion (slow deflagration)†

†Envisioned as a canular arrangement

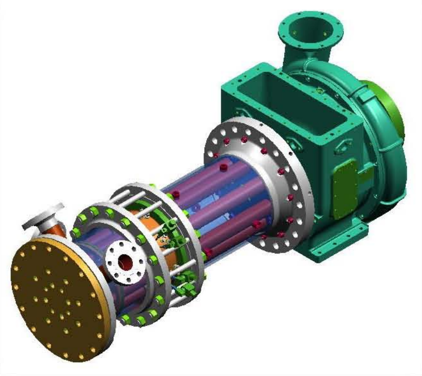


University of Calgary 1989

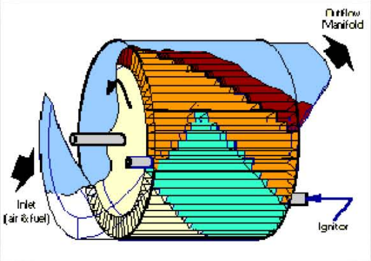


NASA Glenn, 2005

Detonation or 'Fast' Deflagration (gasdynamic)



G.E. Global Research Center 2005



IUPUI/Purdue/LibertyWorks, 2009

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Motivation

Any particular PGC component requires detailed modeling to assess and optimize performance; however, for preliminary system benefits assessment, a low order (e.g. relatively simple), but realistic model is needed.

Motivation

INTERAGENCY AGREEMENT SAA3-3-307 BETWEEN NASA GLENN RESEARCH CENTER AND AIR FORCE RESEARCH LABORATORY

RESPONSIBILITIES:

- *Development of CVC-based thermodynamic performance modeling tools. The primary objective of this task is to develop an NPSS-based engine cycle model to predict the performance of user-defined turbine engine cycles, integrated with a CVC module as either a replacement for the main combustor or augmentor, or as a fan duct burner.*
- *The NPSS model shall be capable of computing overall and component-level performance for multiple engine configurations (i.e. turbofans, turbojets, and turboshafts) and cycle characteristics, including off-design and part-power conditions.*
- *The CVC module shall be capable of computing exit flow conditions from a defined CVC process for different upstream conditions (i.e. mass flow rate, temperature, pressure, fuel/air ratio). The CVC module shall account for all potential pressure loss mechanisms (i.e. valves, detonation chamber, exhaust).*

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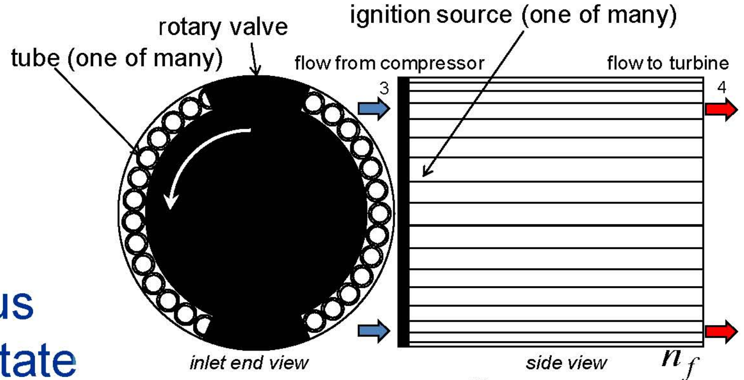
PGC Performance Model Description

Hybrid Approach:AIAA 2010-6717

Notional Detonative Combustor



Follows One of Many Combustor Tubes

Combustion Process Modeled as Instantaneous Jump from Initial to Uniform, Post –Reactive State

- Utilizes the assumption of constant volume combustion
- No finite rate reaction equations required
- Conserves mass and energy

$$q_0 = \frac{n_f}{\gamma R_g \overline{T}_{t3}\left(a/_f + 1 \right)}$$

$$\frac{\overline{T}_{CV}}{\overline{T}_{t3}} = 1 + \gamma(\gamma - 1)q_0$$

$$\frac{p_{CV}}{p_{t3}} = \frac{\overline{T}_{CV}}{\overline{T}_{t3}}$$

Post-Reactive State Used as Initial State for Non-Reacting, simple CFD Algorithm

- Pure Euler equations (no species)
- MacCormack’s method (2nd order accuracy)
- Very fast
- Coarse grid allowed

$$\frac{\partial \overline{w}}{\partial t} + \frac{\partial \overline{F}(\overline{w})}{\partial x} = \overline{S}(\overline{w}, x)$$

$$\overline{w} = \begin{bmatrix} \rho \\ \rho u \\ \dfrac{p}{\gamma(\gamma - 1)} + \dfrac{\rho u^2}{2} \end{bmatrix} \qquad \overline{F} = \begin{bmatrix} \rho u \\ \dfrac{p}{\gamma} + \rho u^2 \\ u\left(\dfrac{p}{\gamma - 1} + \dfrac{\rho u^2}{2} \right) \end{bmatrix}$$

