NATIONAL ENERGY TECHNOLOGY LABORATORY

New Developments in Combustion Technology

Part II: Step change in efficiency

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Course Length: 3 hrs
June 26, 2012

U.S. DEPARTMENT OF ENERGY

Today's presentation

- **New approaches in three ways**
  - Inherent carbon capture: chemical looping combustion.
  - Step-change in generator efficiency: pressure gain combustion
  - Frontier approach (?): making oxy-fuel an efficiency advantage.

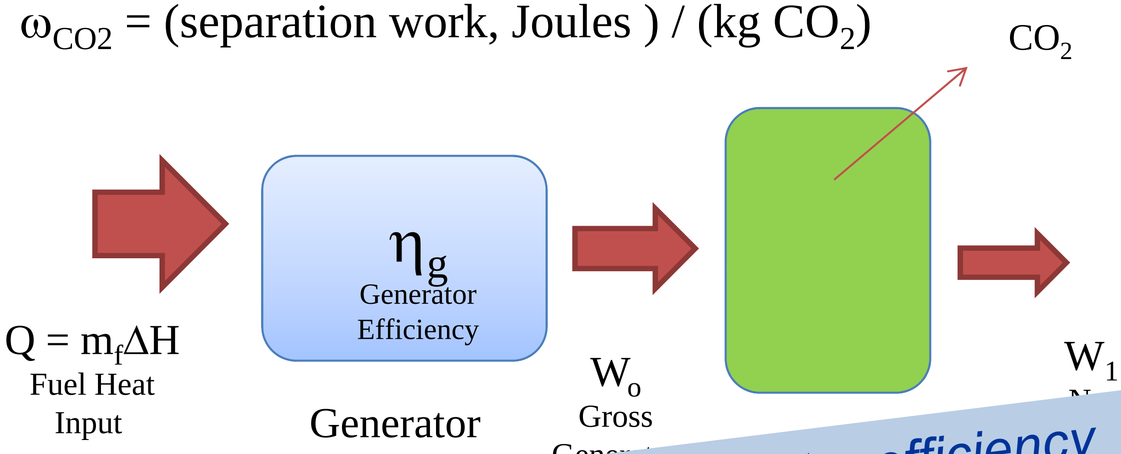



The role of capture AND generator efficiency

Define:

α = (kg CO_2 produced) / (kg fuel burned)

ω_{CO2} = (separation work, Joules) / (kg CO_2)



Can we make a big jump in generator efficiency to offset the capture penalty?

$$\eta_{ov} = \frac{W_1}{Q} = \eta_g - \frac{\omega_{CO2}\,\alpha}{\Delta H}$$

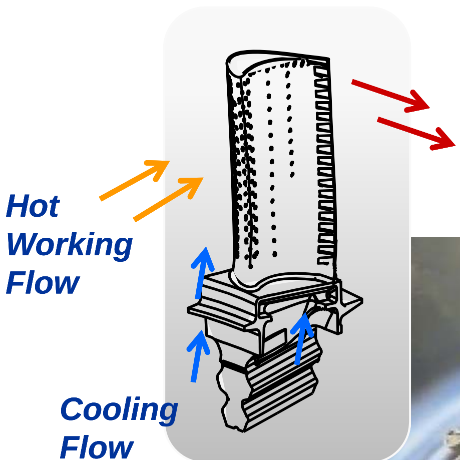
Approx Ranges: (30 – 60%) (6-10%)

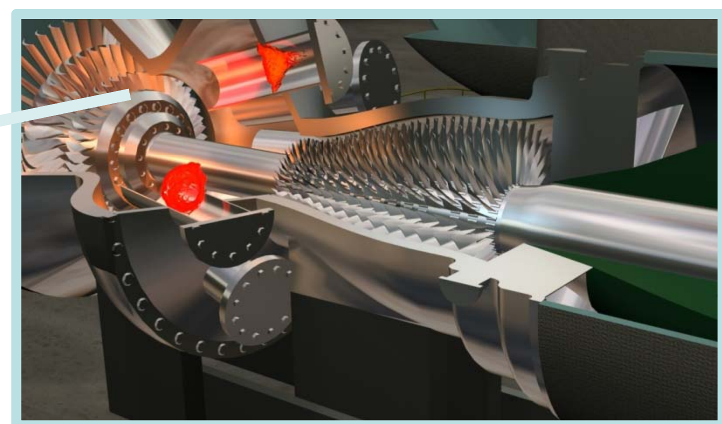
- **A simple heat/energy balance defines the overall efficiency η_{ov} with a carbon separation unit.**
- **Reducing the penalty from carbon capture comes from BOTH:**
  - Decreasing ω_{CO2}
  - Increasing η_g

Turbines for Power and Propulsion

- **Turbines are the workhouse for large power (~>5MW) or propulsion.**
- **Advanced cooling flow and material schemes enable high efficiency (power) and less fuel per flight (propulsion).**

Efficiency gains are linked to advances in firing temperature enabled by cooling and materials





History and Turbine Efficiency

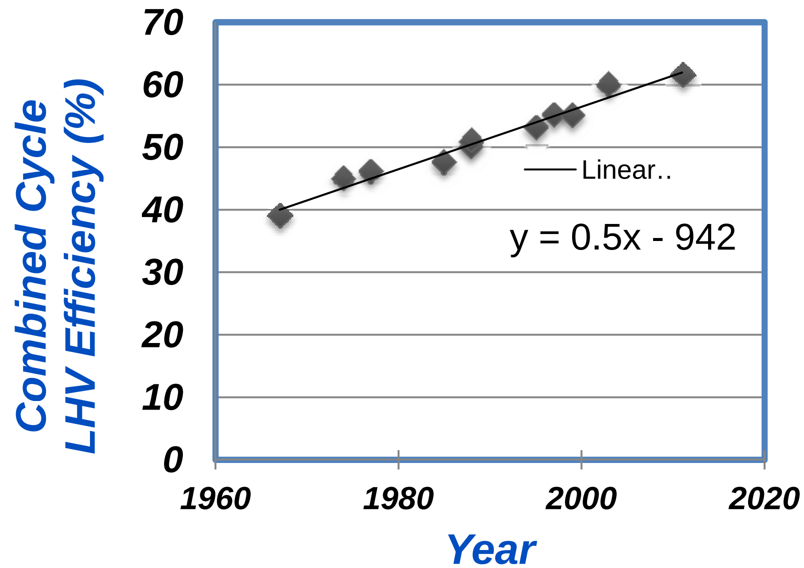
- **Combined Cycle Gas Turbine Efficiency is today + 61% (LHV).**
- **Efficiency gains have occurred with steady progress in materials, heat transfer, and system design.**
  - About +0.5 % per year (right).
- **Impressive performance is still well-below potential:**

$$\eta_{\text{Carnot @ 1600C}} = 1\text{-}293/(1873) = 84\%$$

~ State of the art turbine inlet temperature

- **What can be done to "jump above" the line?**

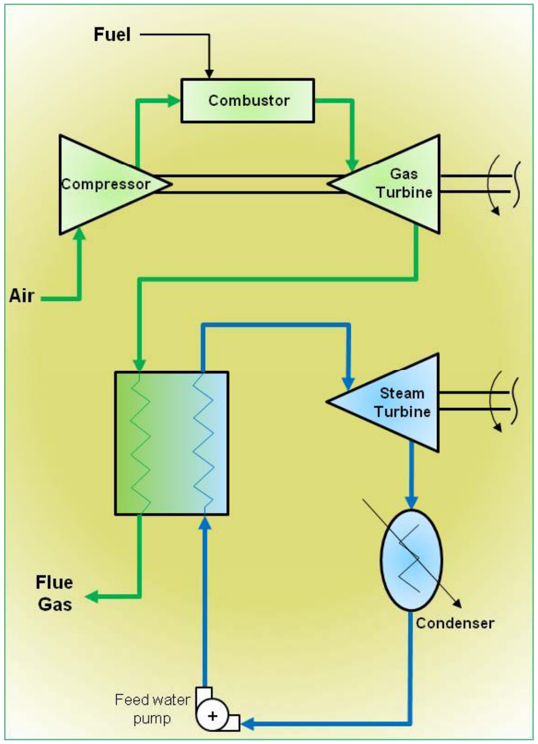
*Gas turbine efficiency trend**



** Sources: (1) Herzog, H., Unger, D. (1998) Comparative Study on Energy R&D Perfrmance: Gas Turbine Case Study, Final Report for Central Research Institute of Electric Power Industry (CRIEPI), Figure B, pp. iii. , http://web.mit.edu/energylab/www/pubs/el98-003a.pdf (2) Gas Turbine World 2012 Performance Specs, 28th ed Vol 42, No1, pp 31.*

A step-change in efficiency

- **Turbine pressure-ratio and firing temperature influence the combined cycle efficiency.**
- **A *combined cycle* exploits the heat rejected by the "hotter" turbine cycle to the "colder" steam cycle.**
- **Further increases in pressure-ratio and firing temperature of the gas turbine can increase the combined cycle efficiency.**
- **If YOU wanted to increase the efficiency above the "historical" line, what would YOU do?**
  - A. *Improve the steam cycle – supercritical CO_2?*
  - B. *Make the turbine a bottoming cycle to a fuel cell.*
  - C. *Find a different thermodynamic CYCLE.*
  - D. *Invent turbine blades made out of diamond (melting point 3550˚C).*
  - E. *Other________________________________*

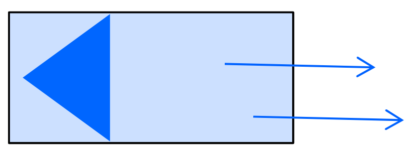


Pressure Gain Combustion

A different cycle

Constant-volume combustion products are at a significantly greater thermodynamic availability than constant-pressure.

