Combined Cycle Power Generation Employing Pressure Gain Combustion

2015 University Turbine Systems Research Workshop
November 3rd, 2015

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This material is based upon work supported by the Department of Energy under Award Number DE-FE0024011.

Background

Vast prior data provide validation/realism to current program performance predictions

- Program Objective: to assess the potential benefit of applying pressure gain combustion (PGC) technology to large scale combined cycle power generation
- DOE’s preliminary estimate is a 1-3% benefit for the combined cycle application
- UTC has a long history of PGC research which includes the DARPA Vulcan program
- This wealth of existing experimental data, analytical capabilities, and experience will be leveraged to facilitate this program
- This analysis focused on the pulse detonation engine (PDE) as the PGC due to the higher TRL

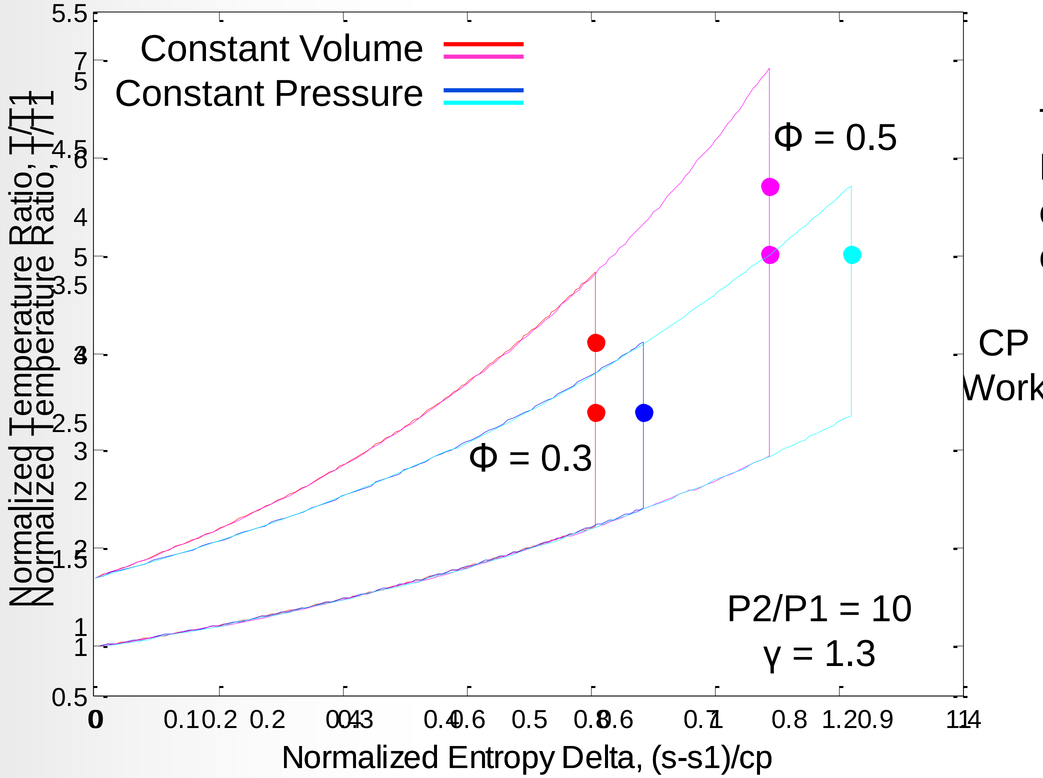
Thermodynamic Benefit

PGC is fundamentally more efficient than standard combustor technology

- Definition of Pressure Gain Combustion (PGC)
  - *A periodic combustion process whereby the effective total pressure of the exit flow, on an appropriately assessed basis, is above that of the inlet flow.*

- Less entropy is generated during heat release resulting in a more efficient process (shown below comparing constant volume combustion (CVC) to constant pressure)