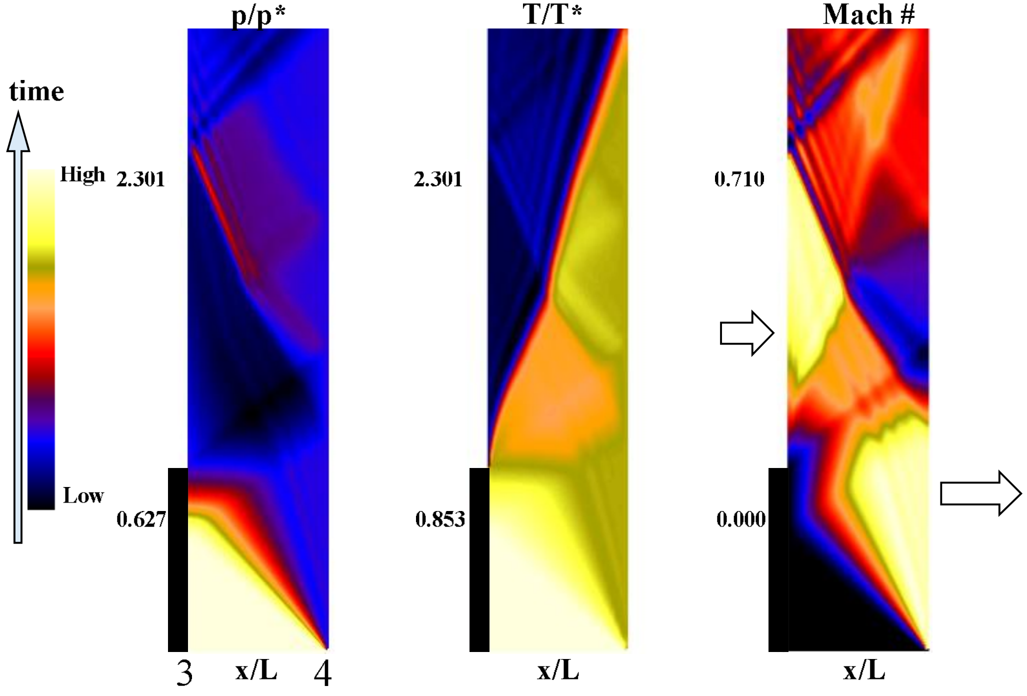
Blowdown and Refill Processes Computed

Cycle Completes When All Mass Originally in Tube is Exhausted

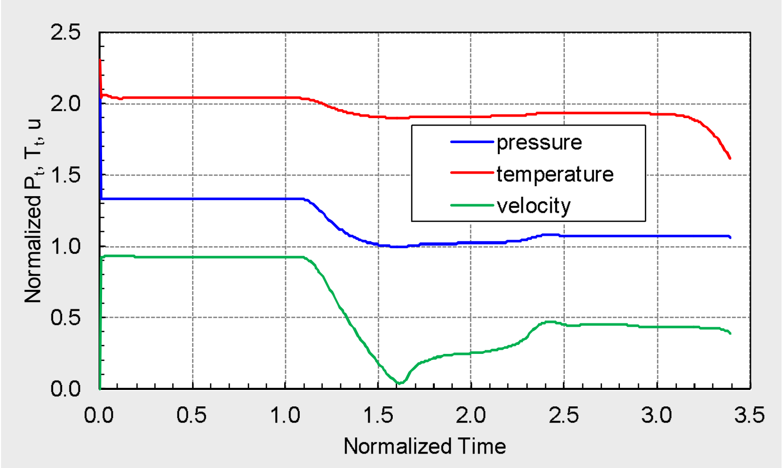
Yields Performance and Sizing Information

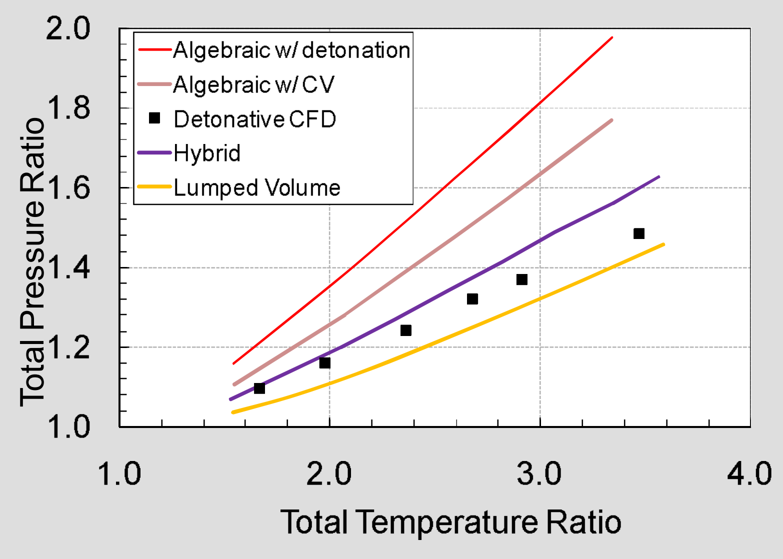
PGC Model Description

Contours of tube pressure, temperature, and Mach throughout cycle



Station 4 distribution throughout cycle





Unsteady station 4 mass, momentum, and enthalpy averaged (mixed) to yield exhaust ‘state’ (P_{t4}, T_{t4})

