AAE 538: Air-Breathing Propulsion

Lecture 7: Introduction to Gas Turbine Engines and Cycle Analysis

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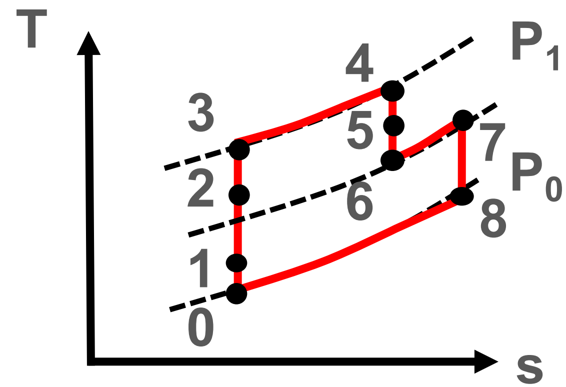
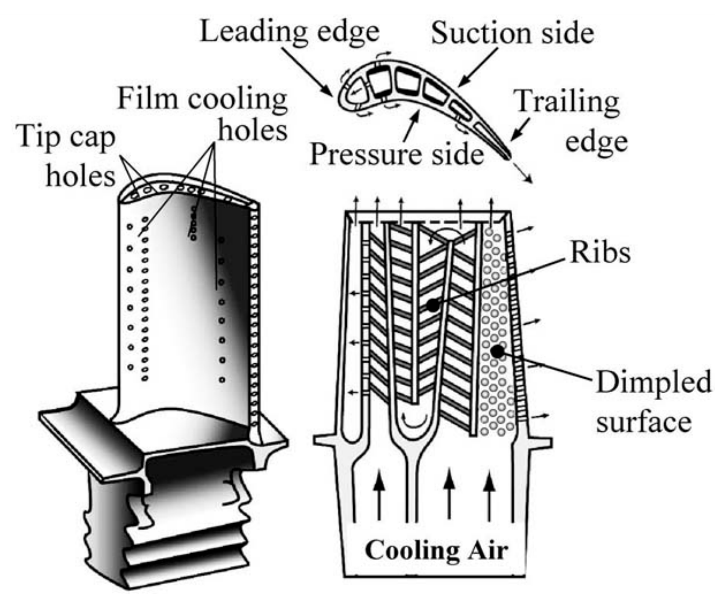
Introduction

Taking Inventory of Where We Are

- Fundamentals of 1D Compressible Flow
- **Subsonic Air-Breathing Propulsion**
  - Engine Cycles and Performance Criteria
  - Ideal and Real Engine Analysis
  - Component Characterizations
    - Compression Systems
    - Turbines
    - Combustors
  - Component Matching
  - Single- and Dual-Spool Machines
  - On- and Off-Design Performance
  - Transient Operating Lines
- Supersonic/Hypersonic Air-Breathing Propulsion
  - Inlet Systems, Starting, and Isolators
  - Aerothermodynamics of Combustion
  - Dual-Mode and Combined Systems
  - Burner-Isolator Interactions
  - Expansion Systems

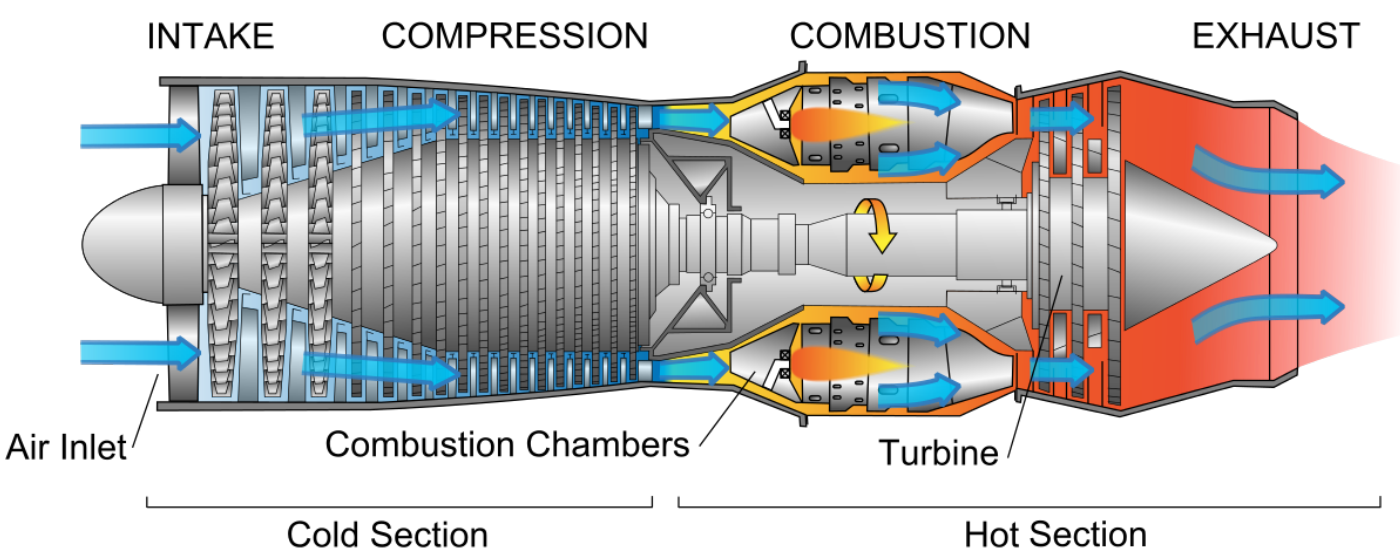




Introduction

Where this is going

- Investigation of the thermodynamic cycles employed in air-breathing engines and discussion of other applications.
- Utilization of the 1-D momentum equation to calculate the thrust of an air-breathing engine and characterize its performance.
- Description of various engine engine cycles in use, then develop their performance and efficiency characterizations.