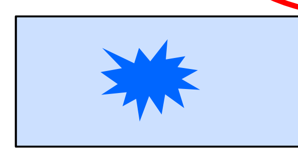
30 bar, 600 K — *30 bar, 1600 K*



Conventional steady combustion (~constant pressure)

$$\Delta H = Q$$
$$C_p \, \Delta T_{cons\ P} = Q$$

30 bar, 600 K — *100 bar, 2000 K*



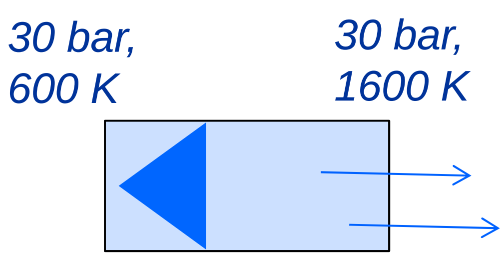
Pressure -gain combustion (~constant volume)

$$\Delta U = Q$$
$$C_v \, \Delta T_{cons\ V} = Q$$

Pressure Gain Combustion

<u>A different cycle</u>

Constant-volume combustion products are at a significantly greater thermodynamic availability than constant-pressure…..but what happens if the pressure is bled off to the ambient - unrestrained?



Conventional steady combustion (~constant pressure)

$$\Delta H = Q$$

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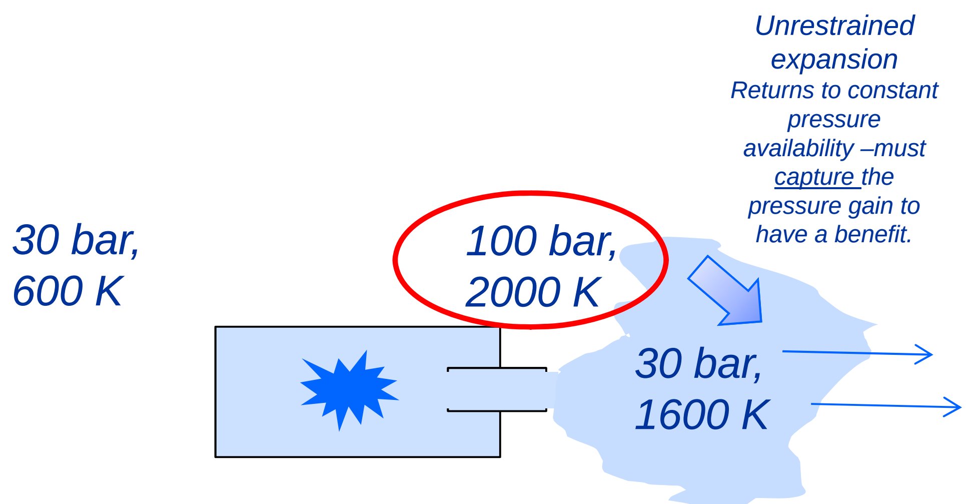


Pressure -gain combustion (~constant volume)

$$\Delta U = Q$$

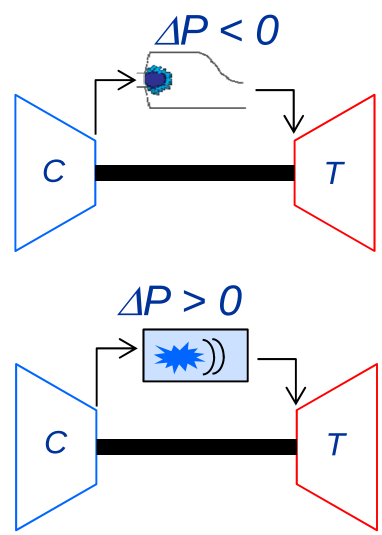
$$C_v \, \Delta T_{cons\ V} = Q$$

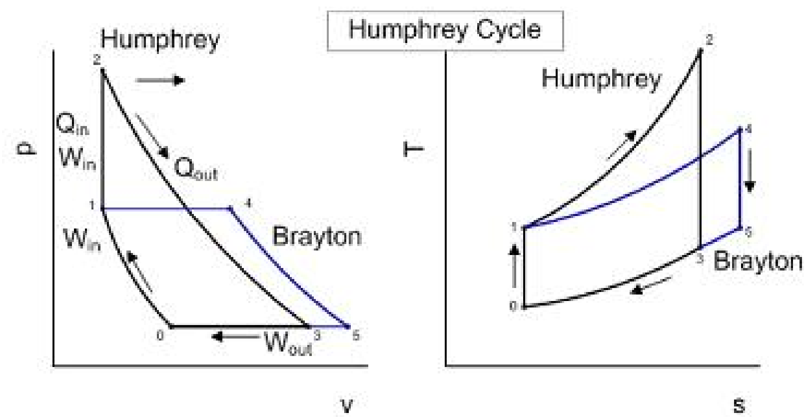
Noisy, but no benefit

Pressure Gain Combustion Cycle

- **Convention gas turbines combustion results in a pressure loss across the combustor** **(Brayton cycle)**

- **Pressure gain with *constant volume combustion*** ***(Humphrey cycle)***
  - *Deflagration or detonation pressure wave* increases pressure and peak temperatures at turbine inlet - reduced entropy production during combustion.





History

- **The idea of capturing the available energy from confined combustion (versus constant pressure) is well recognized.**
  - Piston engines do this already.
  - Early gas turbines used the concept (Holzwarth “explosion” turbine).
  - Compound piston-turbines have been built and flown.
  - Constant-volume combustion eclipsed by easier improvements

THYSSEN-HOLZWARTH OIL AND GAS TURBINES, J*ournal of the American Society for Naval Engineers Volume 34, Issue 3, pages 453–457, August 1922. .*

From the article:
“……Holzwarth-turbine working with a compression of 2.2 atmospheres and an explosion pressure of 17.3 atmospheres absolute….”

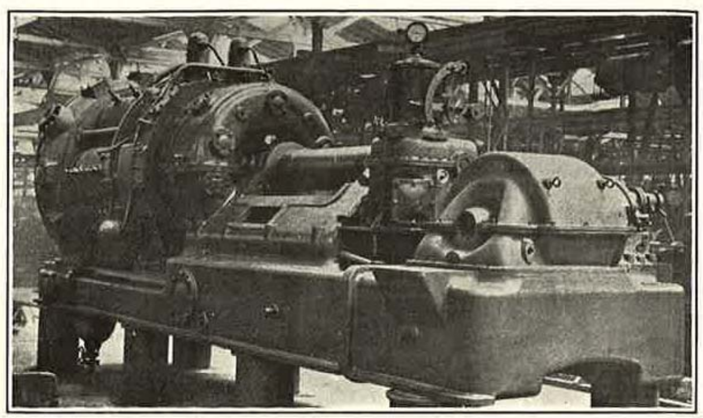
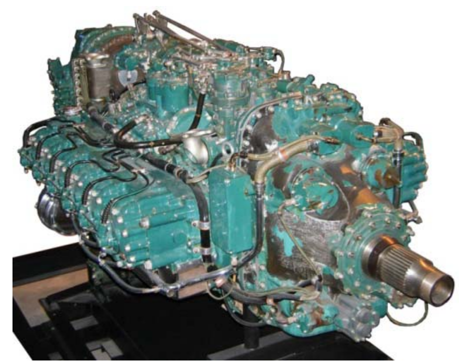
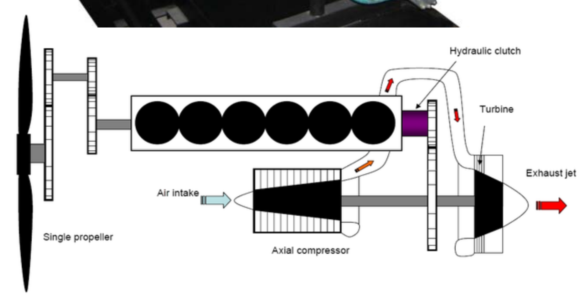


FIG. 8. – THE 500B.H.P. THYSSEN-HOLZWARTH OIL TURBINE, WHICH MAY BE THE POWER OF THE FUTURE FOR MERCHANT SHIPS.

Photo used with permission from Naval Engineers Journal





Napier Nomad Engine (~1950)

Nomad photo credit: Kimble D. McCutcheon via the Aircraft Engine Historical Society. http://www.enginehistory.org/napier.htm

Why is pressure-gain appealing *now*?
Pressure-Gain Combustion for Power Generation

Michael Idelchik, Vice President of Advanced Technologies at GE Research… *Research…Sept 2009 interview on Pulse Detonation for Technology Review published by MIT.*

"An existing turbine burns at constant pressure. With detonation, pressure is rising, and the total energy available for the turbine increases. We see the potential of ***30 percent fuel-efficiency improvement***. Of course realization, including all the hardware around this process, would reduce this.

I think it (efficiency gains) will be anywhere from 5 percent to 10 percent. That's percentage points--say from ***59 to 60 percent efficient to 65 percent efficient***. We have other technology that will get us close [to that] but **no other technology that can get so much at once.** It's very revolutionary technology.