- Thrust averaged mixing model generates entropy (lost availability) which scales with non-uniformity

$$PR \equiv \frac{p_{t4}}{p_{t3}}$$

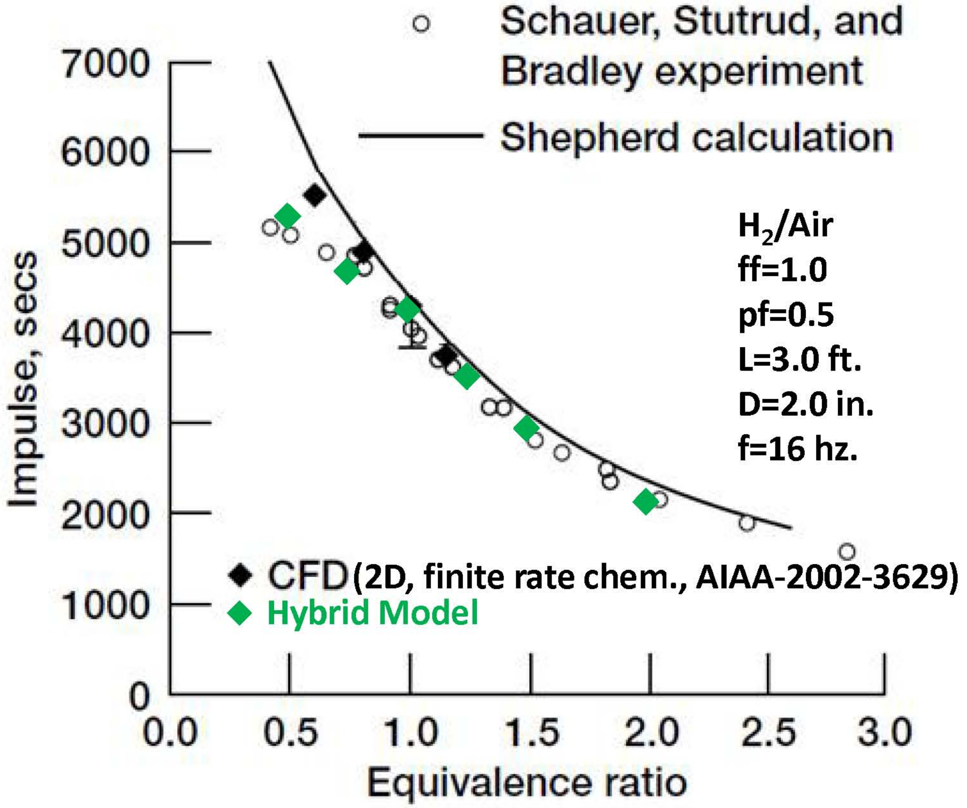
$$\frac{\overline{T}_{t4}}{\overline{T}_{t3}} = 1+(\gamma-1)q_0$$

Model Implemented and Functional in NPSS

Hybrid PGC Model Validation

Unsteady station 4 mass, momentum, and enthalpy can be used to calculate gross thrust

Fuel specific impulse from a laboratory pulse detonation engine, AIAA 2001–1129



H_2/Air
ff=1.0
pf=0.5
L=3.0 ft.
D=2.0 in.
f=16 hz.

Reasonable Agreement With Experiments

Unsteady Turbine Interaction

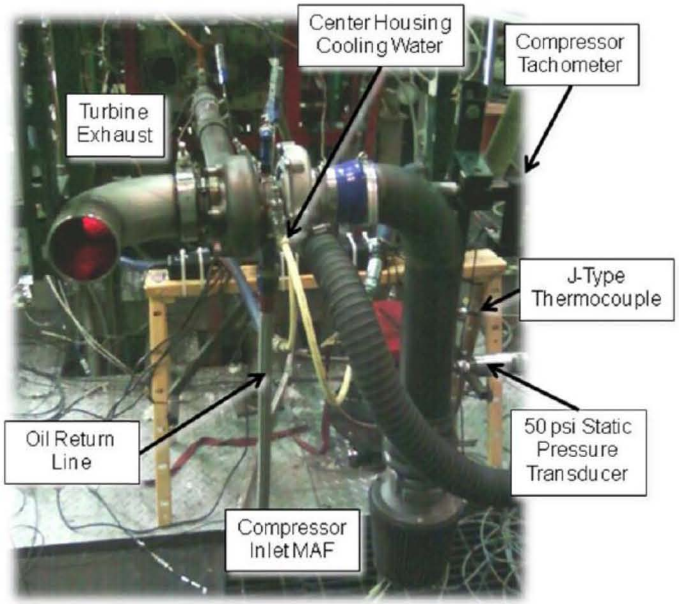
Does the mixed station 4 state, P_{t4}, T_{t4}, with associated entropy, correctly represent the impact of unsteadiness on turbine performance?

Thrust Equivalent Total Pressure: The total pressure which, when ideally expanded to the station 4 static pressure, at the mass averaged total temperature, produces the same gross specific thrust as the PGC device.