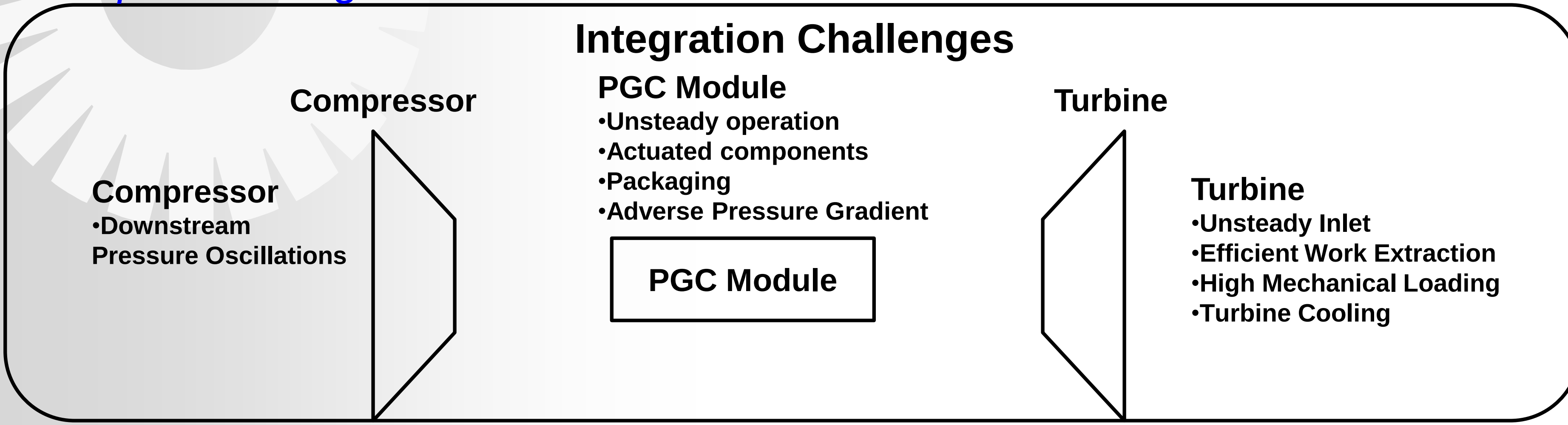
Comparison between constant volume combustion (CVC) to constant pressure (CP)



The potential benefit of PGC scales with the enthalpy ratio across the combustor

Gas Turbine PGC Integration Challenges

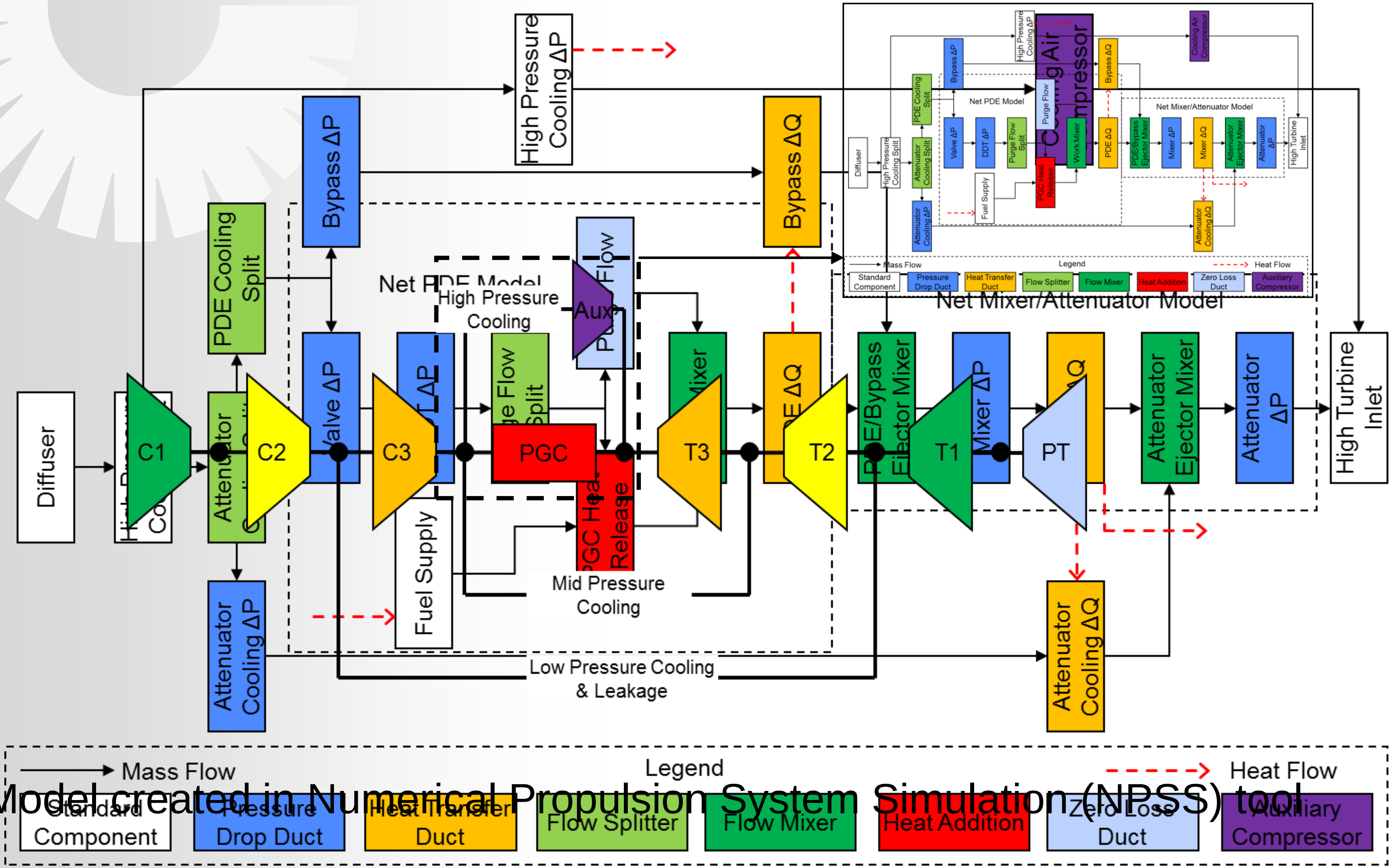
Integrating an unsteady combustor into steady rotating machinery poses unique challenges