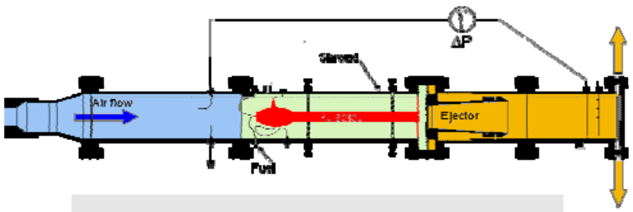
The first application will definitely be land-based--it will be power generation at a natural-gas power plant. "

"If we can turn 5% pressure loss in a turbine into 5% pressure gain, it has the same impact as doubling the compression ratio" – Dr. Sam Mason, Rolls-Royce (2008)*

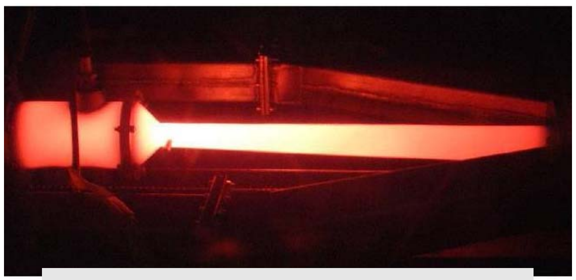
** Quotation courtesy Fred Schauer AFRL*

Current Technology Approaches

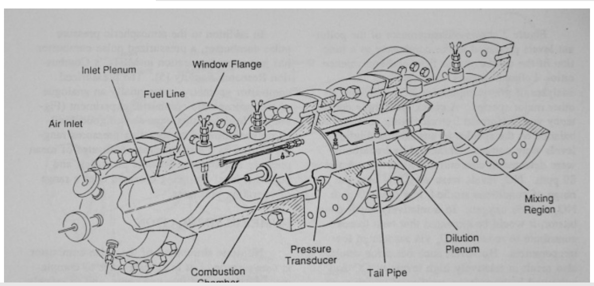
Resonant Pulsed Combustion
(deflagration)†
†Envisioned as a canular arrangement



NASA Glenn, 2005

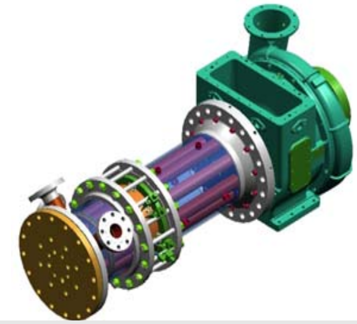


University of Cambridge, 2008

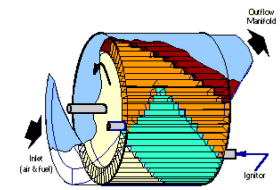


DOE National Energy Technology Laboratory, 1993

Detonation
or
'Fast' Deflagration

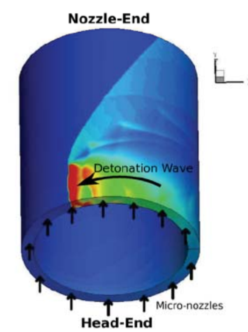


G.E. Global Research Center 2005



IUPUI/Purdue/LibertyWorks, 2009

Rotating Detonation Engine (NRL)



Slide provide by Dan Paxson, NASA Glenn

Pulse deflagration combustion

Current R&D at NASA, Cambridge-Whittle
Past Work at NETL

Aerovalved Pressure Gain Combustor

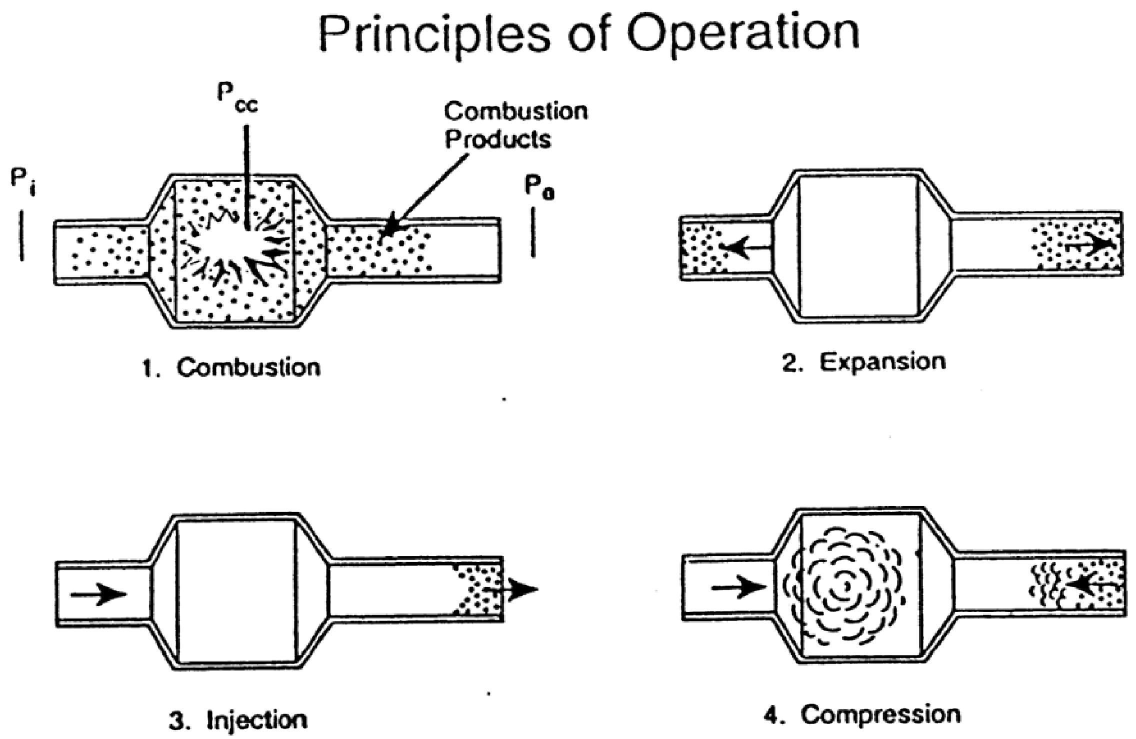
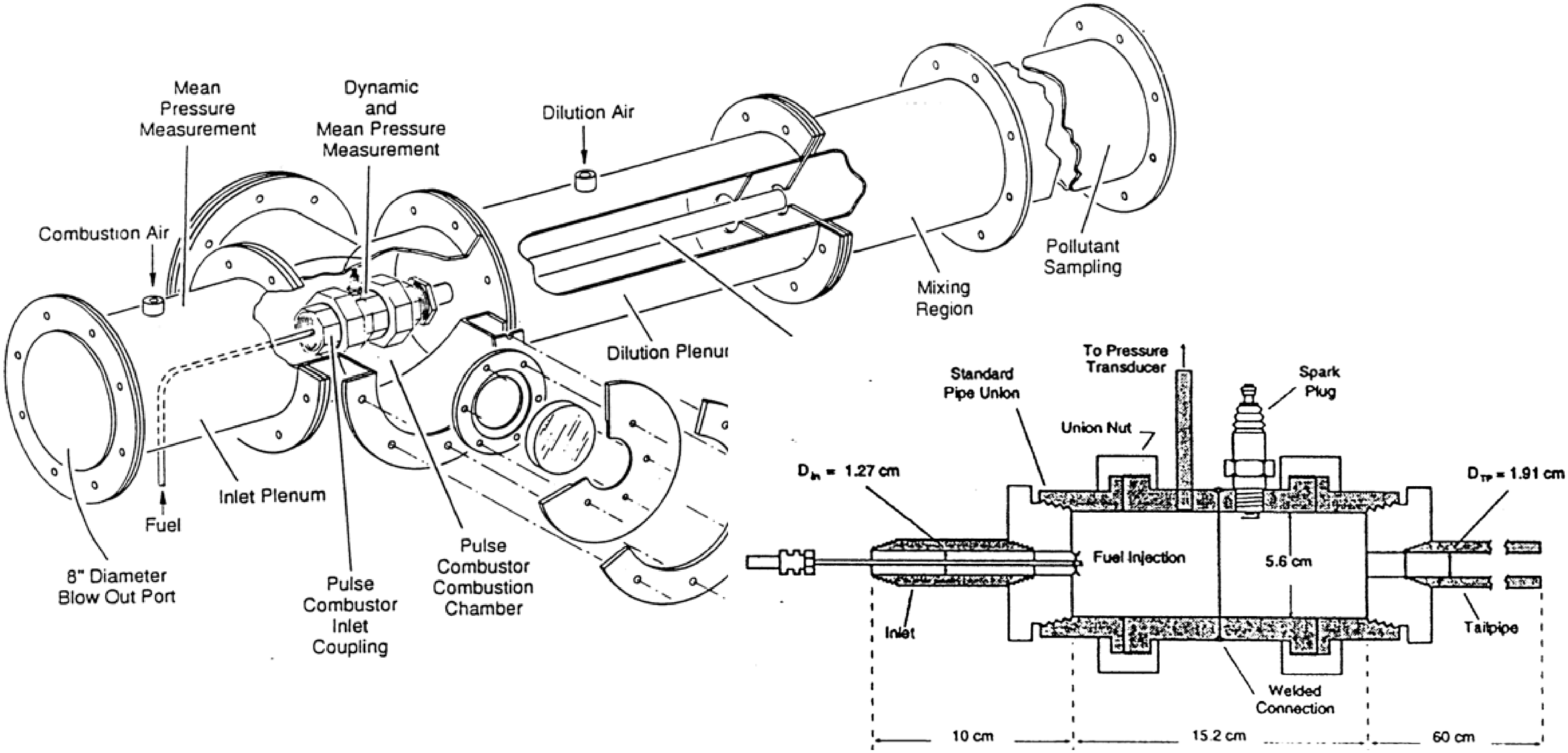


