AME 436
Final Exam Study Guide
May 12, 2009

Format of the exam

The final exam will be open book. You may use any reference materials you want, **but no laptop computers** or other devices capable of running the aircycles4whatever.xls spreadsheets. The format will be the same as the midterm but will be 2 hours long. The exam will have graphical, numerical and short-answer questions.

Short summary of the most important facts

- Hydrocarbon fuels are the most convenient, high-density way of storing energy; compression, combustion, expansion is the most convenient (high power/weight) way of converting this stored energy into useful work
- The simplest estimate of adiabatic flame temperature is $T_{ad} = T_\infty + fQ_R/C_P$ (constant pressure), but at high temperatures, C_P increases and dissociation of CO_2 and H_2O causes T_{ad} to fall below this estimate, even if no heat losses are present
- Practically all chemical reactions of interest in this course have high activation energy, meaning that their rates increase rapidly with increasing temperature. This includes the chemical reactions causing heat release (thus affecting burning velocity of premixed flames), knock and most emissions. If you want to determine how a change in engine operating conditions affects performance, the first thing to check is how temperature is affected
- Flames come in two flavors – premixed and nonpremixed
    - Premixed (e.g. Bunsen burner)
        - Fuel and air are completely mixed before combustion is initiated (e.g. via a spark)
        - Most important characteristic is the burning velocity $S_L \sim (\alpha\Omega)^{1/2}$
        - If the mixture is lean, T_{ad} and thus S_L will be low (bad) but NO emissions will be low (good)
        - If the mixture is too lean, the flame will extinguish completely (very bad)
    - Nonpremixed (e.g. Bic lighter)
        - Fuel and air are un-mixed until combustion occurs
        - There are always stoichiometric surfaces (thus stoichiometric-like flame temperatures) somewhere between the regions of pure fuel and pure air
        - As a result, there are always high reaction rates even when the mixture is lean overall (good) but also high NO and soot formation rates (bad)
        - In most cases the burning rate is limited by mixing rates, not chemical reaction rates
- Engines are air processors – the air takes up most of the spacel, so if you can process more air, you can get more power
- Thermodynamically, the best way to burn is at the minimum volume or maximum pressure (which is really another way of saying, maximum temperature) because this gives you the most efficient Carnot cycle strips
- Reciprocating engines
    - Premixed-charge

        - Performance (power, efficiency) is limited by compression ratio, which in turn is limited because of knock
        - Knock is an explosive, homogeneous reaction of the gas ahead of the flame front ("end gas") before the flame gets to it
        - Knock depends on the temperature of the reactants (T_∞) (whereas flame propagation depends on product temperature T_{ad})
        - Throttling (thus throttling loss) required to adjust power, since you can't go very lean without misfire or flame extinction
    - Non-premixed-charge
        - Burning takes longer since you have to mix and burn, whereas in premixed-charge engines the fuel and air are already mixed before combustion is initiated
        - As a result, the engine can't rotate as fast, thus power is lower for same displacement / engine size
        - Not limited by compression ratio since only air is compressed, but you can't burn near-stoichiometric without major soot, CO, UHC emissions
        - Since non-premixed, can burn very lean overall without throttling
        - Higher compression ratio + no throttling losses means higher efficiency
- Steady-flow (gas turbine) engines
    - Since steady flow, can process more air for engine of given size/weight
    - Compressor aerodynamics are challenging (to make air go from low P to high P without running back to low P)
    - Power is limited by maximum allowable temperature of turbine
    - At low Mach numbers, exit velocity is very high, so propulsive efficiency is low – solution is turbofan (much higher air flow, much lower exit velocity)
- Hypersonic propulsion
    - Can't decelerate incoming air to $M = 0$ because P and T will be too high
    - Easy to get large pressure ratios (thus good thermal efficiency) even without mechanical compressor
    - Large flight velocity, thus propulsive efficiency is good
    - But - difficult to avoid large stagnation pressure losses
- Pollutant formation
    - Emissions are a non-equilibrium phenemon – if everything went to equilibrium there would be no emissions!
    - NOx – rich and cool better (no excess O_2), low temperatures
    - CO, UHC – lean and hot better (excess O_2 to oxidize CO to CO_2 and UHC to CO_2 and H_2O)
    - Soot
        - Premixed - only in rich mixtures, more soot at lower temperatures because soot formation must compete with oxidation
        - Nonpremixed – forms on rich side of flame, no competition between formation and oxidation there, so more at higher temperatures