- Previous analysis has shown that the compressor integration is trivial for a PDE based system provided it has a high performance air valve
- The most difficult integration challenge is between the unsteady combustor and the steady turbine
  - Our approach introduces an attenuation device between the two components to condition the flow prior to entering the turbine
- For all PGC systems, the fundamental issue of the adverse pressure gradient must be addressed

Gas Turbine System Model

Detailed system model was created in a proven performance evaluation tool

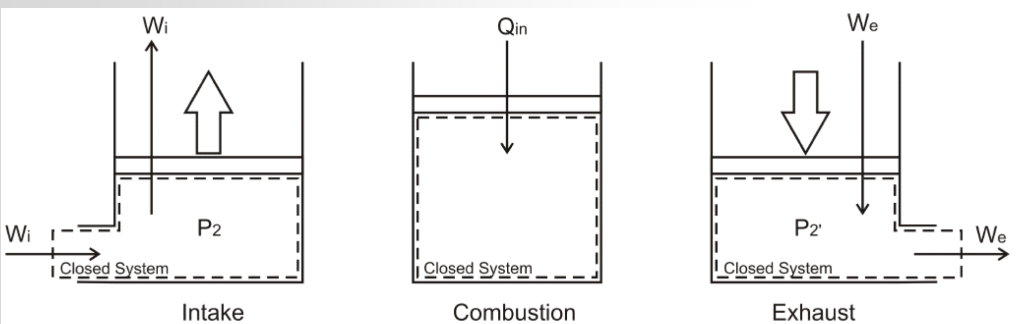


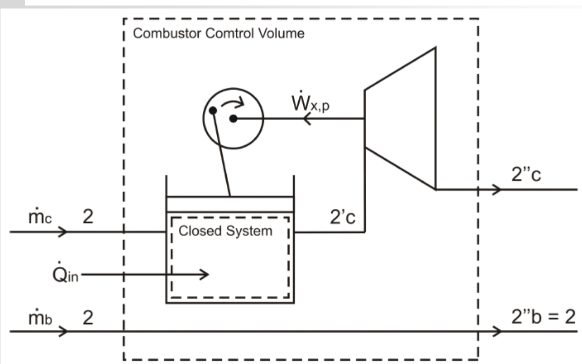
Model created in Numerical Propulsion System Simulation (NPSS) tool