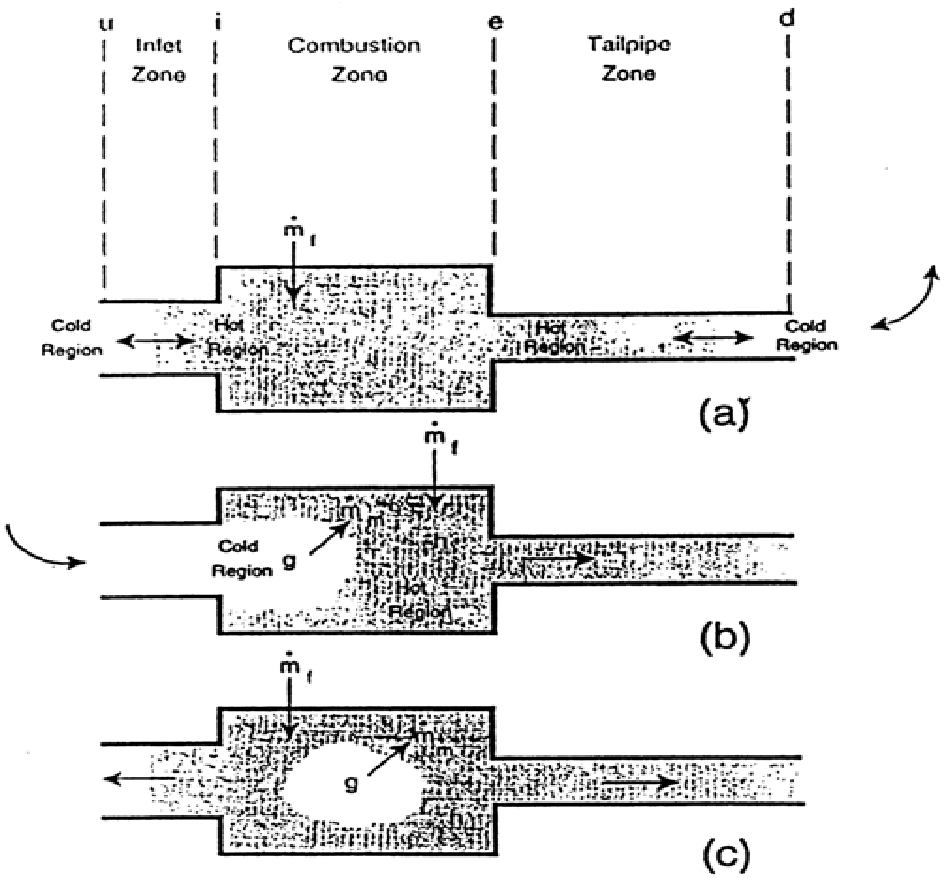
Fig. 1 Operation of an aerodynamically valved pulse combustor. The combustion event (1) raises the pressure in the combustion chamber (P_{cc}), forcing gas out of the inlet pipe and tailpipe (2), the momentum of fluid in the tailpipe draws fresh air through the inlet (3), with a subsequent compression of gases in the combustion chamber (4). On a time average, the flow is from left to right.

NETL Atmospheric Pressure Rig (1991)



- **Combustor constructed with standard pipe fittings.**
- **Allows simple changes in inlet and tailpipe geometry.**

One-Dimensional Modeling



<u>*Characteristic Timescales*</u>

$$\tau_i = \frac{\rho_A V_c}{\dot{m}_i} \quad \text{(inlet flow time)}$$

$$\tau_f = \frac{\rho_A V_c}{\dot{m}_f} \quad \text{(fuel flow time)}$$

$$\tau_e = \frac{\rho_A V_c}{\dot{m}_e} \quad \text{(exit flow time)}$$

$$\tau_c = \frac{P_A}{\dot{Q}(\gamma - 1)} \quad \text{(combustion time)}$$

$$\tau_{HT} = \frac{\rho_A R V_c}{h A_s} \quad \text{(heat transfer time)}$$

$$\tau_m = \frac{\rho_A V_c}{\dot{m}_m} \quad \text{(mixing time)}$$

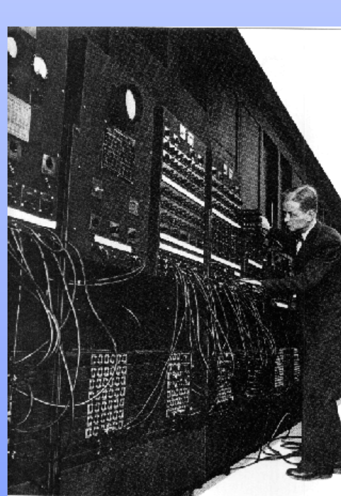
- **Divide combustor into three distinct zones.**
- **Solve conservation equations of mass, momentum and energy.**
- **Provides estimation of frequency and amplitude.**

One-Dimensional Modeling

Why not CFD?

1) Hint: this was 1990.

2) No theory for initial design & scaling.



Nice Computer!

Characteristic Timescales

$$\tau_i = \frac{\rho_A V_c}{\dot{m}_i} \quad \text{(inlet flow time)}$$

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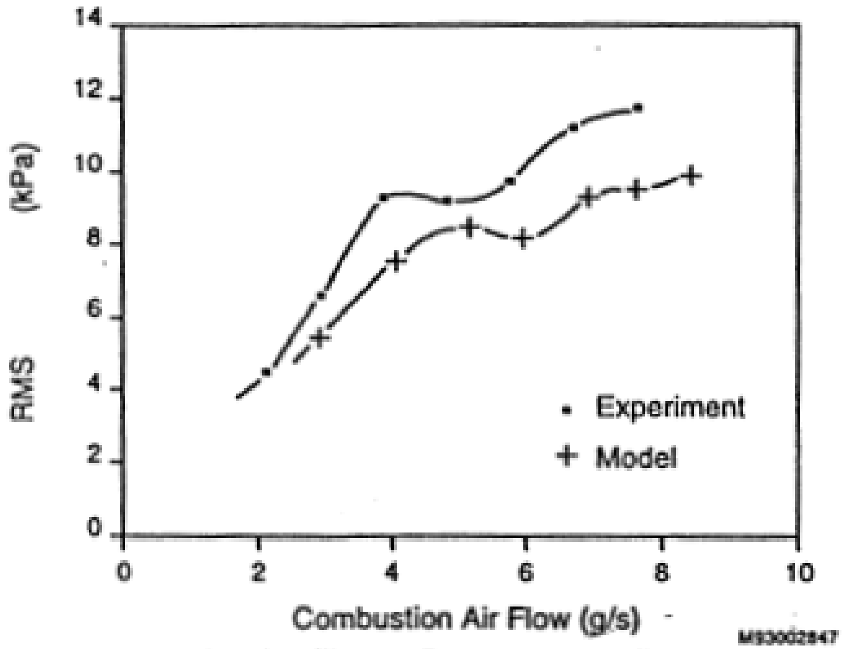
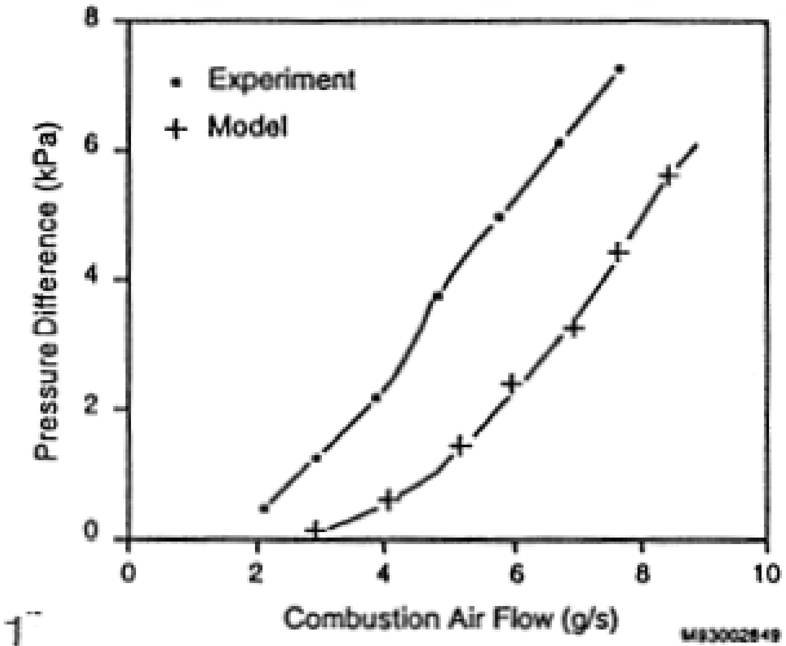
- **...ct zones.**
- **Solve conservation equations of mass, momentum and energy.**
- **Provides estimation of frequency and amplitude.**

Atmospheric Pressure Rig Data

NG/Air ϕ=0.82



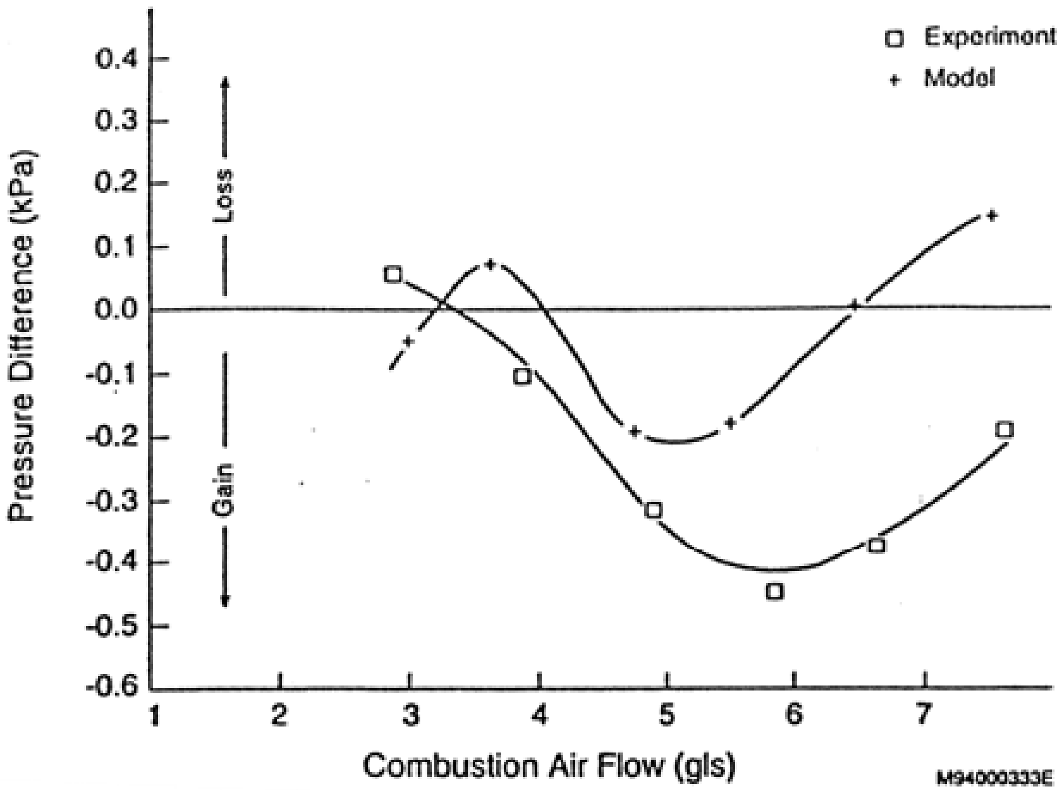
b) Oscillating Pressure Amplitude



c) Inlet - Combustor Pressure Difference

- **Baseline geometry (L_{in}=10 cm, L_{ex}=60 cm).**
- **Resonant frequency ~ 160 Hz**

