New Developments in Combustion Technology

Part II: Step change in efficiency

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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:
\[ \alpha = \frac{\text{kg CO}_2 \text{ produced}}{\text{kg fuel burned}} \]
\[ \omega_{\text{CO}_2} = \frac{\text{separation work, Joules}}{\text{kg CO}_2} \]

- A simple heat/energy balance defines the overall efficiency \( \eta_{ov} \) with a carbon separation unit.
- Reducing the penalty from carbon capture comes from BOTH:
  - Decreasing \( \omega_{\text{CO}_2} \)
  - Increasing \( \eta_g \)

\[ \eta_{ov} = \frac{\eta_g}{Q} = \eta_g - \frac{\omega_{\text{CO}_2} \alpha}{\Delta H} \]

Approx Ranges: (30 – 60%) (6-10%)
Turbines for Power and Propulsion

- Turbines are the workhouse for large power (\(\sim 5\text{MW}\)) 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:
  \[ \eta_{\text{Carnot @ 1600C}} = 1 - \frac{293}{1873} = 84\% \]
  ~ State of the art turbine inlet temperature

- What can be done to “jump above” the line?

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 CO₂?
  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.

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

\[ \Delta U = Q \]
\[ C_v \, \Delta T_{cons \, V} = Q \]
Pressure Gain Combustion

A different cycle

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?

Unrestrained expansion
Returns to constant pressure availability –must capture the pressure gain to have a benefit.

Common steady combustion (~constant pressure)

\[ \Delta H = Q \]

\[ C_p \Delta T_{cons.P} = Q \]

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

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

Photo used with permission from Naval Engineers Journal


Napier Nomad Engine (~1950)

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

Detonation
or
‘Fast’ Deflagration

NASA Glenn, 2005

University of Cambridge, 2008

DOE National Energy Technology Laboratory, 1993

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

Principles of Operation

1. Combustion
2. Expansion
3. Injection
4. Compression

Fig. 1 Operation of an aerodynamically valved pulse combustor. The combustion event (1) raises the pressure in the combustion chamber ($P_{\infty}$), 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

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

Characteristic Timescales

\[ \tau_i = \frac{\rho_i V_i}{\dot{m}_i} \] (inlet flow time)

\[ \tau_f = \frac{\rho_f V_f}{\dot{m}_f} \] (fuel flow time)

\[ \tau_e = \frac{\rho_e V_e}{\dot{m}_e} \] (exit flow time)

\[ \tau_c = \frac{P_A}{\dot{Q} (\gamma - 1)} \] (combustion time)

\[ \tau_{HT} = \frac{\rho_i R V_i}{hA_s} \] (heat transfer time)

\[ \tau_m = \frac{\rho_m V_m}{\dot{m}_m} \] (mixing time)
One-Dimensional Modeling

**Why not CFD?**

1) Hint: this was 1990.

2) No theory for initial design & scaling.

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**Characteristic Timescales**

- \( \tau_i = \frac{\rho \lambda V_c}{\dot{m}_i} \) (inlet flow time)
- \( \tau_f = \frac{\rho \lambda V_c}{\dot{m}_f} \) (fuel flow time)
- \( \tau_e = \frac{\rho \lambda V_c}{\dot{m}_e} \) (exit flow time)
- \( \tau_c = \frac{P_A}{\dot{Q} (\gamma - 1)} \) (combustion time)
- \( \tau_{HT} = \frac{\rho \lambda RV_c}{hA_s} \) (heat transfer time)
- \( \tau_m = \frac{\rho \lambda V_c}{\dot{m}_m} \) (mixing time)

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

**NG/Air $\phi = 0.82$**

- Baseline geometry ($L_{in} = 10$ cm, $L_{ex} = 60$ cm).
- Resonant frequency $\sim 160$ Hz
Optimized Geometry

- 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

Phase I
Pressure gain in free stream

Phase II
Large rise in loss as vortex exits

Cause of loss: Vortex interacting with vane suction surface.

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

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?

Pow!
Typical Pulse Detonation Cycle

1. **Fill**
   - $P_1 \rightarrow P_0, V = 0$

2. **Upstream end closes**
   - Fuel-Air Mixture
   - Rarefaction Wave Initiated

3. **Detonation initiated (DDT)**
   - Detonation Initiation
   - Rarefaction Wave

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

5. Detonation wave exits tube. Remaining gas at elevated T and P.
   - $P_3 \rightarrow P_2 \rightarrow P_1 \rightarrow P_0$

6. Rarefaction wave propagate upstream to assist with purging burned gases
   - $V = 0 \rightarrow \text{Exhaust} \rightarrow P_0$

7. **Exhaust complete**
   - $V = 0 \rightarrow P_U$
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).

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

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

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)

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.

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.**

![Image of experiment at AFRL](image)

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

![Diagram of higher pressure, ~ steady flow to turbine](image)

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

From tests at AFRL

Side View

End view

Rotation rate
~ 5000 Hz

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

Side

Experiment at AFRL
Courtesy Fred Schauer

Movie

End
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?

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.

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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?
Power generation classes:

- Turbines and Reciprocating Engines

Relative sizes & scales:

- Combined cycle turbines: 100 MW Power
- Simple cycle turbines
- Reciprocating engines

- Where would a +5% efficiency boost get the most interest?
- What would the cost of development be for each class?
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.