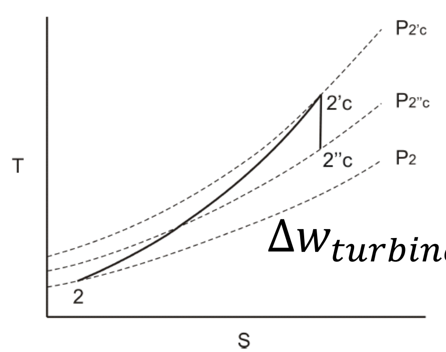
PGC Combustor Representation

Simplified PGC representation implemented in NPSS

- For the system cycle model, a simple PGC representation is required
- A model based on the method documented in Ward et.al. was implemented
- It utilizes a two step calculation to determine the partially relaxed state







Piston Work

$$\Delta w_{piston} = w_e - w_i = (P_{2'} - P_2)v$$

Constant Volume Heat Addition

$$q = u_{2'} - u_2 \approx c_v(T_{2'} - T_2)$$

Turbine Expansion Work

$$\Delta w_{turbine} = h_{2'} - h_{2''} \approx c_p T_{2'} \left[1 - \left(\frac{P_{2''}}{P_{2'}}\right)^{\frac{\gamma-1}{\gamma}}\right]$$

Ward, C.M. and Miller, R.J., “Performance Analysis of an Ejector Enhanced Pressure Gain Combustion Gas Turbine”. 50th AIAA Aerospace Sciences Meeting, AIAA 2012-0772

Non-Ideal PGC Combustor Representation

Practical PGCs are not perfect constant volume combustors

- The previous PGC representation was that of a perfect constant volume combustor
- A modified version of the same framework was implemented to retain the correct PGC physics with tunable parameters
- The tunable parameters allow for the PGC model to be calibrated to experimental data or analytical results for a specific design
  - Non-ideal version implemented into system model PGC module

$$\Delta w_{piston} = v\,[(1+\Delta v)P_{2'} - P_2]$$ ⟺ Non-constant volume

$$\eta_{comb\_eff}\, q = u_{2'} - u_2 = h_{2'} - h_2 - v[(1+\Delta v)P_{2'} - P_2]$$ ⟺ Incomplete heat release

$$\Delta w_{int\_turbine} = h_{2''} - h_{2'} = \eta_{int_{turbine}}(h_{2''_{ideal}} - h_{2'})$$ ⟺ Non-ideal blowdown process

Component Performance Update

Completed component performance update and NPSS model calibration

- All component performances were derived from a wealth of existing data
- High level methodology was:
  - Extract relevant existing data from prior work
  - Evaluate the methods used to obtain the data
  - If necessary, perform additional analysis to update performance estimate
  - Calibrate NPSS modules based on existing data
  - Evaluate how the DOE design will modify the component performance
  - Estimate range of component performance

Component Losses			
Air Valve Pressure Loss	2.41%	Bypass Pressure Loss	1.86%
DDT Pressure Loss	2.67%	Ejector Efficiency	53.62%
PGC Volume Expansion	10.84%	Mixer Pressure Loss	8.36%
PGC Combustion Efficiency	99.90%	Attenuator Pressure Loss	5.60%
PGC Internal Turbine Efficiency	96.50%	Turbine First Blade Efficiency Decriment	0.65%

Gas Turbine Performance

PGC gas turbine is more efficient and produces more power than the baseline system