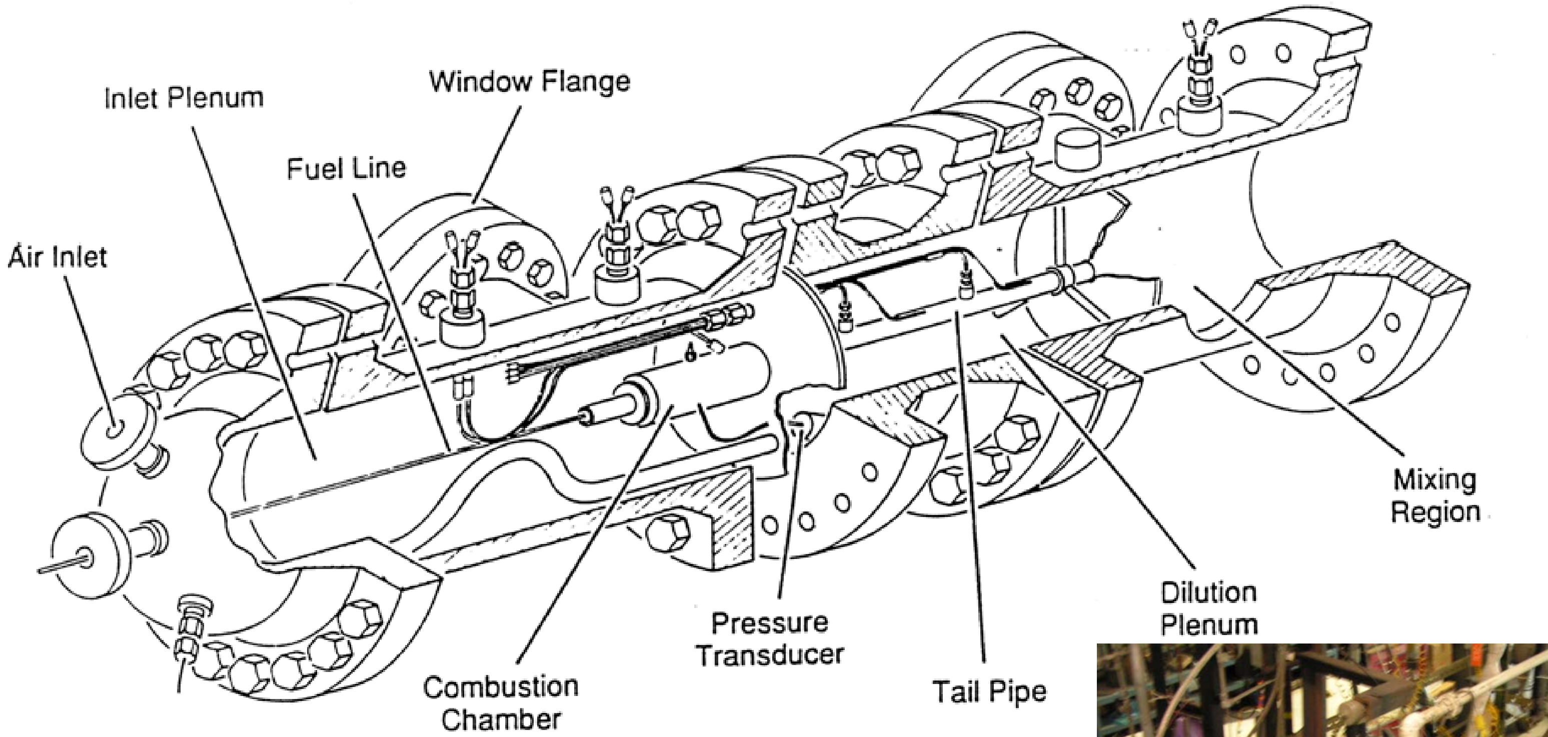
Optimized Geometry

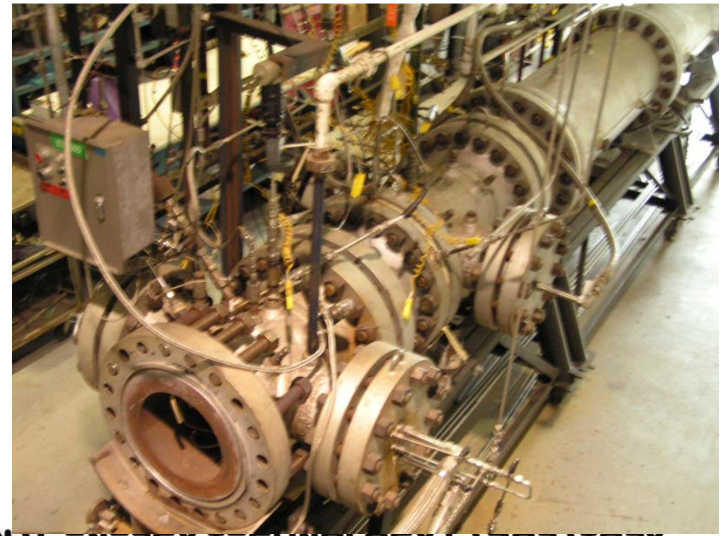


Lengths (m)			Diameters (m)		
Inlet	L_i	0.152	Inlet	D_i	0.0222
Tailpipe	L_{tp}	0.900	Tailpipe	D_{tp}	0.0191
Combustor	L_{comb}	0.152	Combustor	D_{comb}	0.0556

- **Maximum of 0.45% pressure gain achieved.**

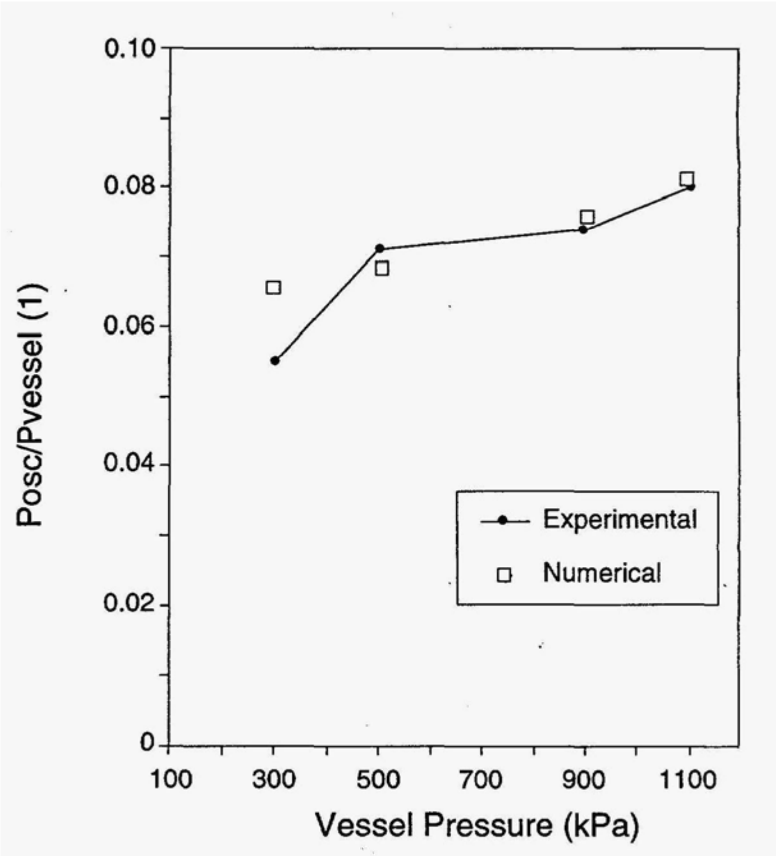
NETL High Pressure Rig (1994)





- **NG/Air up to 11 atm.**
- **Simple non-rectified design.**

High Pressure Results



- *Pressure controlled with a control valve on chamber exhaust.*
- *Flow rates increased linearly with pressure.*

- **Little effect of pressure when flow-rates are scaled linearly with pressure.**
- **Slight gain likely due to reduced frictional and heat losses.**

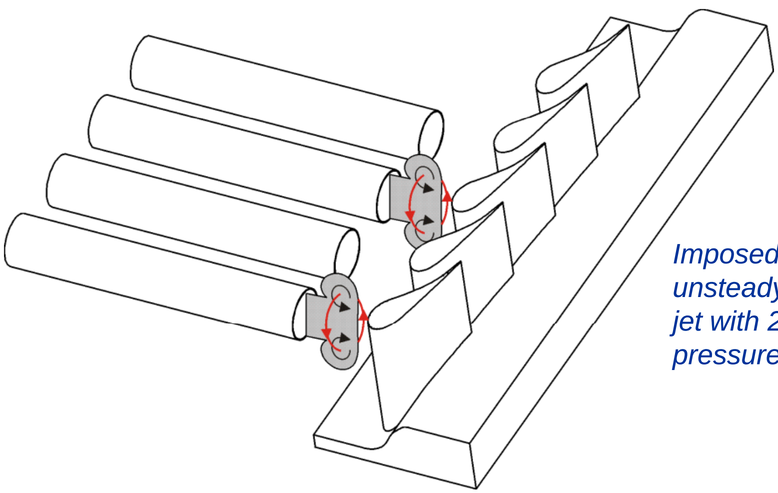
Some challenging problems

- **Predicting a design that will produce oscillations.**
  - Progress in eliminating oscillations in premixed gas turbines makes this (relatively) easy.
  - But, at what operating condition?
- **Developing an oscillating design that will also have a pressure gain.**
  - Qualitative understanding, but no fundamental criterion, theory.
  - Modern CFD may be the enabler!
- **Capturing the energy of the unsteady flow**