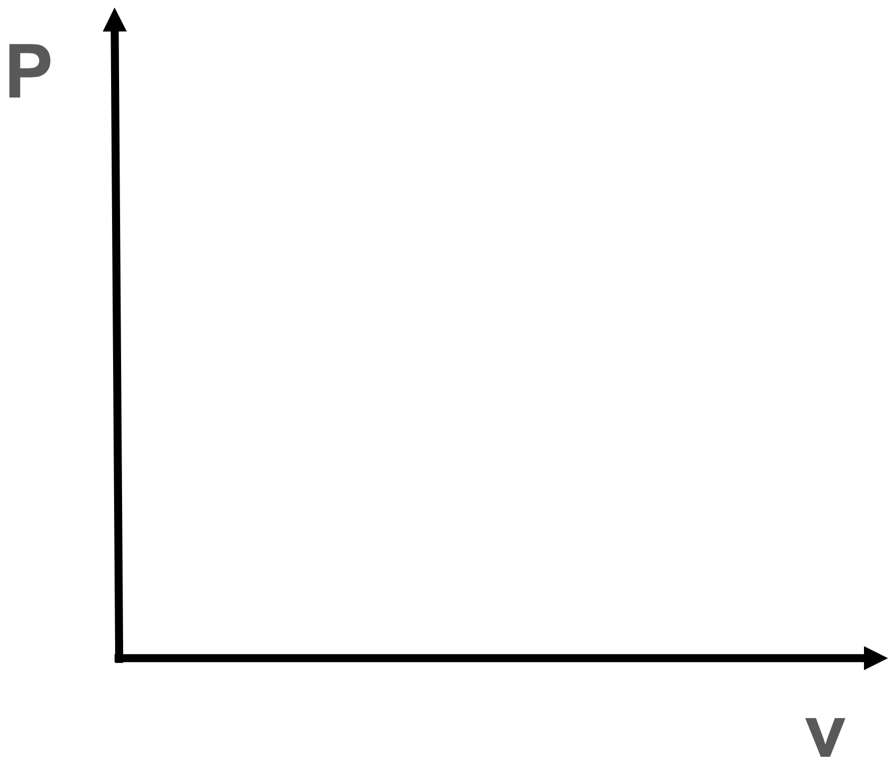


Processes in Engines

Overview

- Truly cyclic (closed cycle) heat engines employing a gas as a working fluid are not currently found in many applications. Instead, most applications ________________ ____.
  - These open cycle engines approximate the performance of many air-breathing engines including gas turbine engines, 'internal combustion' (piston-cylinder) engines, and other more advanced concepts.
- A common mechanism to represent a cycle on paper is with P-v and T-s diagrams.
  - In general, gas cycles can be understood as a series of ___________________ processes, which obey
  - Where n has values from zero to infinity
    -
    -
    -
    -

Processes in Engines



- To evaluate the slopes of the curves formed by these processes, write

- Then differentiate assuming n is constant

- Now examining the slope that passes through the point (p_i, v_i), we get:

Processes in Engines

- A similar analysis can be performed for the T-s diagram.
  - Beginning with the entropic state relation for a perfect gas (Gibb's Relation)

$$Tds = de + pdv =$$

  - Dividing through by $T\ dT$

  - Using the ideal gas law and the expression for polytropic processes, we can eliminate the dependence on p and v
    - Differentiating the ideal gas law

$$pv = RT \quad \longrightarrow$$

Processes in Engines

- Differentiating the relation for polytropic processes

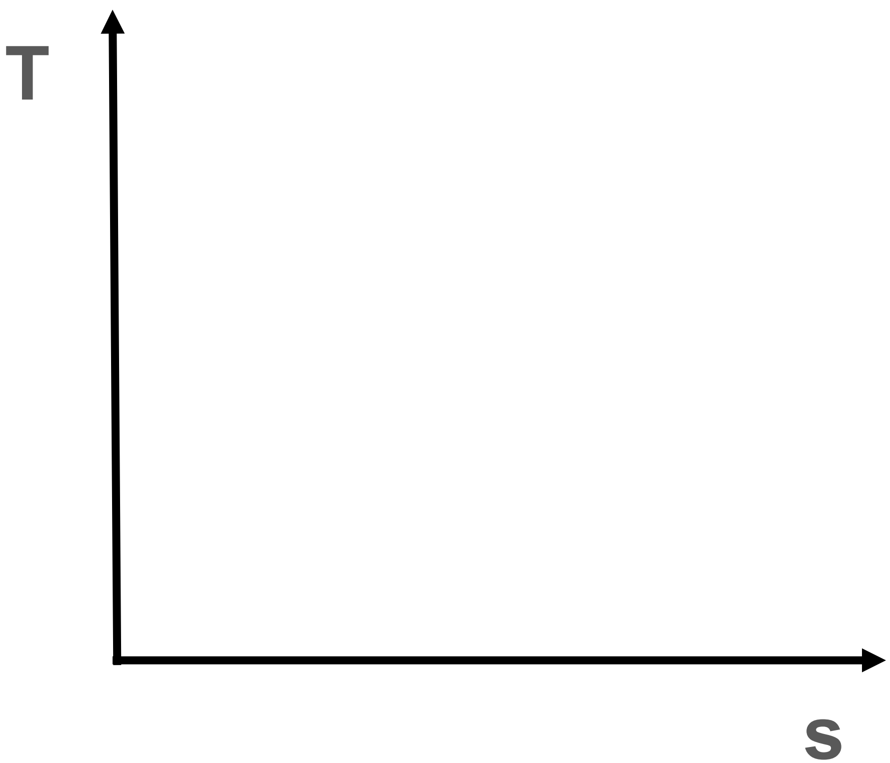
$$pv^n = constant \longrightarrow$$

- Subtracting these two equations yields and expression for dv/dT

- Substituting back into our rearranged form of the Gibb's relation

$\longrightarrow$

Processes in Engines



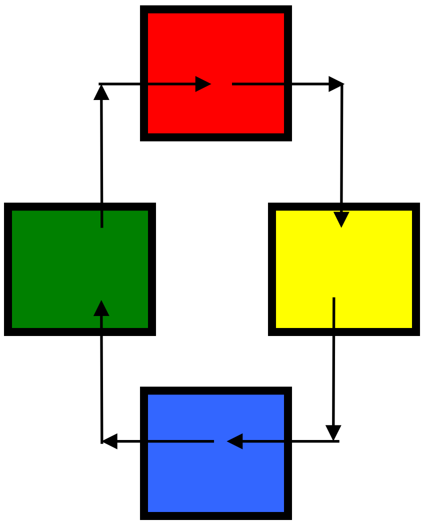
$$\frac{dT}{ds} = \frac{(1-n)T}{c_p(1-n/\gamma)}$$