Initial Validation

AIAA 2010-1116

PDE-driven turbine delivers 41% more specific work than equivalently fueled, conventional, constant pressure combustor-driven turbine



Basic Thermodynamics

$$\frac{p_{t4})_{PDE}}{p_{t4})_{CPC}} = 1.21$$

PDE vs. CPC pressure ratio required to produce 41% more specific work

Rig Validated CFD Simulation of PDE

$$\frac{p_{t4})_{PDE}}{p_{t4})_{CPC}} = 1.23$$

PDE vs. CPC thrust averaged pressure computed based on experimental conditions

Thrust Averaging (Mixing) is Reasonable

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Unsteady Turbine Interaction: A Closer Look

AIAA 2012-0770

Does the mixed station 4 state, P_{t4}, T_{t4}, with associated entropy, correctly represent the impact of unsteadiness on turbine performance?

Approach-Utilize a Simple PGC Model, Then:

Simulate the work extraction process using so-called quasi-static turbine (QST) assumption

- Develop a representative extended turbine map
- PGC model output is turbine map input
- Integrate over a cycle and calculate specific work extraction

‘Truth Model’-closer to reality

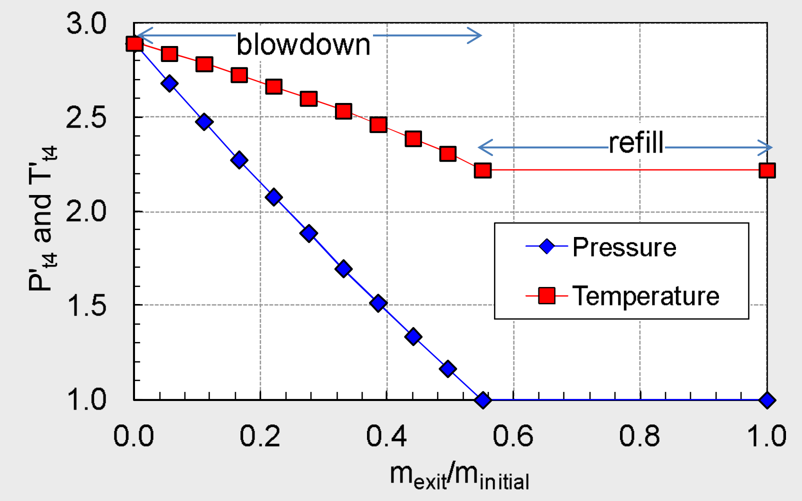
Average the model output using current method

- Develop an ‘equivalent’ PGC output state
- Equivalent output is turbine map input
- Calculate equivalent specific work extraction
- Compare to integrated cycle specific work

What we currently do in NPSS

Unsteady Turbine Interaction

Lumped Volume Distribution of Pressure and Temperature Referenced to Station 3

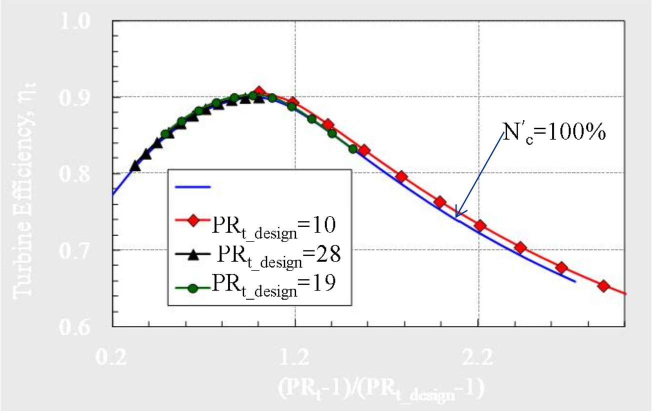


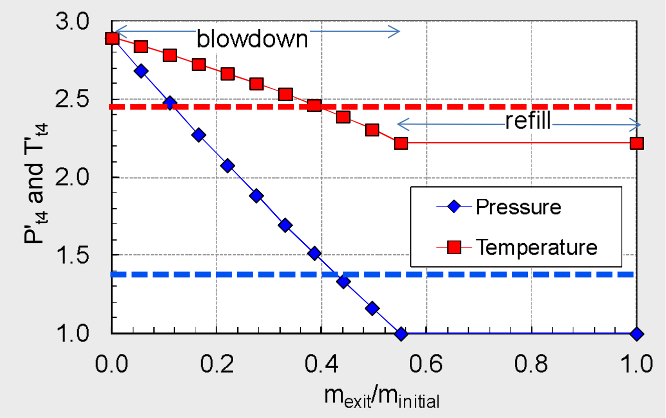
Averaging Model

- ϕ=0.325
- γ=1.33
- P_{t3}/P_{t0}=10
- Alt.=0.0 ft.
- Mach=0.0
- NPR=1.0

Truth Model

$$\eta_t = f\left(PR_t, T'_{t4}, T'_{t4\_design}, N_c, PR_{t\_design}\right)$$





mass average

thrust average

$$\eta_t = f\left(\overline{PR_t}, \overline{T'_{t4}}, T'_{t4\_design}, N_c, PR_{t\_design}\right)$$

$$W'_{t\_Equ} = \eta_t \overline{T'_{t4}}\left[1 - \overline{PR_t}^{-\left(\frac{\gamma-1}{\gamma}\right)}\right]$$