Capturing the pressure-gain

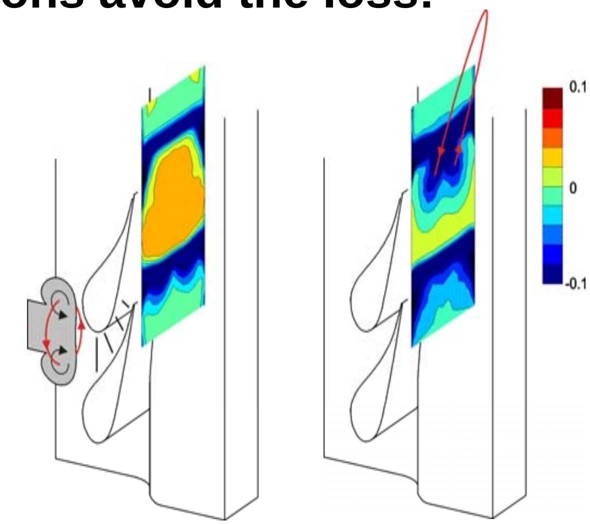
Courtesy R.J.Miller, Whittle Lab, Cambridge University

- **Time resolved experimental data.**
- **Vortex-induced separation leads to loss in Phase II.**
- **Work in progress: some configurations avoid the loss!**



Transonic test facility

Imposed unsteady jet with 2-3% pressure gain



Color corresponds to pressure gain fraction (0.1 = 10% pressure gain)

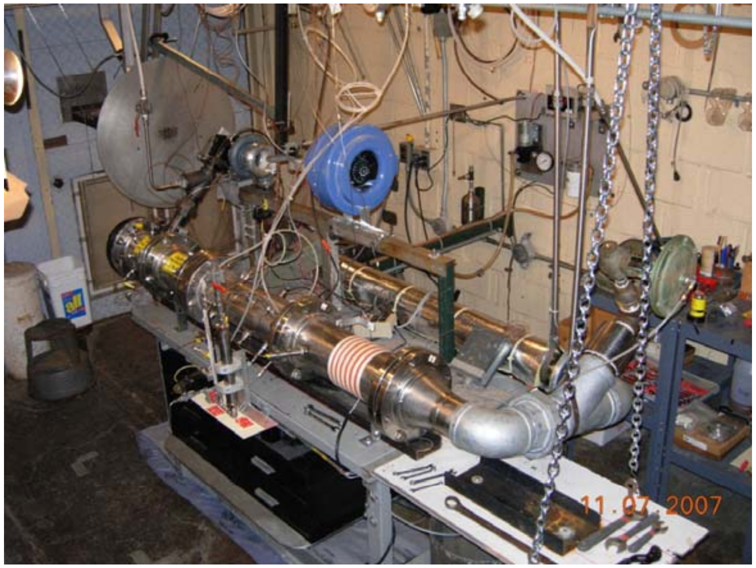
<u>Phase I</u> Pressure gain in free stream

<u>Phase II</u> Large rise in loss as vortex exits

Cause of loss : Vortex interacting with vane suction surface.

Work at NASA

- **Demonstrated pressure-gain and small turbine operation.**
- **Simulations of pulse jet using commercial CFD.**

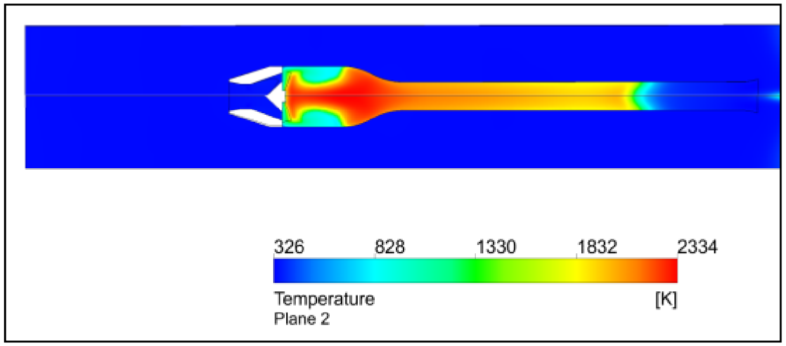


Liquid fueled.

Automotive turbocharger "turbine"

Reed-valve pulse combustor.

Experimental results:*
Combustor pressure ratio 1.035 at temperature ratio 2.2



Simulation of pulse-jet behavior –with NOx emissions and experimental validation.

Graphics courtesy Dan Paxson, NASA Glenn

** Paxson, D. , Dougherty, K. (2008). Operability of an Ejector Enhanced Pulse Combustor in a Gas Turbine Environment NASA/TM—2008-215169*

Pulse Detonation (Tubes)

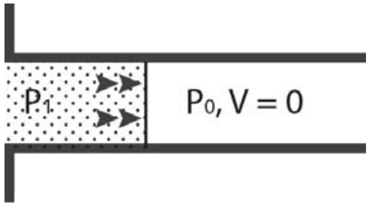
The detonation essentially “traps” the combustion behind the shock.

Compared to pulse deflagration, much higher pressure gains are possible.

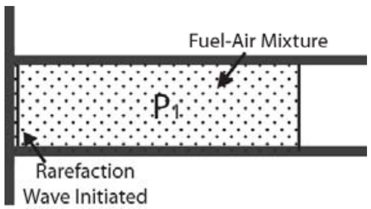
This may be the only *constructive* applications of detonations?

Typical Pulse Detonation Cycle

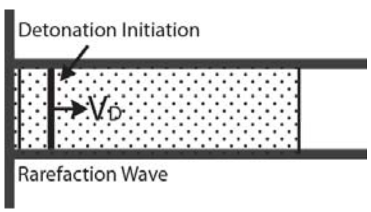
1. Fill



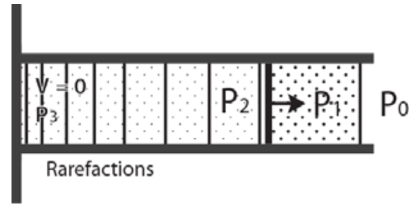
2. Upstream end closes



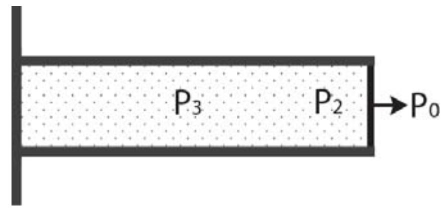
3. Detonation initiated (DDT)



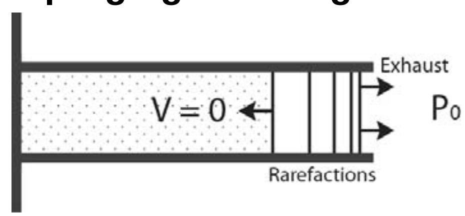
4. Detonation wave propagates at CJ velocity with coupled combustion wave



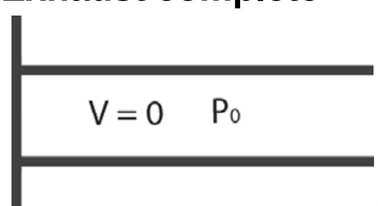
5. Detonation wave exits tube. Remaining gas at elevated T and P.



6. Rarefaction wave propagate upstream to assist with purging burned gases



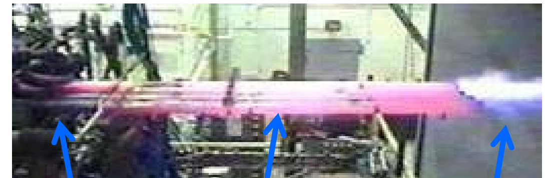
7. Exhaust complete



Pulse Detonation for Propulsion

- **Pulse detonation tube concept has been extensively studied.**
- **“Direct” propulsion: simple!**
  - No turbomachinery.
  - Conventional recip. engine valve assembly for inlet.
  - Progressed to flight demonstration.
- **A key scientific issue:**
  - Optimizing deflagration/detonation transition (DDT).

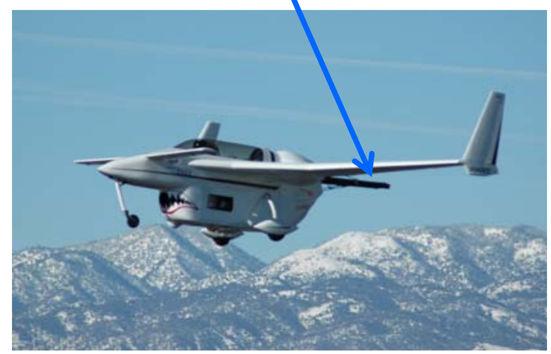
Lab test



Valve Assembly

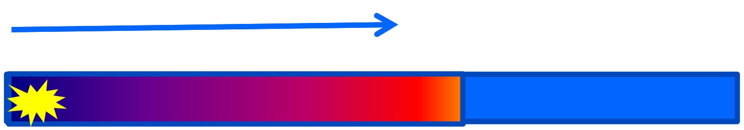
Pulse tubes

Propulsion!