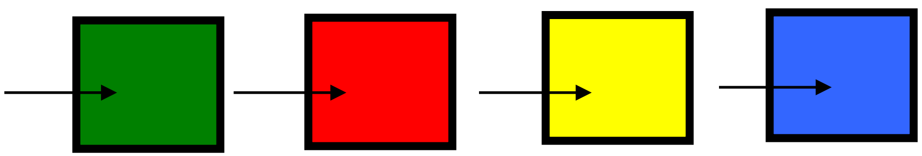
- Keep in mind that, in both of these developments, we are only plotting slopes (tangents to curves) and that the slopes are functions of the gas-phase properties
  - For example, for $n = 0$ the slope of the $T - s$ curve increase with temperature…
    - This is why isobars diverge.

Engine Cycles

Air Standard Power Cycles

- In thermodynamics, we learned that thermal engines made use of high-temperature and a low-temperature reservoirs in a closed cycle to generate useful work.
  - Air-breathing engines (including spark ignition, diesels, gas turbines) all make use of an ______________________________ to provide the energy necessary to act as a 'high temperature reservoir' that is then used to convert thermal energy into work.





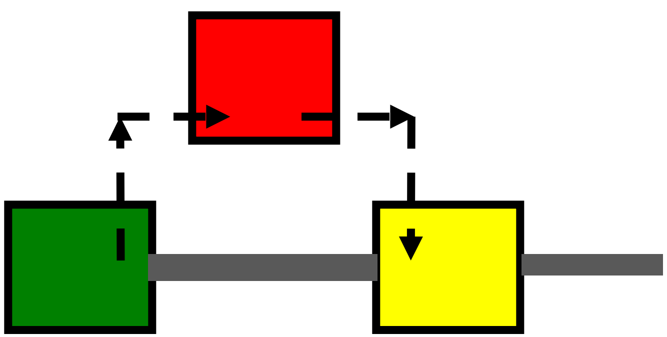
Engine Cycles

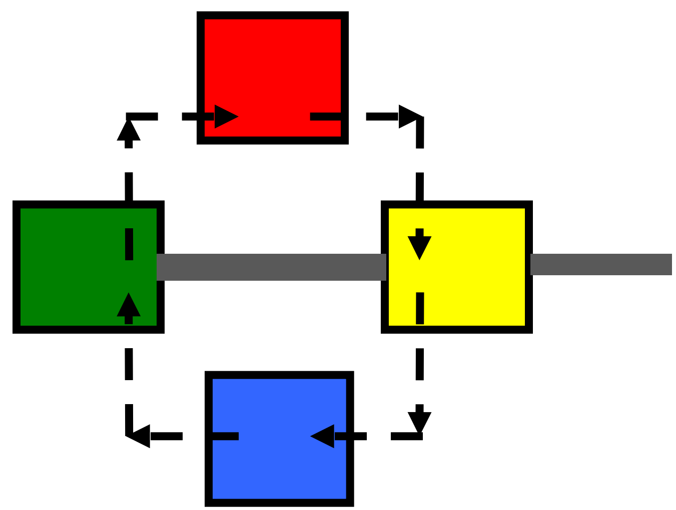
- Actual engines differ from their theoretical counterparts in this way. However, we can still analyze real engines with these idealized closed-cycle processes called ____.
  - The following assumptions are implicit with modeling real engines using air standard cycles:
    -
    -
    -
    -
    -
  - The most common air-standard cycles in air-breathing propulsion applications is the Brayton Cycle

Engine Cycles

The Air Standard Brayton Cycle

- The air standard Brayton cycle approximates the operation of a gas turbine mechanical cycle.
  - The real cycle is an open-cycle since we combust an air-fuel mixture at constant pressure the exhaust the products gases after expansion through the turbine
  - The air-standard cycle replaces the combustion process with heat transfer from a high-temperature reservoir and the cycle is closed by cooling the ‘working fluid with a low temperature reservoir