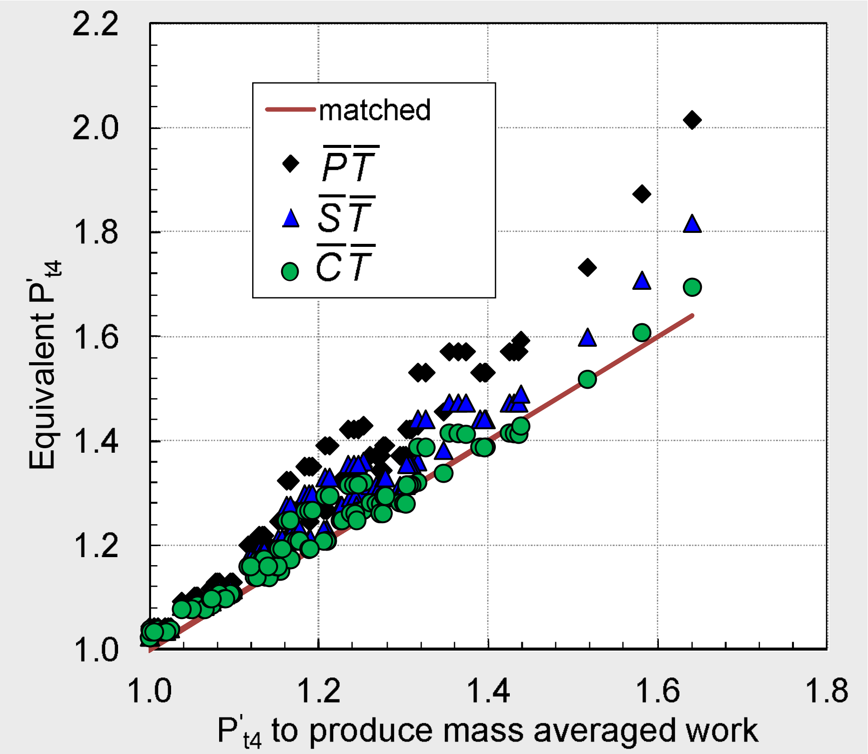
Compare

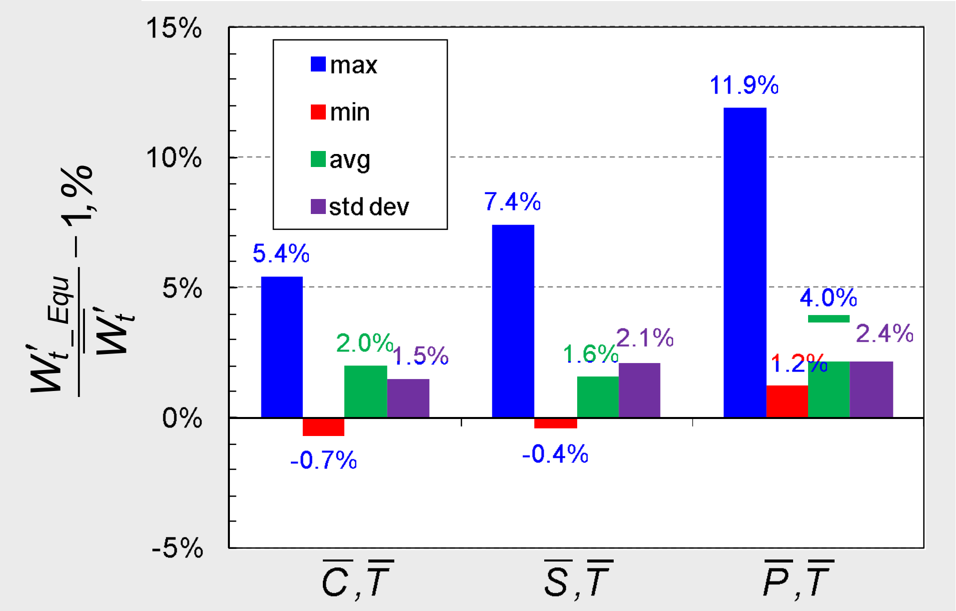
$$\overline{W'_t} \equiv \frac{(\gamma-1)W_t}{m_{initial}\gamma R_g T_{t3}} = \int_0^1 \left\{\eta_t T'_{t4}\left[1 - PR_t^{-\left(\frac{\gamma-1}{\gamma}\right)}\right]\right\} dm'_{exit}$$

Unsteady Turbine Interaction

Averaging: Statistical Experiment

Parameter	Value
Mach	0.0, 0.5
Altitude	Sea Level
CPR	10, 20, 30
NPR	1.01 (M=0 only), 1.5, 2
ϕ_{design}	0.4
$\phi_{off\text{-}design}$	0.3, 0.2, 0.1
Turbine Map	Sensitive, Less Sensitive