Flight Demonstration

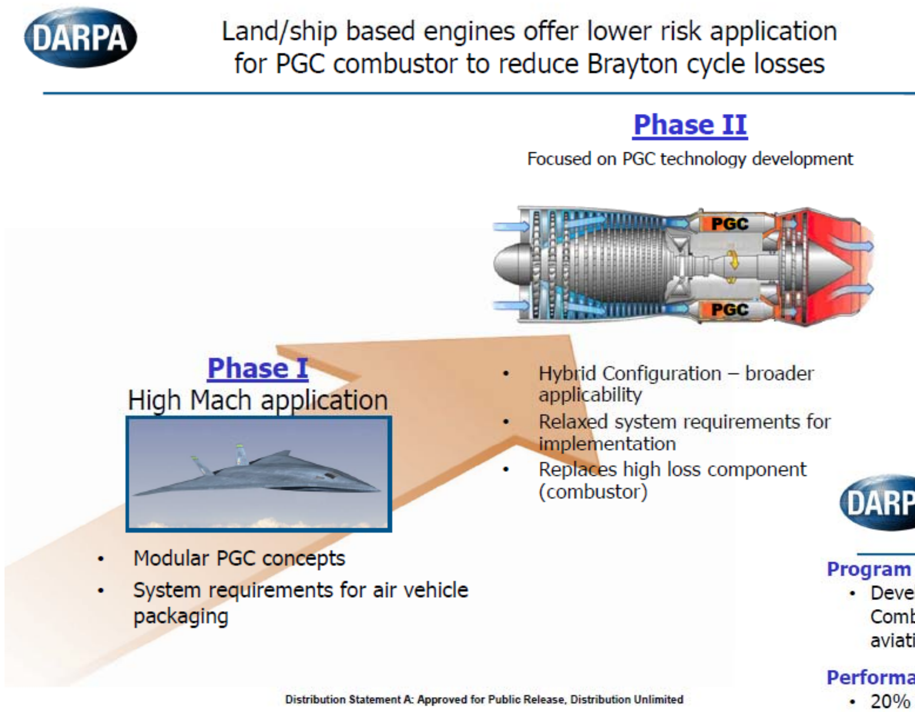
Photos courtesy Fred Schauer, AFRL



The run-up to detonation sets the length.
***Obstacles** can accelerate – but add losses.*

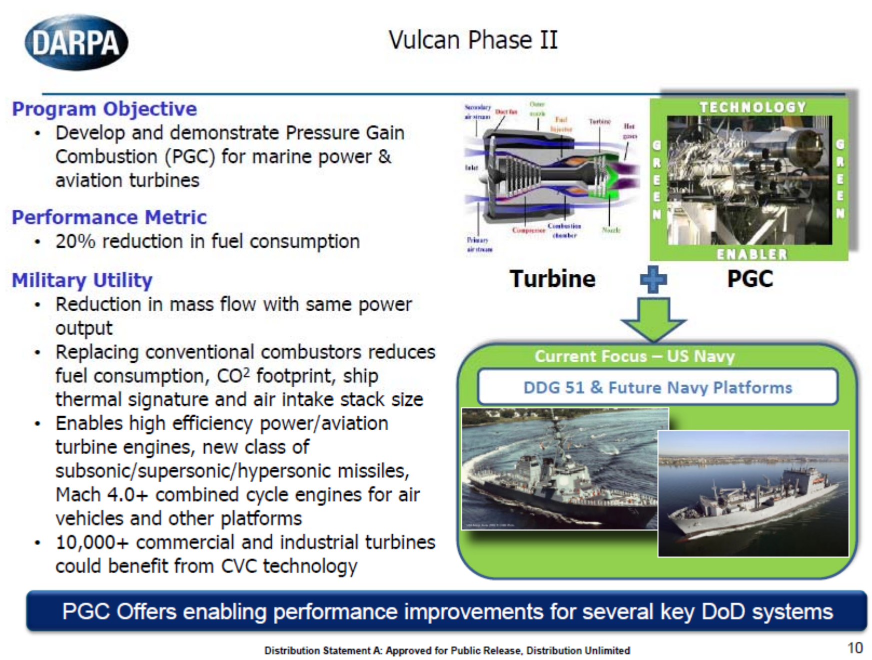
“…The applicability of a single combustion model to cover all the regimes of turbulent flames, which are encountered in confined high-speed flame transitioning to a detonation…..is yet to be established” Tangirala et al, Proc. Combustion Institute 30 (2005) 2817-2842

DARPA Vulcan Project



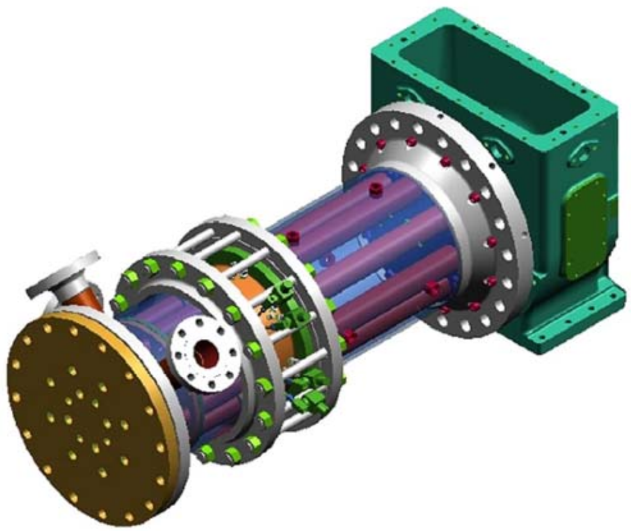
- **Integration in a turbine – humphrey cycle.**

- **Combines the PDE with turbomachinery**



Multitube PDC-Turbine Hybrid System

- **Eight tubes arranged in a can-annular configuration coupled to a single stage axial turbine**
- **Accumulated 144 minutes of PDC fired operation**
- **Turbine performance was indistinguishable between steady flow operation and pulsed flow at 20 Hz per tube**



GE Global Research

Some work supported from:
NASA Constant Volume Combustion Cycle Engine Program

Tangirala, V., Rasheed, A. and Dean, A.J., "Performance of a Pulse Detonation Combustor-Based Hybrid Engine", GT2007-28056, ASME Turbo Expo, Montreal, Canada, May 14-17, 2007.

A different approach

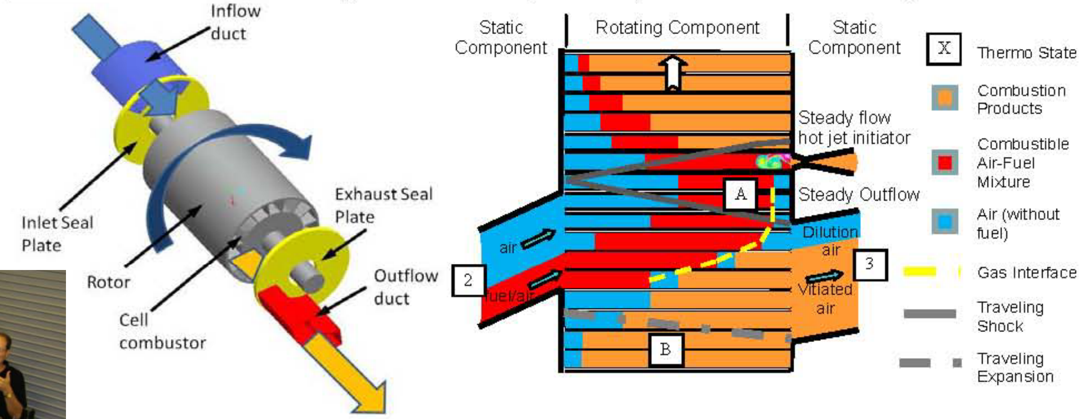
- **Wave Rotor Pressure Gain Combustor.**
- **Developed by Rolls-Royce Liberty Works, IUPUI*, and Purdue Zucrow Lab**
- **Tubes on a rotor spin past inlet and exit ports – containing combustion.**
- **Does not require detonation – just rapid flame propagation.**

** Indiana University - Purdue University at Indianapolis*

Benefits:
Almost steady air flow
Steady torch ignition
Balanced thrust load

Challenges:
Sealing
Weight (for flight applications)

Figure 1.Wave-rotor pressure-gain combustor (WRPGC) schematic and internal processes



Successful test of wave rotor pressure gain combustor (2009)

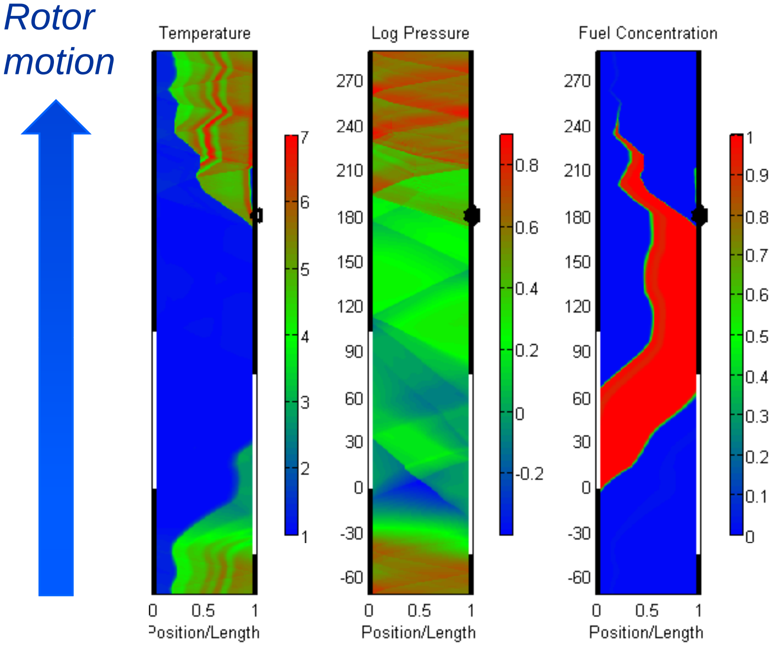
The channels in the sketch at the right represent the tubes in the rotor at the left - but "unwrapped" at a moment in time. The rotor revolution is driven by a motor at a speed selected to allow the flame to complete the channel combustion within a rotation.