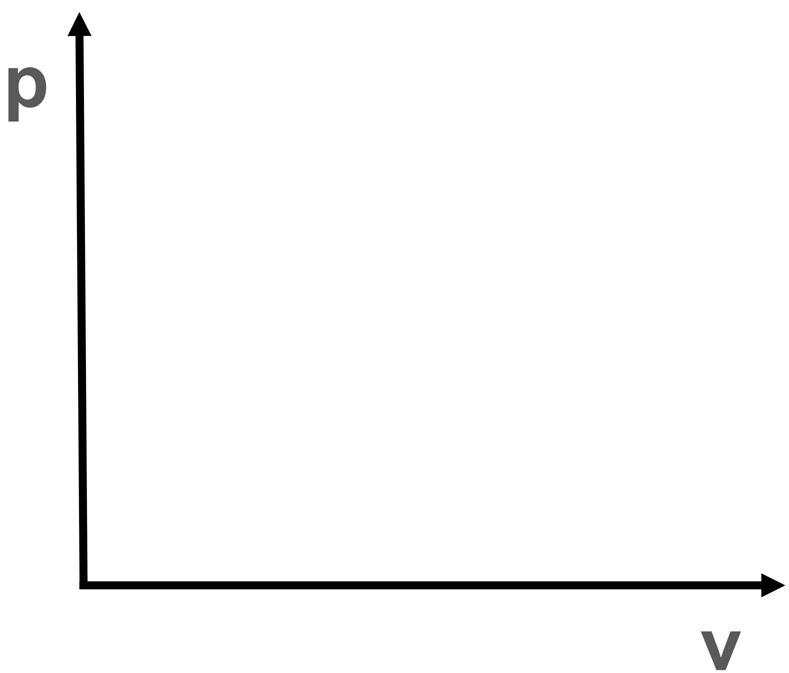


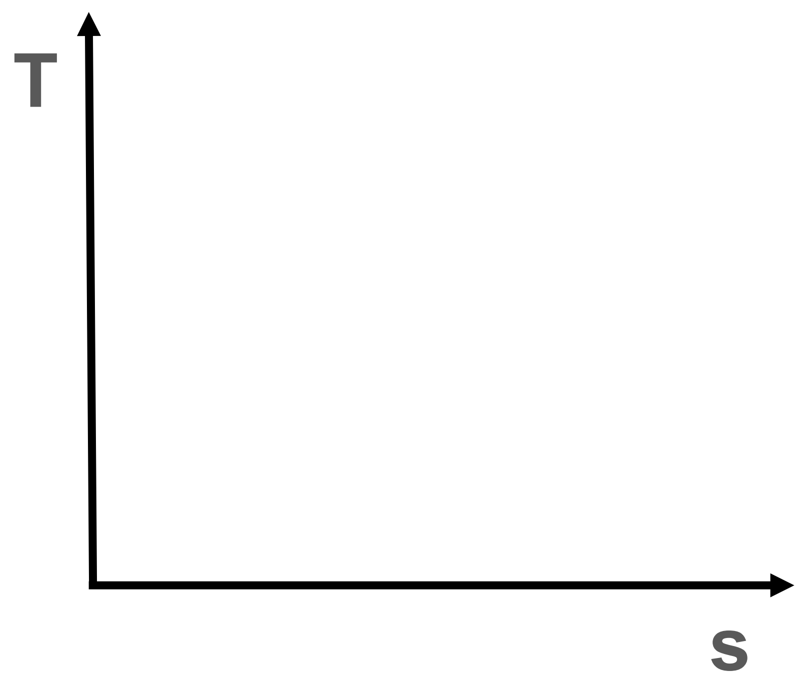


Engine Cycles

The Air Standard Brayton Cycle

- The p-v and T-s diagrams for the A-S Brayton cycle represent the four processes that complete the cycle in a physically-tractable form.
  - The inlet and compressor are modeled as
  - The combustor is modeled as
  - An isentropic expansion represents
  - Heat rejection closes the cycle





Engine Cycles

The Air Standard Brayton Cycle

- As before, we can write the thermal efficiency for this process as:

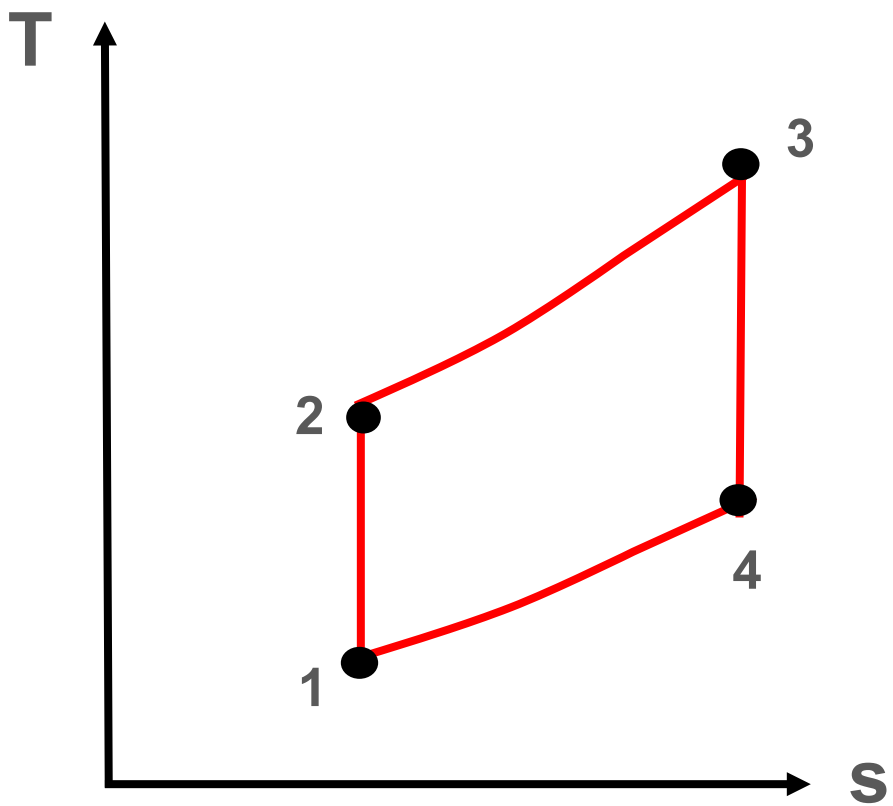
- Assuming calorically-perfect gases

- In this case, our P-V diagram shows us that

Engine Cycles

The Air Standard Brayton Cycle

- Where, for isentropic compression/expansion processes, we can write



- Where we can obviously see

- Such that

Example

Given

$$q = 200\,BTU/lb_m \qquad P_1 = 14.7\,psi$$

$$T_1 = 70\,^oF = 530^o R \qquad \frac{P_2}{P_1} = 20$$

Find $T_2, p_3, T_3, p_4, T_4, \eta_{th}$

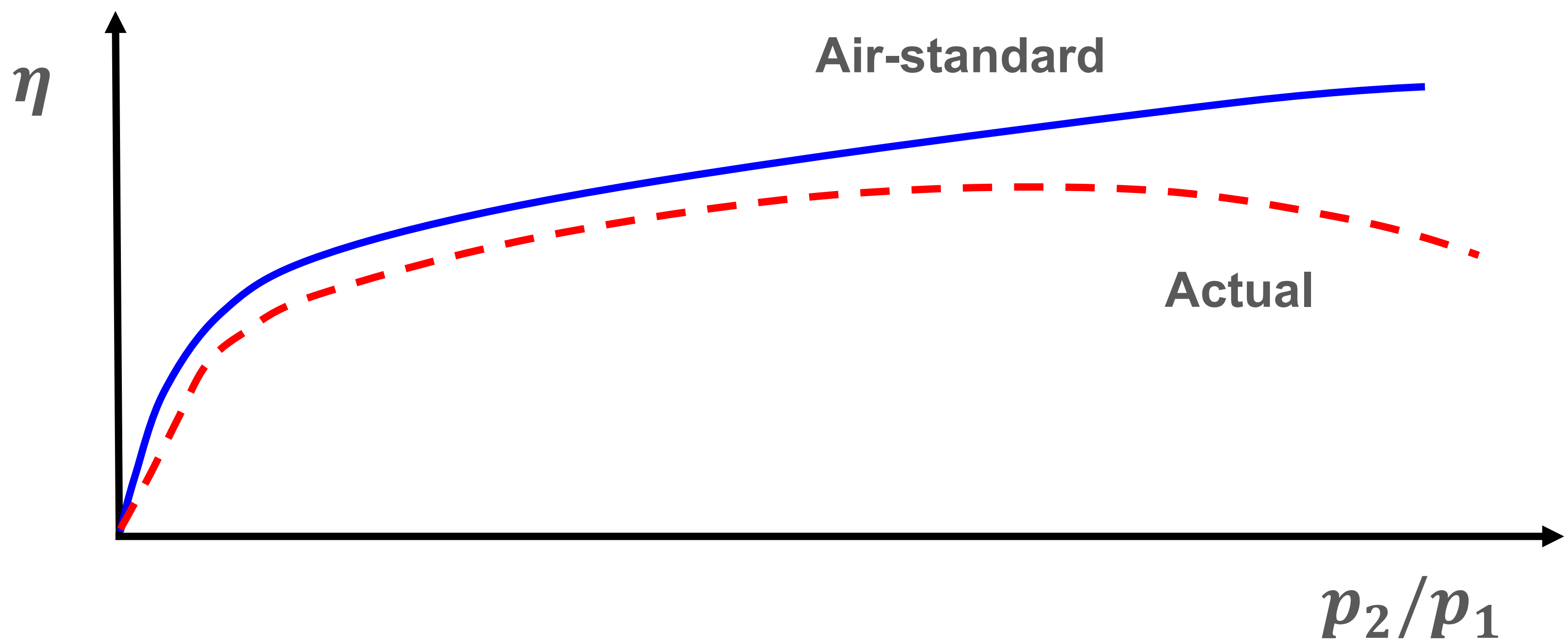
Example

Example

Engine Cycles

Some Final Notes on the Brayton Cycle

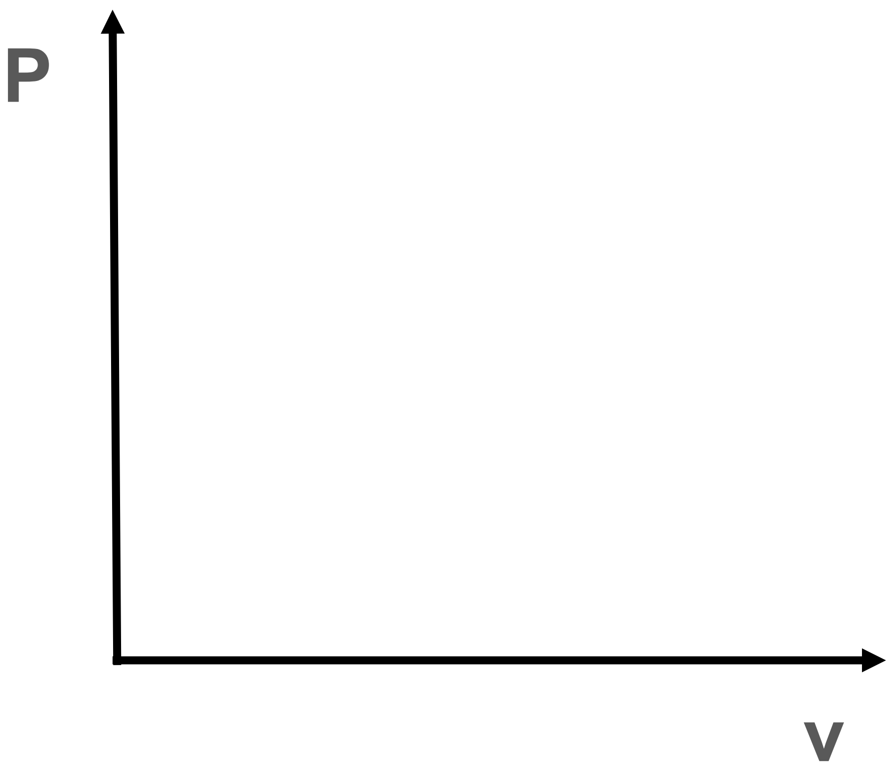
- Comparing efficiency trends of real and ideal engines as a function of pressure ratio
  - At low pressure ratios, the curves are similar
  - Within increasing pressure ratio, the efficiency of the real engines ____________
    - Heat transfer and friction losses become much more significant at high pressure cycles;
    -