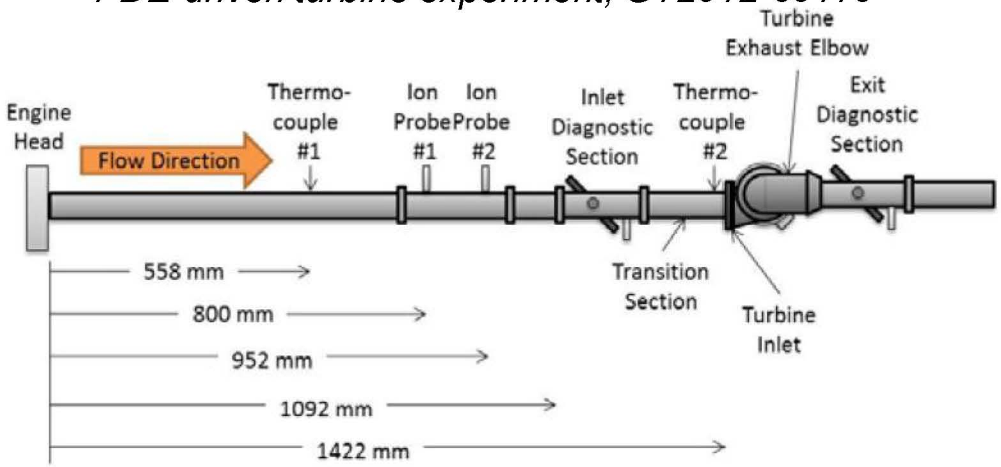


Thrust Averaging ($\overline{C}$,$\overline{T}$) Used in NPSS Produces Close Match to Turbine Work Truth Model

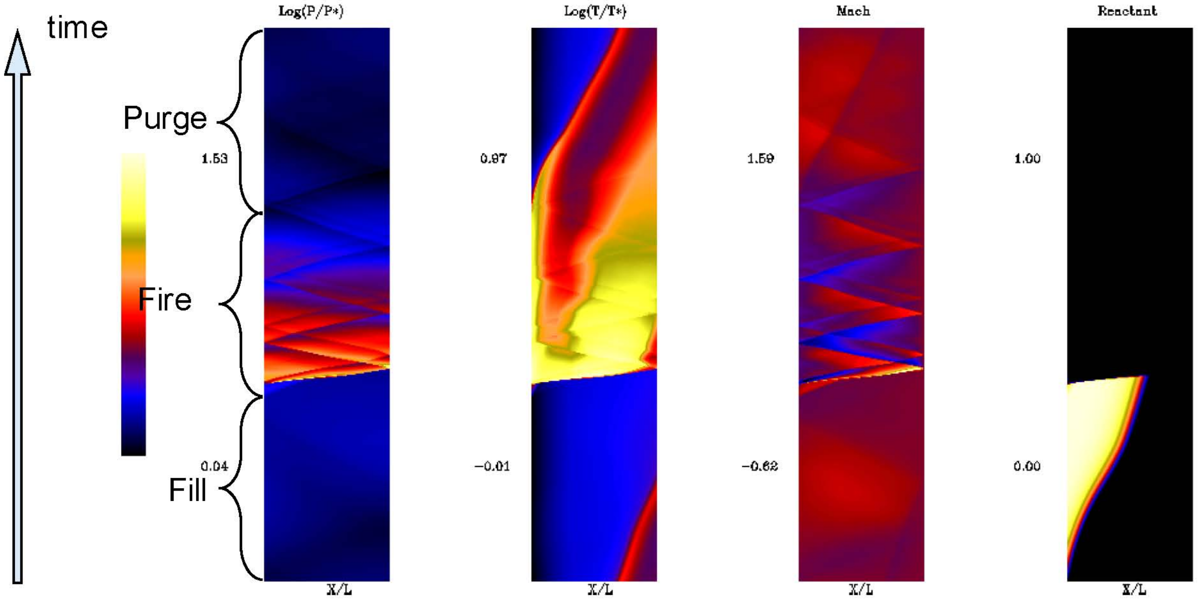
Aside:Does QST Methodology Work?