Material covered

- Engineering scrutiny

- Review of thermodynamics

- Classifications of IC engines; advantages and disadvantages of each type

- Alternatives to IC engines

- Introduction to combustion
    - Fuel types
    - Chemical thermodynamics
        - Stoichiometry, lean & rich mixtures, mass & mole fractions
        - 1st Law of Thermodynamics for chemically reacting systems
        - Heating value
        - Adiabatic flame temperature
        - Degrees of reaction freedom
        - Conservation of atoms
        - 2nd Law of Thermodynamics for chemically reacting systems; chemical equilibrium, equilibrium constants
        - Isentropic expansion with frozen and equilibrium products
    - Elementary combustion theory
        - Chemical reaction rates
        - Homogeneous reaction
        - Premixed flames (deflagration)
            - Effects of turbulence
        - Non-premixed flames

- Unsteady flow engines
    - Design parameters
        - r_c, V_d, N
    - Performance parameters
        - Indicated and Brake work, torque, power, MEP
        - Efficiency - thermal, mechanical, volumetric
        - Emissions
    - Air-cycle (also called "ideal gas cycle") analysis
        - KNOW T-S AND P-V DIAGRAMS BACKWARDS AND FORWARDS!
        - Otto and Diesel cycles and variations (e.g. complete expansion)
        - Cycle comparisons
    - Fuel-air cycles
    - Modifications to ideal cycles
        - Irreversible compression/expansion
        - Heat transfer
        - Slow burn
        - Exhaust residual
        - Friction
    - Combustion in unsteady flow engines
        - Knock
            - What is it and why is it bad?
            - Effect of fuel type and fuel structure

        - Effect of operating conditions
    - Flammability/misfire limits
    - Incomplete combustion / flame quenching

- Steady-flow engines
  - Thrust calculation
  - Propulsive, thermal and overall efficiencies
  - Brequet range equation

- Compressible flow
  - Frictionless, adiabatic, variable area
  - Frictionless, diabatic, constant area, pressure or temperature
  - Frictional, adiabatic, constant area
  - Frictionless, adiabatic, constant area (shock solutions)
  - Stagnation conditions

- Airbreathing propulsion systems
  - Gas turbines
    - Ideal Brayton-cycle turbojet analysis (lots of algebra!)
    - τ_λ limit
    - Performance maps - T/ma & TSFC vs. τ_λ, M, π_c
    - Afterburner
    - T-s diagrams
    - Turbofan
      - Effect of bypass ratio and fan pressure ratio
      - Optimization
    - Non-ideal cycles
      - Component efficiencies
      - Effects on cycle performance
  - Ramjets
  - Hypersonic propulsion systems
    - Advantages over rocket propulsion - carry only fuel, use wing lift
    - Challenges - high stagnation temperature and pressure
    - Burning at finite Mach no.
    - T-s diagrams

  - Pollutant formation and control
    - NO_x
      - Zeldovich mechanism - high E_a
      - "Prompt" mechanism

    - Effect of operating conditions
- CO - due to incomplete combustion, bad mixing
- UHC - similar to CO but with effects of crevices, deposits, etc.
- Particulates
    - Soot - mostly applicable to nonpremixed engines – forms on rich side of flame at high temperatures
- Treatment of pollution
    - CO, UHC - lean and hot
    - NO_X - rich and cool
    - Modern systems - $\phi = 1$, EGR, catalyst

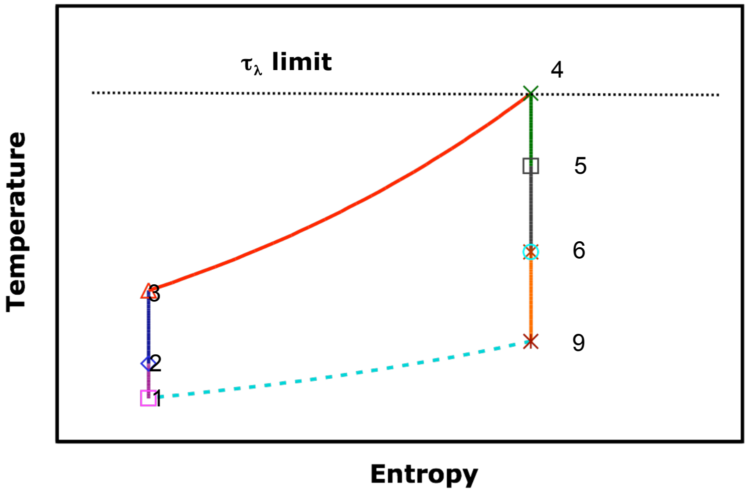
Last year's final exam (average score was 61/100)

Open book exam. Use any printed reference materials you want, but **no laptop computers, pocket PCs, Palm Pilots, etc. capable of running excel spreadsheets are allowed**. (Of course, calculators are allowed.) 120 minutes allowed. Note point values and budget your time accordingly. Write your answers on the exam sheet; if you mess up or need more space, use the back sides of the pages.