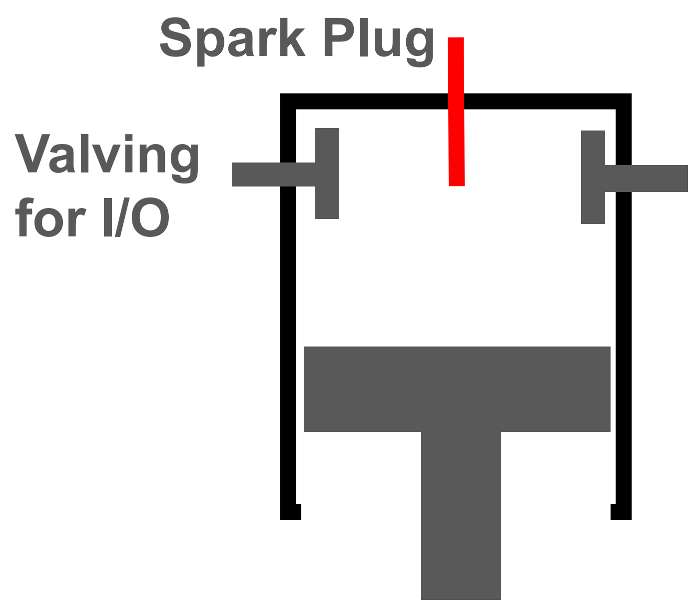


Engine Cycles

The Air Standard Otto Cycle

- The air standard Otto cycle approximates the operation of a spark ignition internal combustion engine.
    - The real cycle is an open-cycle since we combust an air-fuel mixture which leaves the system during the exhaust stroke of the piston



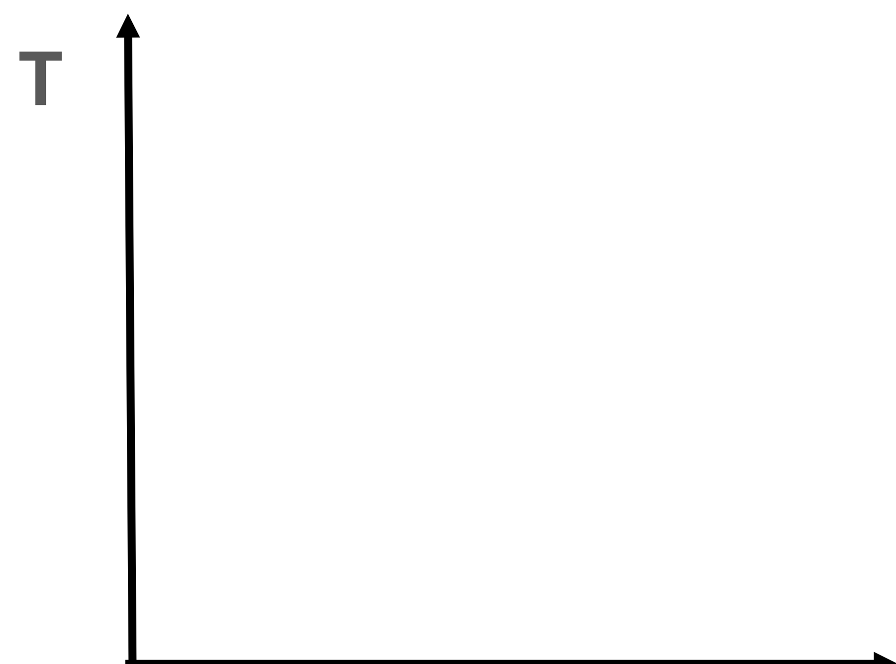


Mechanical cycle of a single piston in an internal combustion engine

Engine Cycles

The Air Standard Otto Cycle

- The air standard cycle that approximates this process omits the intake and exhaust phases and uses a fixed volume of gas (by definition of a closed cycle). The cycle is modeled by:
  - An isentopic compression process (1 – 2)
  - ____________________ heat addition (2 – 3)
  - An isentropic expansion process (3 – 4)
  - Constant volume heat removal (4 – 1)



Engine Cycles

The Air Standard Otto Cycle

- For this idealized cycle, we can write the thermal efficiency as:

- Assuming calorically-perfect gases, we can write:

- For isentropic expansion and compression processes.

Engine Cycles

The Air Standard Otto Cycle

Engine Cycles

Comparison of the Otto and Brayton Cycles for ABP

OTTO

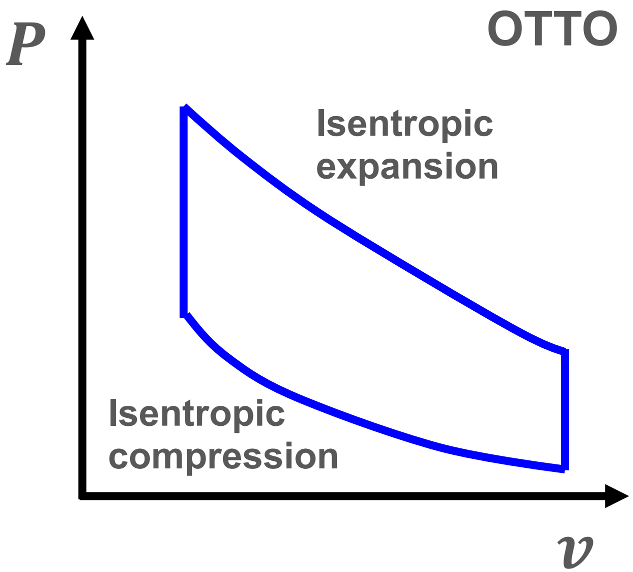
- Small volume of high pressure, high temperature gas for combustion
  - Appropriate for engines with low total power requirements; e.g. automobiles and small planes
- Friction losses are higher due to gearing and mechanical components
  - Particularly when the engines get large; more, bigger pistons
- Translating machinery is high maintenance.
- Purchase cost is low