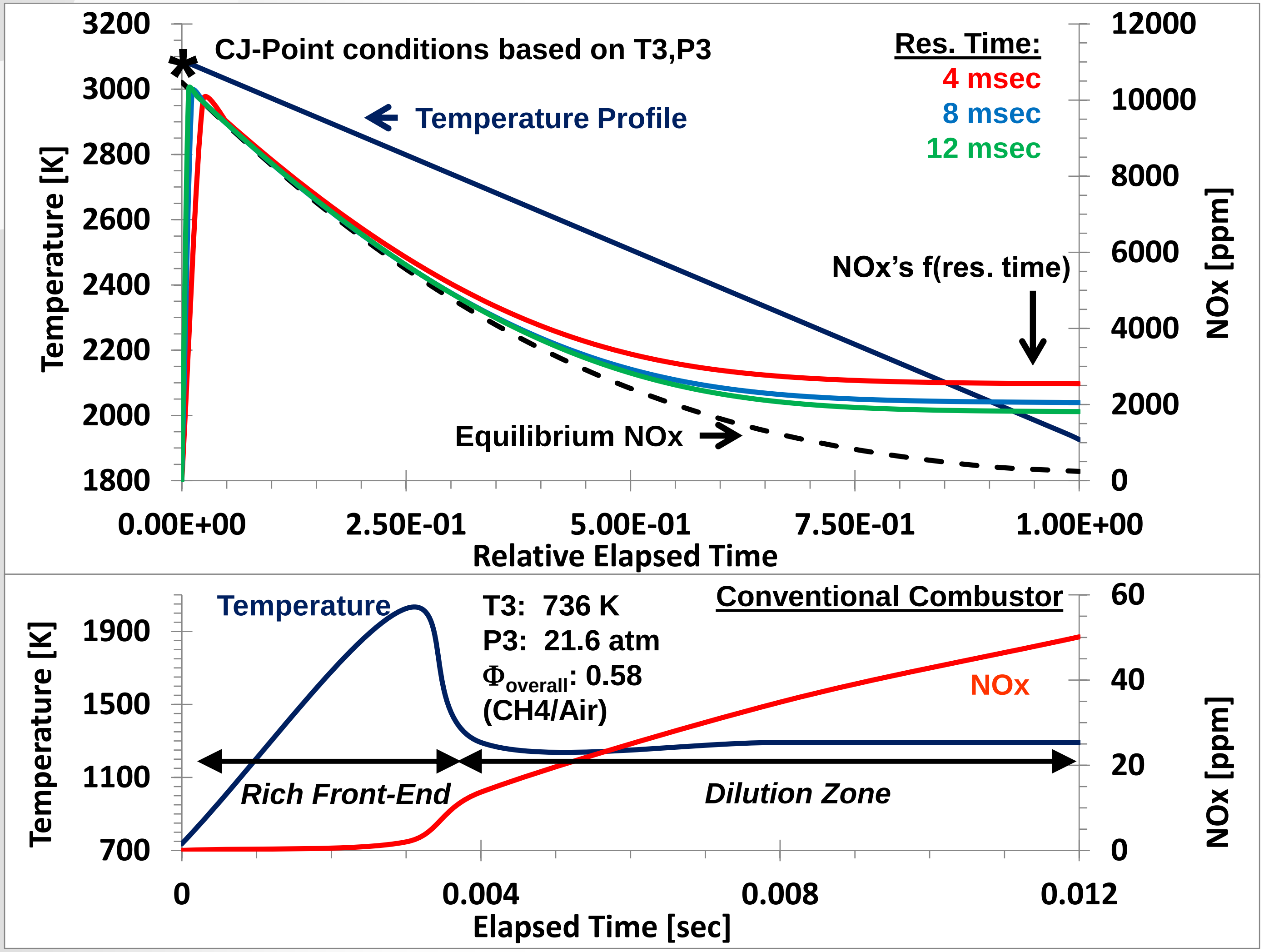
- Baseline and PGC system have the same mass flows and compressor
- All system changes applied to the combustor and turbine

	Units	Baseline	PGC
P3 (Compressor Exit)	psia	335	335
T3 (Compressor Exit)	F	866	866
Total Cooling Air Flow Rate	lbm/s	242	112
Combustor Exit Pressure	psia	318	507
Combustor Exit Temperature	F	3045	3687
Ejector Efficiency	NA	-	53.6
Net Attenuator Pressure Loss %	%	-	14.5
P4.1 (Turbine First Blade Row Inlet)	psia	307.0	385.5
T4.1 (Turbine First Blade Row Inlet)	F	2727	2729
High Turbine Inlet Guide Vane Pressure Loss	%	3.5	-
Turbine First Stage Adiabatic Efficiency Decrement	NA	-	0.65
T9 (Engine Exit)	F	1200.5	1126.1
Parasitic Power Losses	kW	-	3495
Electrical Generator Power	kW	344,916	371,778
Gas Turbine Efficiency	NA	**44.00**	**47.42**
Percent Power Increase	%	NA	**7.79**