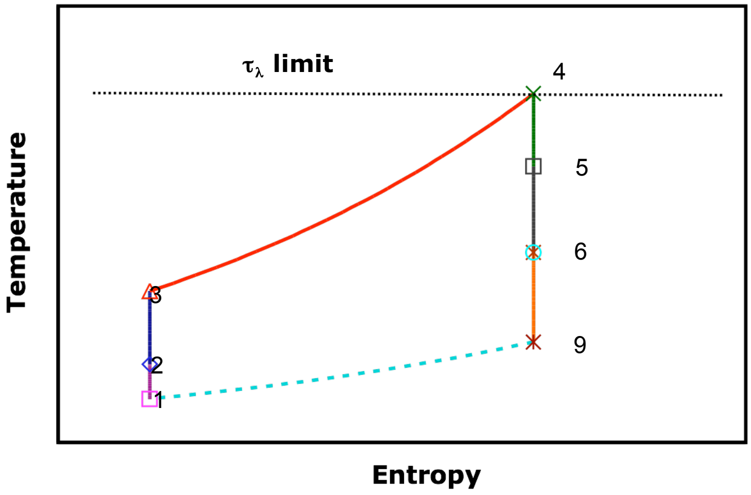
Problem #1 (the dreaded T-s diagrams) (20 points total; 5 points each part)

In an ideal τ_λ-limited turbofan, shown on the next page, how would the T-s diagram be affected if the following changes are made. In some cases there may be no change to the cycle. Assume that the compressor pressure ratio is the same for all cycles. When useful, add statements like "this ΔT = that ΔT," "this area = that area," etc. *Please make your modifications clear; cycles that look like random scribbles and have no explanations don't get much credit!*

a)

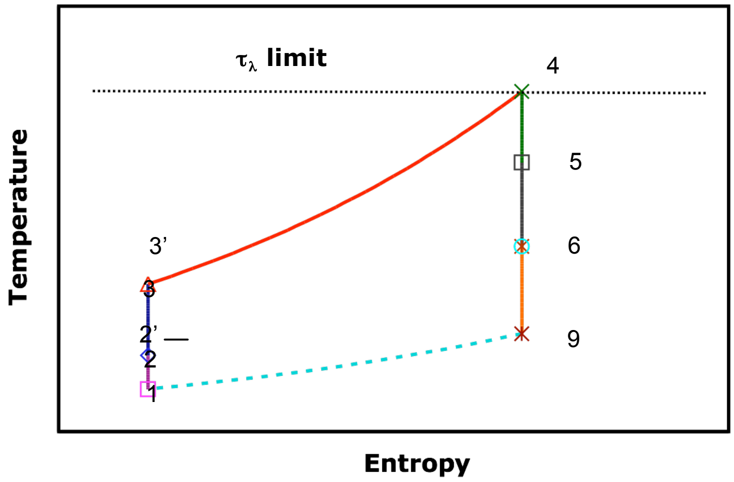


The fan is removed, but the redesigned turbine that supplies power to the compressor is irreversible b)



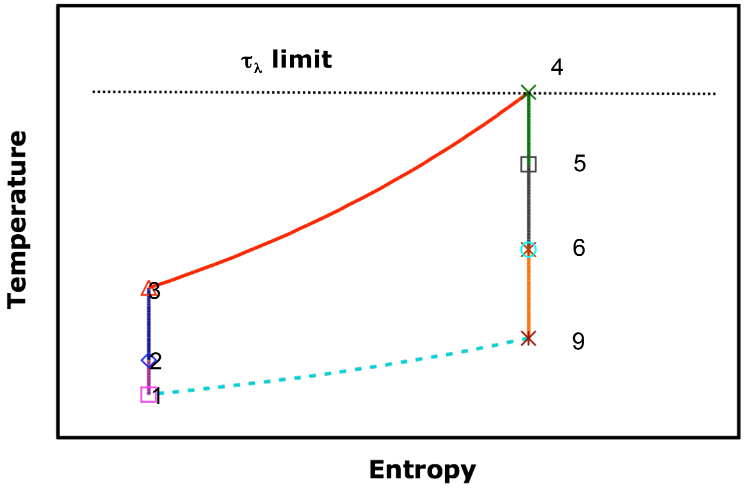
A **constant-area** afterburner is added, with the maximum possible heat addition (no τ_λ limit for the afterburner, but the main combustor still has the same τ_λ limit as always.)

c)