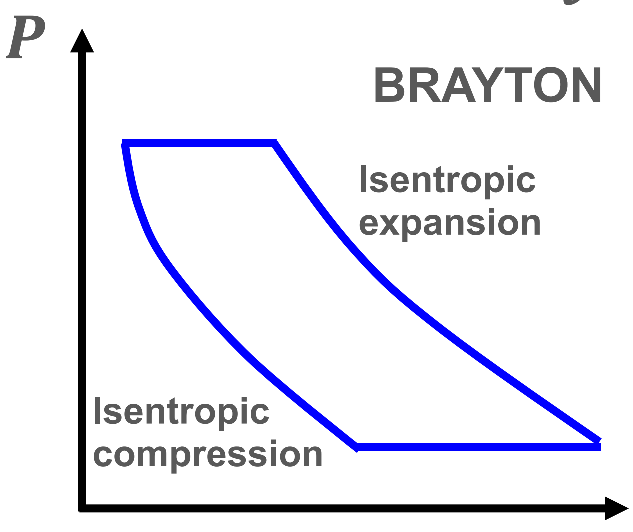
BRAYTON

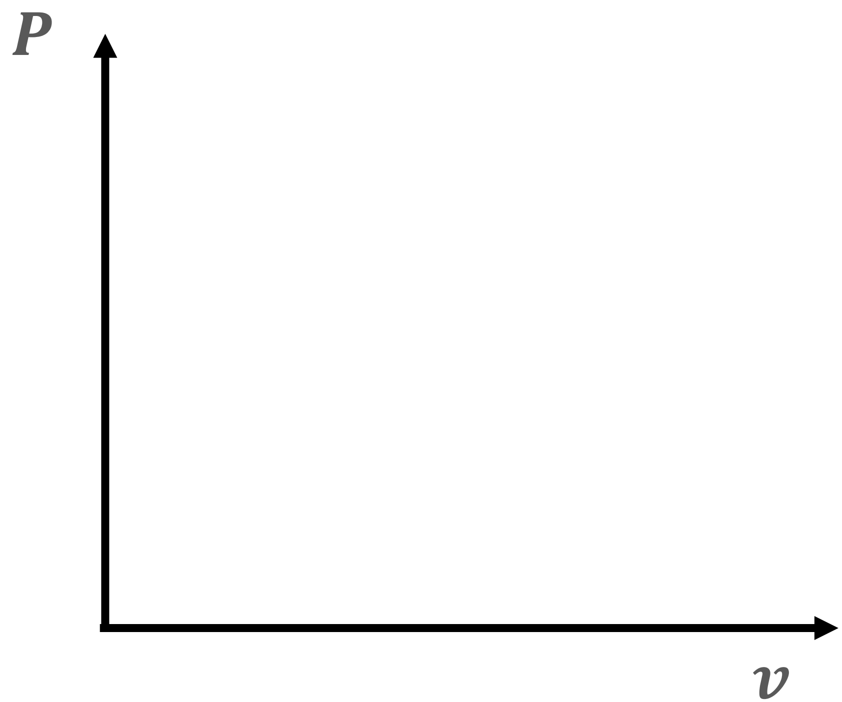
- Large reactant volumes at lower pressure and temperature
  - This condition is acceptable when the power requirement is large anyways; e.g. in aircraft where massive vehicles have to move at very high speeds.
- Friction losses become less important as gas turbine engines increase in size
- Rotating machinery is more reliable
- Very expensive to buy a turbine because of the exotic materials and other high-level technology required.

Other Cycle Concepts

Can we do better?







Other Cycle Concepts

Pressure Gain Combustion…

- Wave-Rotor Concept
  - Deflagration-based constant volume combustion in chambers with ‘valving’ accomplished by rotor end-plates.