Validation

PDE-driven turbine experiment, GT2012-69116



Validated CFD simulation of the experimental PDE

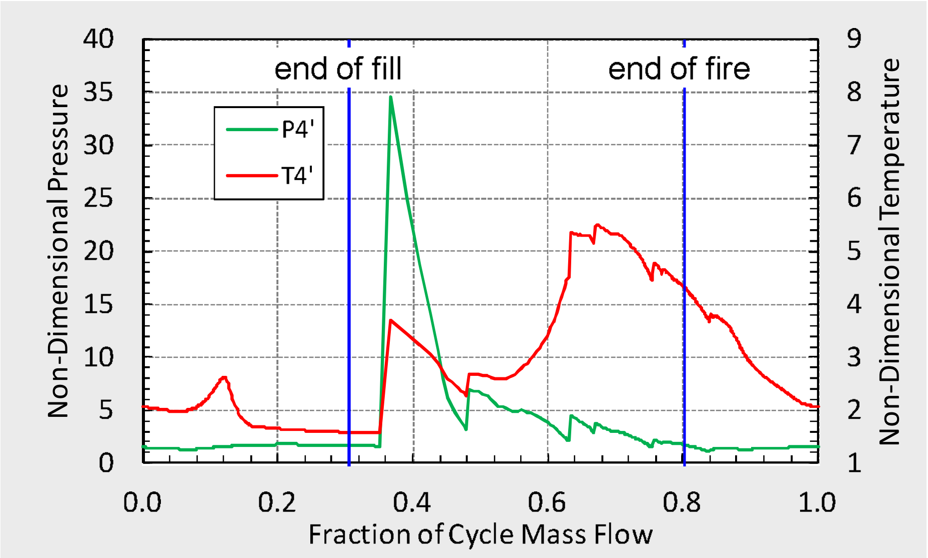


PARAMETERS

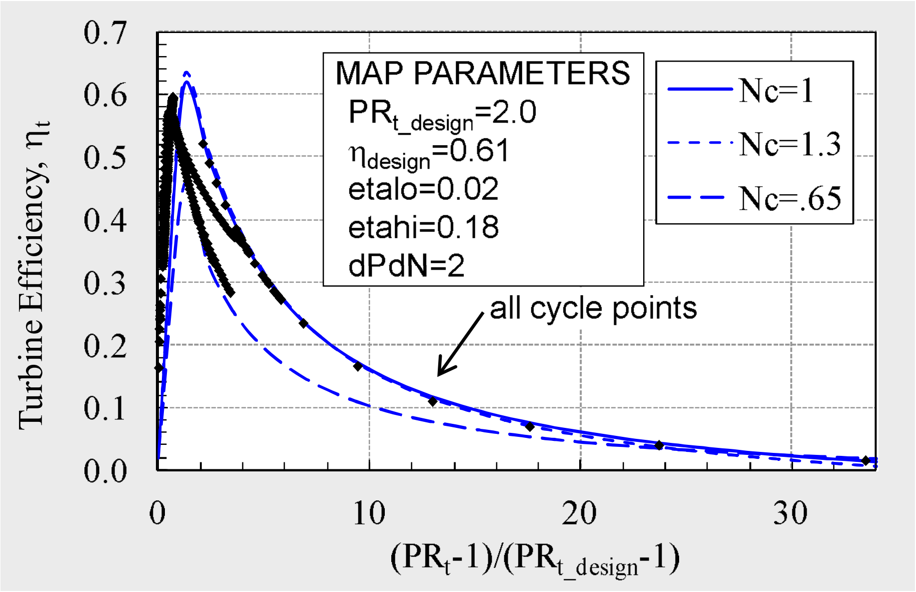
- $L=56$ in.
- $D=2.06$ in.
- H2/Air
- FF=.71
- PF=.71 (based on 1 Atm. @ 520 R)
- $\phi=1.0$
- f= 30 Hz.
- $T_w=900$ R (assumed from paper info.)
- $L_{spiral}=18$ in.
- $\gamma=1.264$
- $R_g=73.92$ ft-$lb_f/lb_m/R$
- m_dot =7.56 kg/min (from paper)
- $AR_{exit}=0.2403$ (best fit to map)

Does QST Methodology Work?

Computed PDE exhaust plane distribution



Turbine map



$$\eta_t = f\left(PR_t, T'_{t4}, T'_{t4\_design}, N_c, PR_{t\_design}\right)$$

$$\overline{W'_t} \equiv \frac{(\gamma-1)W_t}{m_{initial}\gamma R_g T_{t3}} = \int_0^1 \left\{\eta_t T'_{t4}\left[1-PR_t^{-\left(\frac{\gamma-1}{\gamma}\right)}\right]\right\} dm'_{exit}$$

	Experiment	Calculated
$\dot{W}_t$	10.72 kW	11.74 kW†

†10 kW assumed lost to housing upstream of turbine, consistent w/ experiments

QST Is Reasonable
(at least in this case)