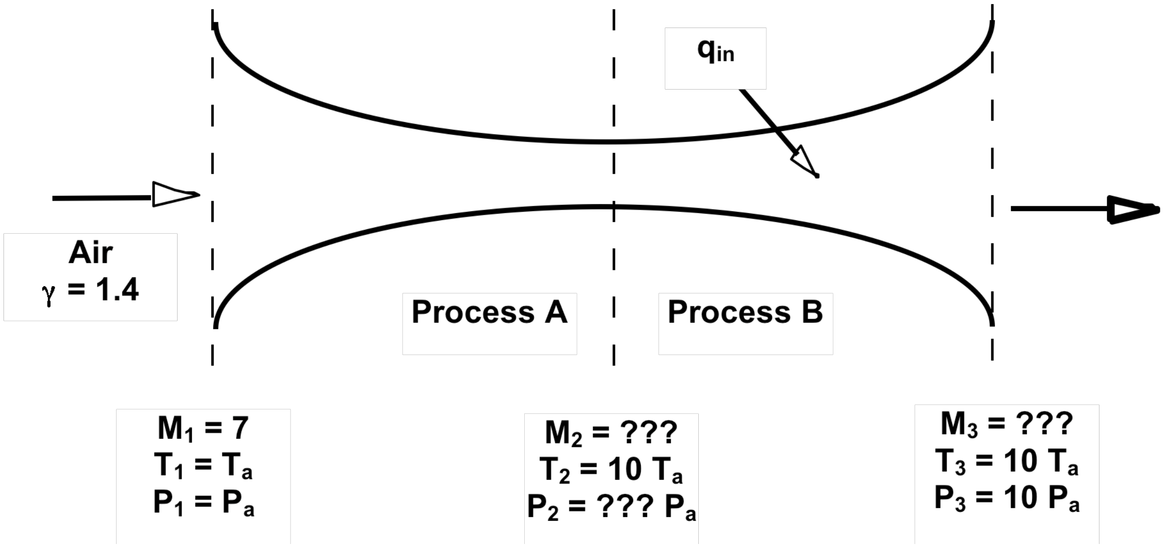
The flight Mach number is increased

d)



The ambient air **temperature** increases, but the ambient air **pressure** does not change

Problem #2 (hypersonic propulsion, compressible flow) (30 points total, 5 points each part)



Consider a simple hypersonic propulsion system for an aircraft at an initial Mach number of 7 that consists of two processes:

> **Process A**: Decelerate the incoming flow reversibly and adiabatically until the static temperature is 10 times the ambient temperature T_a
> **Process B**: Add heat at constant temperature until the pressure is equal to 10 times the ambient pressure

Assume air is an ideal gas with constant specific heats, and the fuel-to-air ratio (FAR) << 1.

a) Compute the Mach number after deceleration (station 2)

b) Compute the static (not stagnation) pressure relative to P_a after deceleration (station 2)

c) Compute the Mach number at the exit (station 3)

d) Compute the non-dimensional specific thrust

e) Compute the overall efficiency

f) Are the area changes between stations 1 and 2 and between stations 2 and 3 shown in the figure qualitatively correct? Why or why not?

Problem #3 (engine performance) (16 points total, 4 points each part)

- Engine A is a premixed-charge reciprocating-piston engine with a volume compression ratio of 10 that burns a lean ($\phi = 0.7$) octane-air mixture.
- Engine B is a stationary (Mach number = 0) gas turbine engine with a compressor pressure ratio of 10 that uses a non-premixed octane-air flame and has a turbine inlet temperature limit of 1200K. **Engine B is sized such that it has the same air mass flow rate as engine A** (which obviously means it's smaller and lighter.)

Both engines are being considered for producing shaft power to drive an electrical generator, not for ground vehicle or aircraft propulsion. Which engine, A or B, would have

a) More power

b) Higher thermal efficiency

c) Higher engine RPM

d) More NO_x emissions (assume no catalytic converter or other exhaust treatment for either engine)

Problem #4 (Miscellaneous) (24 points total, 3 points each part)

On Planet X the constant-pressure specific heats (C_p) of air and all other gases are 10% **higher** than they are on earth. All other properties of the atmosphere are exactly the same as on earth, in particular the mole-based ideal gas constant ($\mathfrak{R}$), molecular weight (M), thermal conductivity (k), density (ρ), mole fraction of O_2 in the atmosphere, etc. In particular, state whether each of these properties a) – h) will be higher, lower or the same on Planet X, and if different, by less than, more than, or exactly a factor of 10%. **Very short answers are sufficient.**

a) Gas specific heat ratio (γ)

b) Heating value of methane burning in air

c) Constant-volume adiabatic flame temperature

d) Equivalence ratio at the lean misfire limit of a premixed-charge engine

e) Brake thermal efficiency of a nonpremixed-charge engine

f) Thrust of an ideal τ_λ-limited turbojet (same flight velocity and τ_λ on earth and Planet X)

g) NO_X emission from a lean premixed flame

h) Amount of soot formation in a **nonpremixed-charge** engine

Problem #5. General cycle knowledge (10 points total, 5 points each part)

Answer the following questions (T-s diagrams will be much appreciated…)

a) Why do reciprocating or steady-flow internal combustion engines need to compress the air or fuel-air mixture before burning? What would happen if there were no compression, could thrust or work still be generated?

b) Why is it necessary to add heat to generate work or thrust?