Same Compression
Initial Pressure Gain ~1.5x
Combustor Burns Hotter and at Higher Pressures
Final Pressure Gain ~1.15x
Attenuator Losses to Condition the Flow
Removal of HPT Inlet Guide Vane
Final Exit State is Same Temperature Higher Pressure
Residual Unsteadiness Results in Turbine Efficiency Loss
Less Residual Energy Available to Steam Cycle
~1% Parasitic Losses are Required to Operate the PGC System
PGC System is More Efficient and Produces More Power

PGC NOx Production

"Time at temperature" notion for NOx production valid for conventional combustor, but not for PDE



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Steam Cycle Impact

Changes in the gas turbine performance were propagated to the steam cycle

- PGC technology doesn't inherently impact the steam cycle of the power plant
- Consequently, this program focused on the gas turbine and a simple approach was taken to assess its impact on the steam cycle
- Only change to the steam cycle was the input heat
- HRSG exit state was held constant
- Steam cycle efficiency was either held constant or a small reduction can be introduced
- With these two assumptions the power produced by the steam cycle can be calculated

$$Q_{a\_exit\_HRSG} = Constant$$

$$Q_{H_{steam}} = Q_{a\_exit\_Turbine} - Q_{a\_exit\_HRSG}$$

$$\eta_{steam\_PGC} = \eta_{steam} - delta$$

$$\eta_{steam} = 1 - \frac{Q_{L_{steam}}}{Q_{H_{steam}}}$$

$$Power_{steam} = Q_{H_{steam}} - Q_{L_{steam}}$$

Power Plant Performance

PGC based combined cycle power plant is significantly more efficient

- A portion of the performance gains in the gas turbine are offset by the steam cycle

Gas Turbine	units	Standard Baseline	PGC System (Maintain P3, T3)	Steam Cycle Efficeincy Impact	PGC System Mod. (Hold P4, Fuel Flow)	PGC System Mod. (Hold P4, H4)
Exit Specific Enthalpy	kJ/lbm	**449.3**	**427.3**	427.3	438.2	451.5
Gas Electrical Power Produced	kW	**344916**	**371778**	371778	357080	373168
Gas Turbine Efficiency		44.00%	47.42%	47.42%	45.55%	45.59%
Percent Change in Gas Turbine Power			7.79%	7.79%	3.53%	8.19%
Steam Cycle						
Total Gas Tubine Exit Q	kW	**1219932**	**1160053**	1160053	1189911	1225917
Heat Flux at Exit of HRSG	kW	**451972**	**451972**	451972	451972	451972
Qh Steam Cycle	kW	**767960**	**708081**	708081	737939	773944
Ql Steam Cycle	kW	**447005**	**412151**	419232	429531	450488
Steam Cycle Efficiency		**41.79%**	**41.79%**	40.79%	41.79%	41.79%
Steam Cycle Electrical Power	kW	**298123**	**274877**	268300	286468	300446
Percent Change in Steam Cycle Power			-7.80%	-10.00%	-3.91%	0.78%
Power Plant						
Net Power	kW	**981987**	**1011187**	1004248	994019	1040941
Net Efficiency		**62.63%**	**64.49%**	64.05%	63.40%	63.59%
Change in Efficiency			**1.86%**	1.42%	0.77%	0.96%
Percent Change in Power			**2.97%**	2.27%	1.23%	6.00%

Extra Work Extraction in the Gas Turbine Reduces Available Energy to the Steam Cycle

Constant Efficiency Assumption Due to Minor Change in Input Energy Results in Less Power Generated in the Steam Cycle