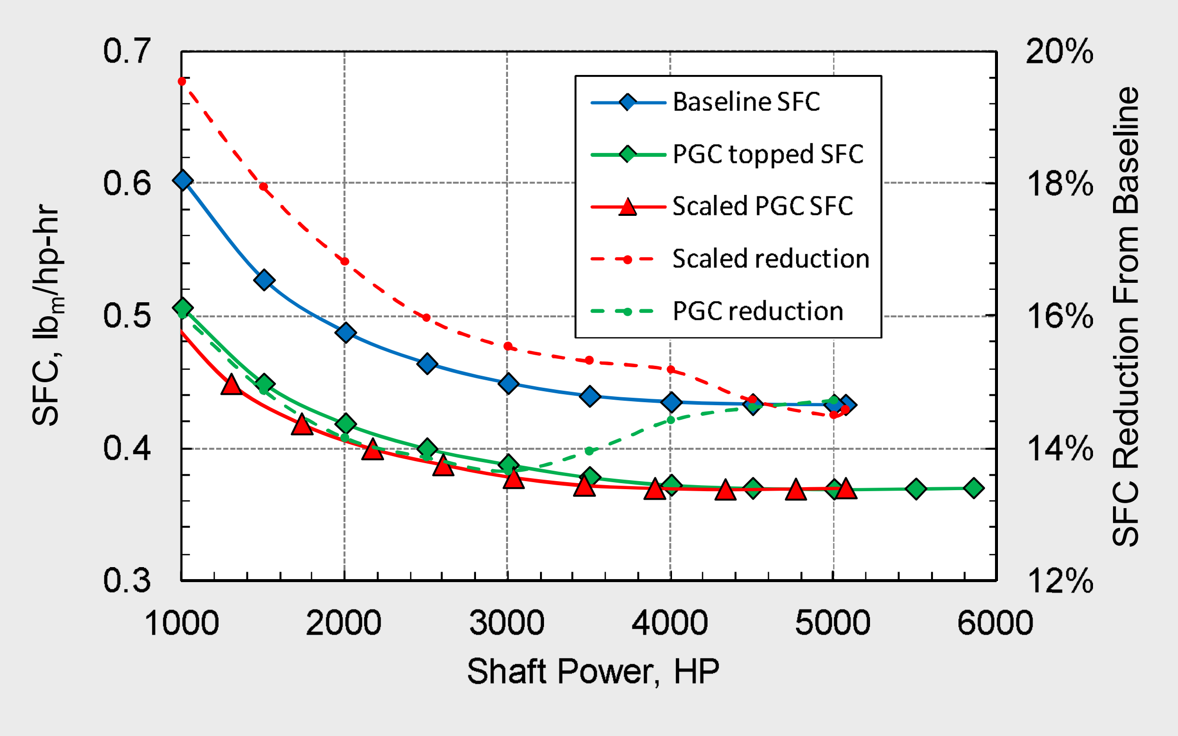
Unsteady Turbine Interaction Adenda

- Quasi-Steady turbine assumption partially validated using AFRL Single Tube PDE-Driven Turbocharger Experiment
- Applicability to turbines driven by multiple tubes is unclear
- Quasi-Steady assumption requires an extended turbine map ($PR >> PR_{des}$) for which no data exists. The treatment of this regime and the flow through it remain under discussion.

This Is An Area Of Investigation That Is Of Intense Interest To The PGC Community.

Example Results: Turboshaft

OPR	18.0
SHP	5071
SFC	0.43



Note

- Power turbine run at constant speed

Example Results: Turbofan Mission Benefits

- PGC topped engine performance data from NPSS
- Mission analysis from FLOPS

	Regional Jet (ERJ190 like)			Intra-Continental (737-800 like)			Inter-Continental (777-200ER like)		
	CF34 -type engine			CFM56 -type engine			GE90 -type engine		
	Baseline	*PGC*	*% change*	*Baseline*	*PGC*	*% change*	*Baseline*	*PGC*	*% change*
Compressor OPR	23.4	23.7		29.9	29.9		39	39	
BPR	5.1	5.3		5.5	5.9		8.5	8.8	
Engine Pod Weight, WENG, lb	4147	3929*		5731	5523*		22157	22792*	
Engine Pod Length, XNAC, ft	10.7	10.22		11.36	10.83		22.16	22.15	
Nacelle Max Diameter, DNAC, ft	5.4	5.41		6.93	6.93		12.57	12.57	
Rated Thrust of Engine, THRSO, lb	14031	14257		27560	27560		86799	86800	
Number of Passengers	98	98		160	160		301	301	
Design Range, nmi	2400	2400		2875	2875		7725	7725	
Engine Thrust, lb	22896	21934	-4.20%	27122	26726	-1.46%	91848	89716	-2.32%
Takeoff Gross Weight, lb	127490	121629	-4.60%	170229	164033	-3.64%	655839	640622	-2.32%
Operating Weight Empty, lb	73601	70529	-4.17%	85504	83475	-2.37%	318202	316411	-0.56%
Block Fuel, lb	26901	24679	**-8.26%**	39128	35741	**-8.66%**	248553	236550	**-4.83%**
Economic Range, nmi	600	600		1000	1000		4000	4000	
Engine Thrust, lb	22896	21934	-4.20%	27122	26726	-1.46%	91848	89716	-2.32%
Takeoff Gross Weight, lb	107450	103241	-3.92%	143937	140035	-2.71%	523608	515167	-1.61%
Operating Weight Empty, lb	73601	70529	-4.17%	85504	83475	-2.37%	318202	316411	-0.56%
Block Fuel, lb	7815	7167	**-8.29%**	14087	12886	**-8.53%**	122121	116599	**-4.52%**

**** WENG for PGC runs include a doubling of the burner weight to estimate the weight of the PGC technology***

Concluding Remarks

- A realistic, low-order, physics-based pressure gain combustion (PGC) performance model has been developed and validated
- The model has been implemented in the Numerical Propulsion System Simulation (NPSS) environment
- The model can be used for PGC configurations which produce thrust directly or those that are coupled to turbomachinery
- The impact of PGC unsteadiness on turbomachinery is accounted for with a reasonable mixing/loss calculation
- The model has already been used by several government and industry organizations for benefits analyses
- For gas turbine-based PGC systems, 4%-19% SFC or mission fuel burn reductions have been calculated compared to the baseline engine

END