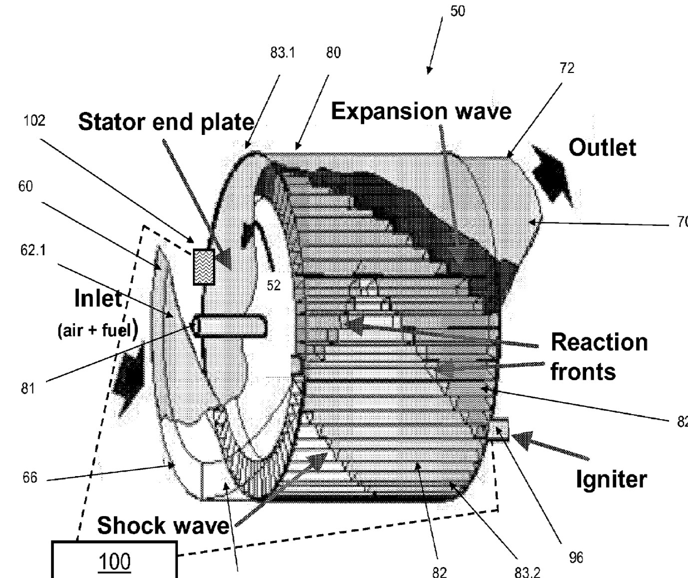
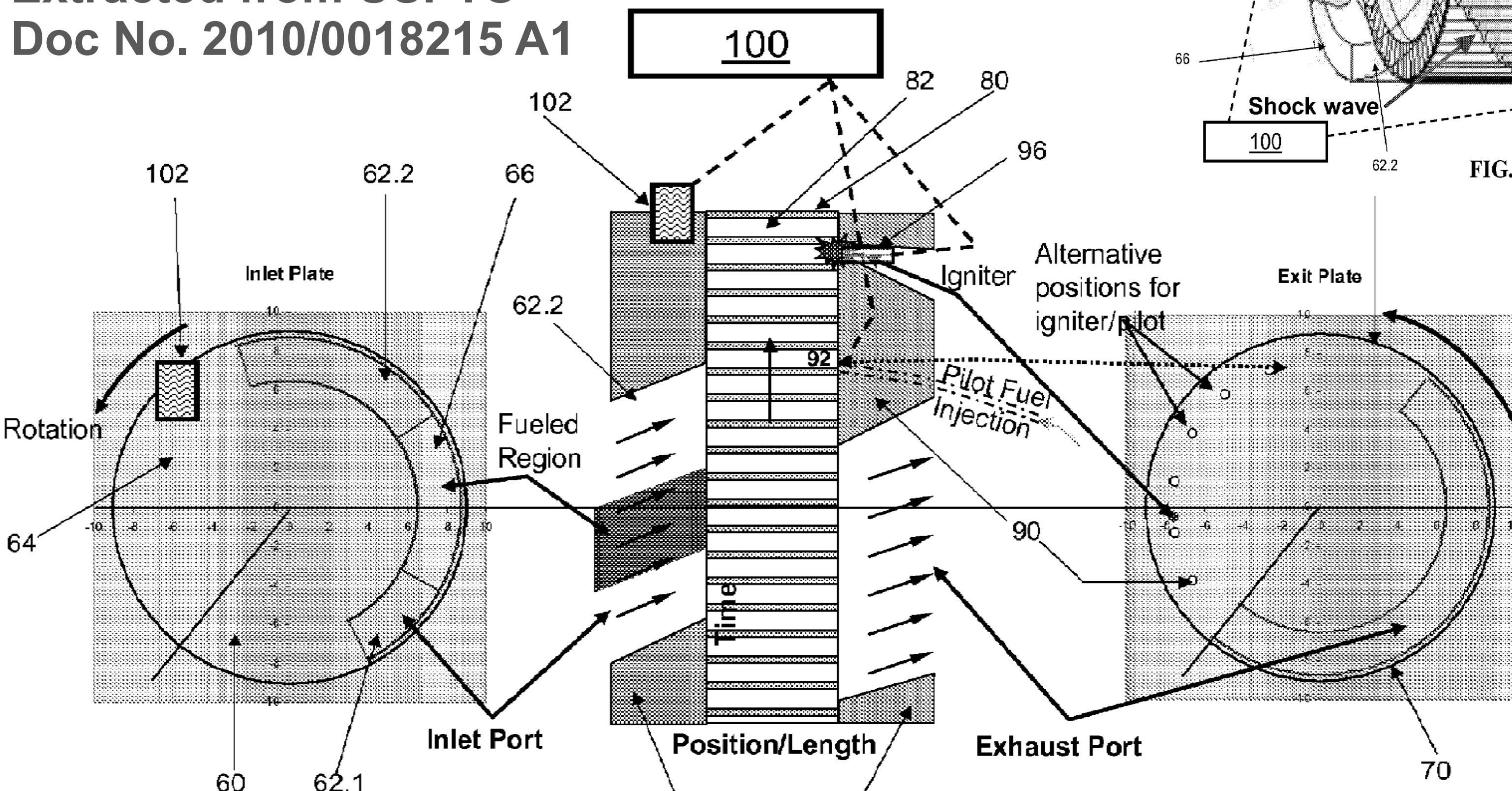


FIG. 5

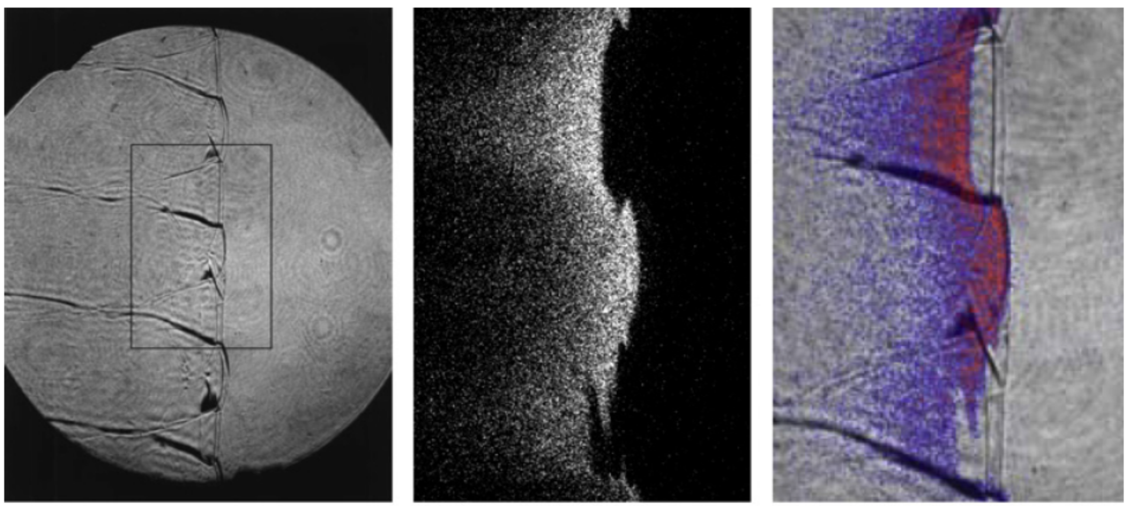
Extracted from USPTO Doc No. 2010/0018215 A1



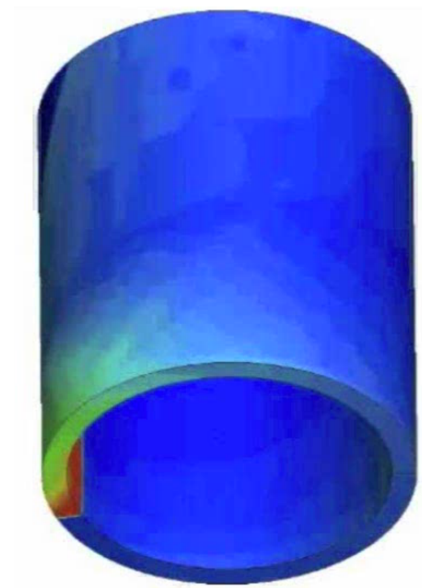
Other Cycle Concepts

Pressure Gain Combustion…

- Detonation-Based ’Constant Volume’ Combustion
  - Time-scales of combustion processes so much shorter than gas expansion that localized pressure-rise can be generated without actual physical boundaries.



Shepherd, Proceedings of the Combustion Institute, 2009



Schwer, D., and Kailasanath, K., AIAA 2010-6880, 2010.