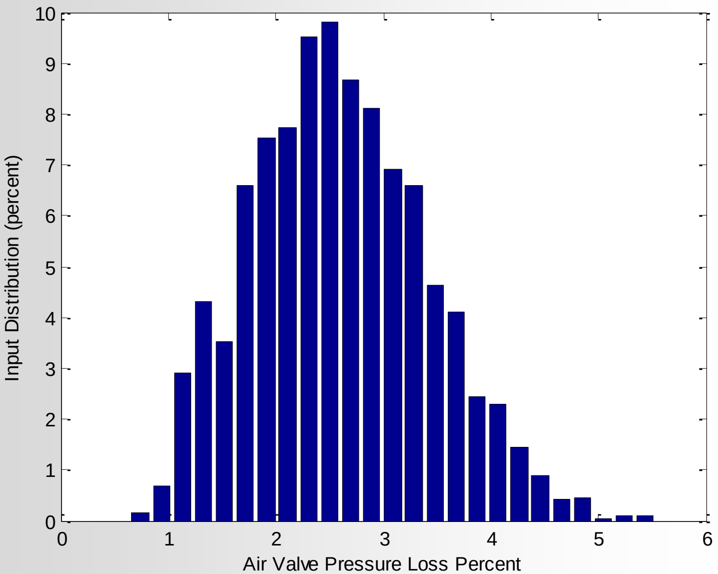
Net Power Produced Still Greater by Twin Turbine Pack

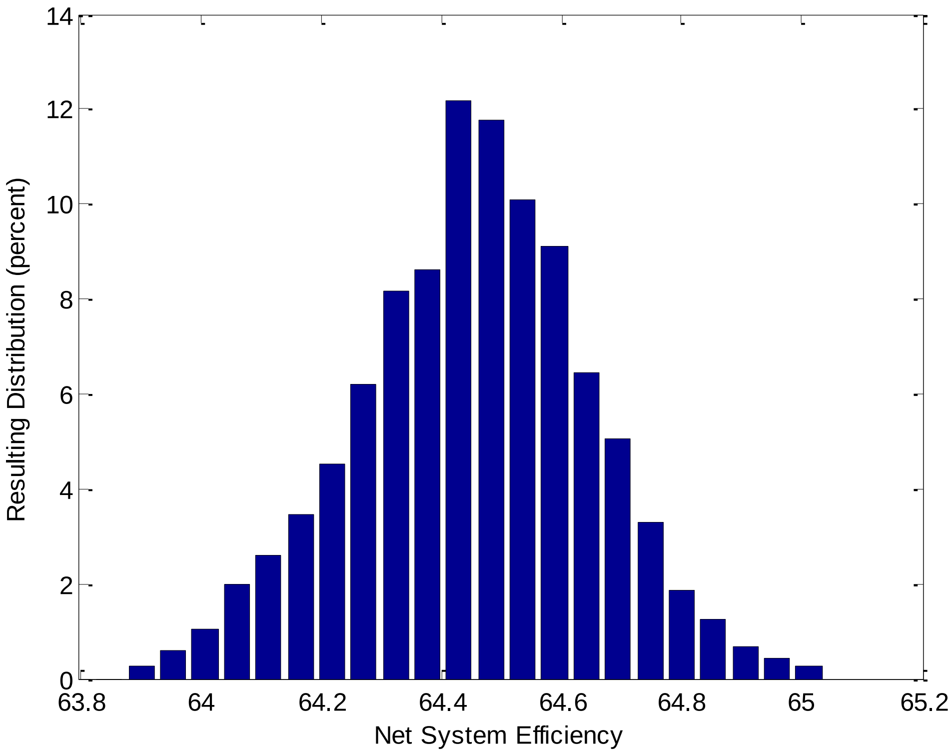
Power Plant is More Efficient and Produces More Power

Range of Performance Estimate

Full range of performance estimate show a benefit over the standard system

- To estimate the range of possible outcomes a Monte-Carlo method was employed for all PGC specific performance parameters
- Normal and skewed distributions were used depending on the specific parameter
- Distributions were defined by:
  - Likely (mid point)
  - Best and Worst (5% likelihood)





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Technical Conclusions

Performance assessment of PGC technology has been completed

- Approximately ~2% increase in the power plant efficiency is predicted
- Approximately ~3% increase in total power plant power is also predicted (equates to a ~3% reduction in CO_2 production)
- This analysis was for a PDE based system, but a similar result would be expected for any detonative PGC (RDEs) if similar component performances can be achieved
- Other gas turbine improvement technologies would compound with the benefits of PGC technology
- The NOx produced by a PGC system is significantly higher than that of standard combustors
- Program still working to complete technology maturation plan, commercialization assessment, and final documentation

Questions?

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