All photos and graphics: courtesy Dr. Phil Snyder (R-R)and Professor Razi Nalim (Purdue)

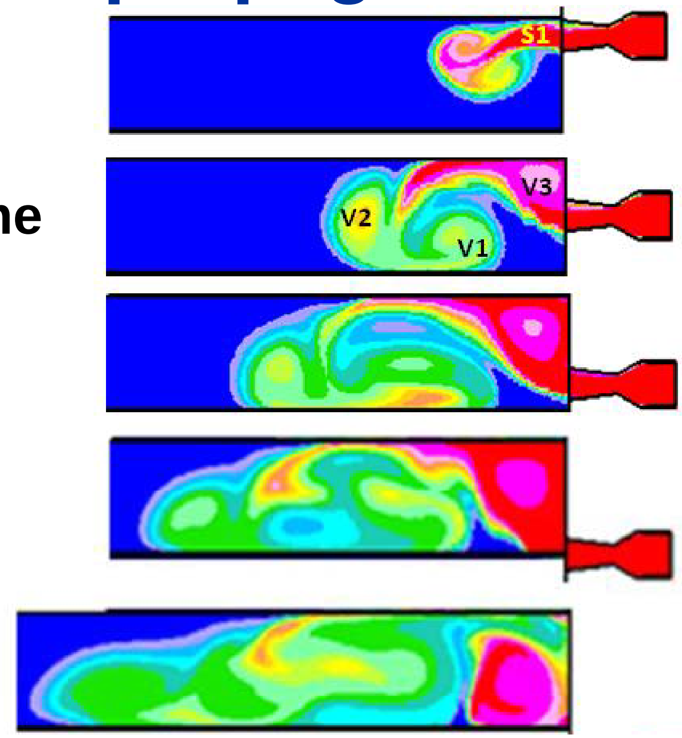
Understanding the flame propagation

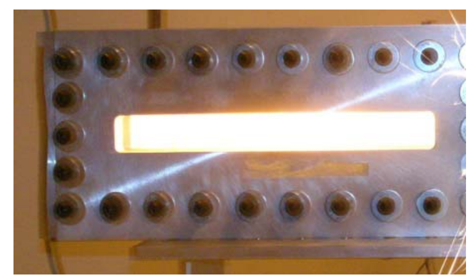
- **Simulation development from basic studies (right) leads diagnosis of experiments for pressure rise and flame propagation.**

Rotor motion



Snapshot of rotor tubes "unwrapped" (simulation).
Experiments and simulations used to establish design rotor speed and flow rate for fuel conversion and pressure rise.



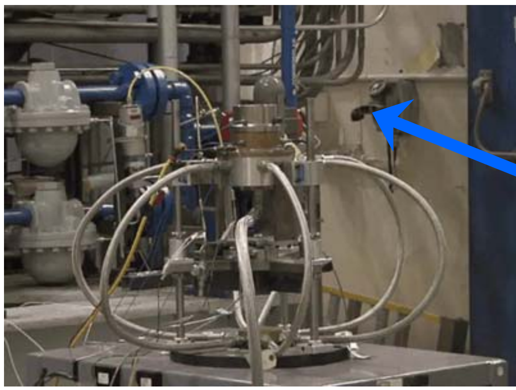


Study of flame propagation in a channel experiment with a moving entrance.

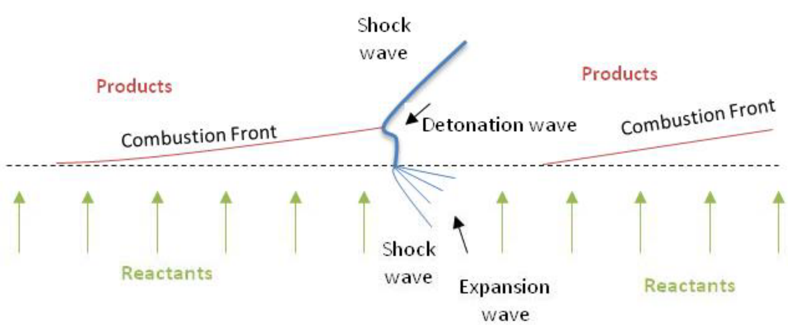
All photos and graphics: courtesy Dr. Phil Snyder (R-R) and Professor Razi Nalim (Purdue)

Rotating Detonation Wave Engine

- **Objective: detonation pressure rise with ~ steady output.**
- **Rotating detonation idea has been in the literature since 1950s.***
- **Recent studies have demonstrated new potential for the concept.**



Experiment at AFRL
Courtesy Fred Schauer

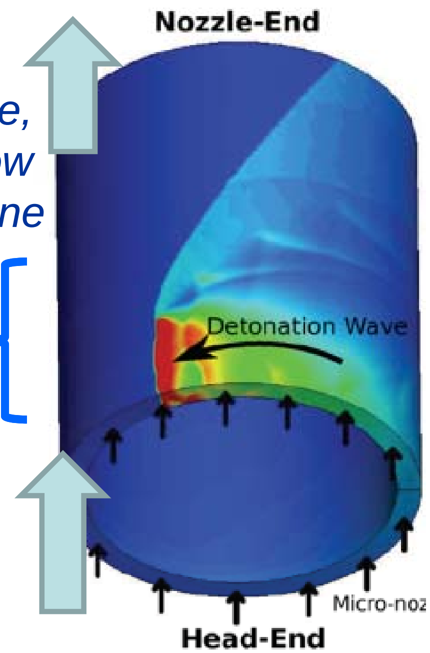


Combustion annulus unrolled. Reactant flow from the bottom.
Detonation moving right to left

Higher pressure, ~ steady flow to turbine

Rotating Detonation

Inlet from compressor

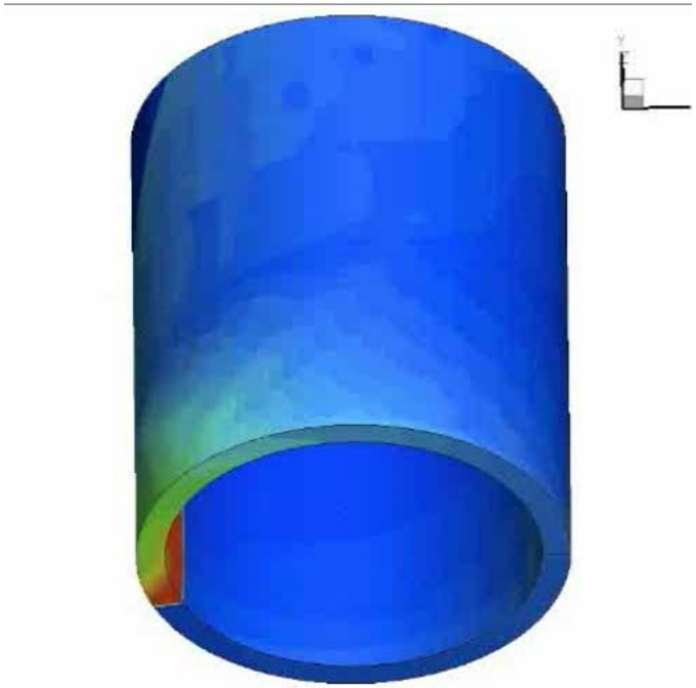


Simulation results courtesy K. Kailasanath, U. S.. Naval Research Laboratory

**see Kailasanath, K. (2011). The Rotating-Detonation –Wave Engine Concept: A Brief Status Report ,AIAA 2011-580.*

End view

From tests at AFRL



Side
View

Movie

Side

Experiment at AFRL
Courtesy Fred Schauer

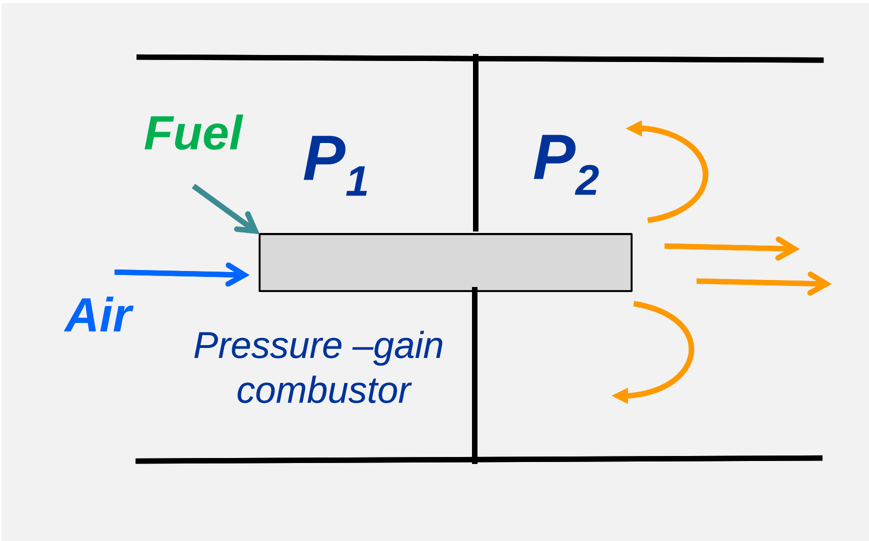
Movie

End

Rotation rate
~ 5000 Hz

Simulation results courtesy K. Kailasanath,
U. S.. Naval Research Laboratory

Some comments



- **Component comparison is complicated by difficult performance measures:**
  - Can you compare P_2 and P_1 to assess performance of this device?
  - What should you compare?
  - See Nalim, M. R. (2002)* for guidance.

Pollutant emissions (NOx, CO, UHC) have received relatively less attention to date.

Heat transfer and turbine cooling are concerns; but don't appear to be show-stoppers.

"Head-to-head" performance (steady combustion versus P-gain) has not been measured in an engine.

** Nalim, M. R. (2002). Thermodynamic Limits of Work and Pressure Gain in Combustion and Evaporation Processes,* AIAA Journal of Propulsion and Power, *Vol. 18, No. 6 pp. 1176-1182.*

Discussion/Thinking Questions: Pressure-gain Combustion

- **What are the *combustion* research issues associated with different types of pressure-gain?**

- **In your opinion, what is the greatest challenge to development of the pressure gain technology?**

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Summary of Pressure-gain combustion

- **Potential for an efficiency breakthrough.**
- **Similar past concepts recognized; eclipsed by “conventional” improvements.**
- **Successful demonstrations for direct propulsion tubes.**
- **Promising work on turbine applications:**
  - Pulse deflagration
  - Detonation tubes integrated with engine
  - Constant volume combustion wave-rotor
  - Rotating detonation wave combustor
- **Combustion and thermal science research needs discussed.**