AME 436
Final Exam Study Guide
May 4, 2016

Format of the exam

The exam will be open book exam **only** to the extent of the hard copies of the course lecture notes, your personal notes, homework sets and solutions and the (optional) textbooks. The use of laptop computers and tablets is NOT permitted (but calculators are, of course). The format will be the same as the midterm but will be 2 hours long.

About 2/3 of the final exam will cover material since the 2^{nd} midterm (i.e. steady-flow engines); the other 1/3 will cover material on the first (chemical thermodynamics and combustion) and second (unsteady-flow engines) parts of the course.

Short summary of the most important facts (of the whole course)

Fuels, combustion, emissions

- 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
- Engines are air processors – the air takes up most of the space, so if you can process more air, you can get more power
- Thermodynamically, the best way to operate an engine is at the minimum volume or maximum pressure (which is really another way of saying maximum temperature) and expanding back to ambient pressure (which is another way of saying, reject heat at the minimum temperature possible) because this gives you the most efficient Carnot cycle strips
- 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
- Pollutant formation
    - Emissions are a non-equilibrium phenomenon – 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

Unsteady-flow 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, which futher reduces power compared to premixed-charge engines
    - Since non-premixed, can burn very lean overall without throttling
    - Higher compression ratio + no throttling losses means higher efficiency

Steady-flow (gas turbine, ramjet, scramjet) engines

- Since steady flow rather than stop/start, can process more air for engine of given size/weight and thus obtain more power or thrust than an unsteady-flow (e.g. reciprocating piston) engine
- Compressor aerodynamics are challenging (to make air go from low P to high P without allowing it to do what it wants to do, i.e. run from high P back to low P). Reciprocating engines get around this problem by having valves that open and close at the appropriate times, creating a positive seal and thus allowing one to compress as slow as one wants without losing pressure (and thus temperature).
- Power is limited by the allowable fuel addition, which in turn is limited by the maximum allowable temperature at the turbine inlet, which in turn is limited by the turbine materials and cooling system

- The basic turbojet cycle is
    - Decelerate air from the flight Mach number to M = 0
    - Compress by a specified pressure ratio (π_c)
    - Add heat up to a specified maximum allowable temperature ($\tau_\lambda T_1$)
    - Expand through a turbine, extract only enough work to supply compressor
    - Expand though a nozzle until exit pressure = ambient pressure
- A weakness of the basic turbojet is that since the turbine inlet temperature is limited, one can't add the stoichiometric amount of fuel; this can be remedied by adding more fuel **after the turbine** (in an **afterburner**) which greatly increases thrust but at the expense of much lower thermal efficiency since heat is being added at lower temperature.
- At low flight Mach numbers, the exit velocity will typically be very high, so propulsive efficiency is low – solution is turbofan
    - Extract more work from turbine than just that needed to drive the compressor
    - Use this extra turbine work to drive a fan
    - Much higher total air flow and much lower average exhaust velocity for the same total kinetic energy – higher propulsive efficiency

Material covered since the 2nd midterm

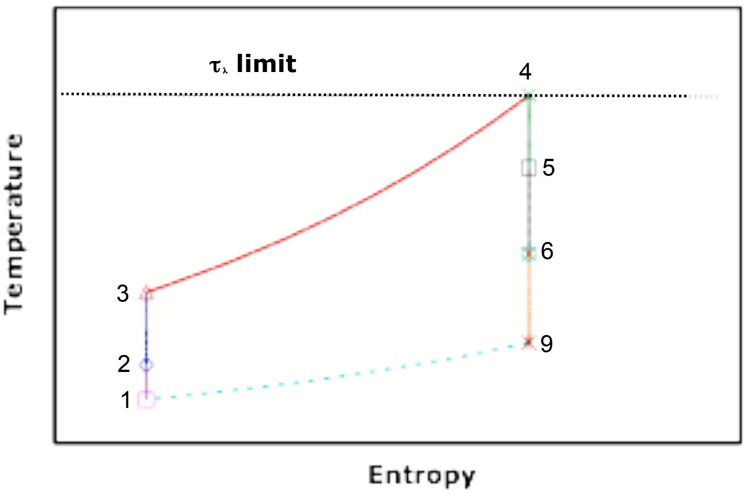
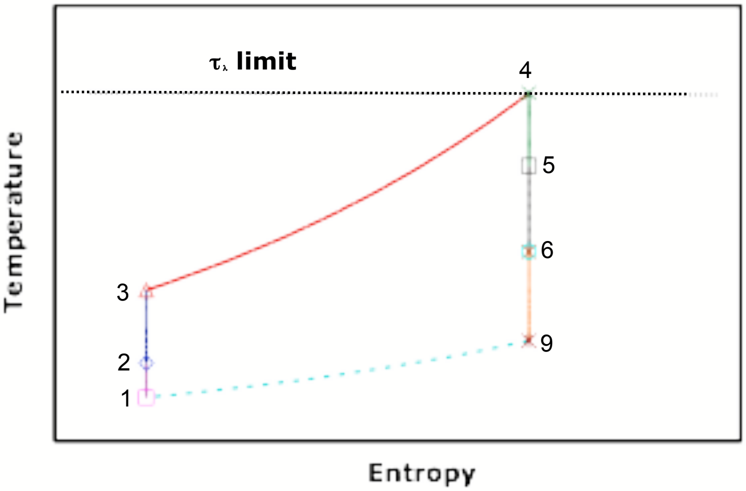
- Steady-flow engines
    - Thrust calculation
    - Propulsive, thermal and overall efficiencies
    - Brequet range equation, rocket equation
- Compressible flow
    - Frictionless, adiabatic, variable area (others below not covered this year…)
    - ~~Frictional, adiabatic, constant area~~
    - ~~Frictionless, diabatic, constant area, pressure or temperature~~
    - ~~Frictionless, adiabatic, constant area (shock solutions)~~
    - ~~Stagnation pressure and temperature~~
- 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 (α) and fan pressure ratio (π_c')
            - Optimization
        - Non-ideal cycles
            - Component efficiencies
            - T-s diagrams

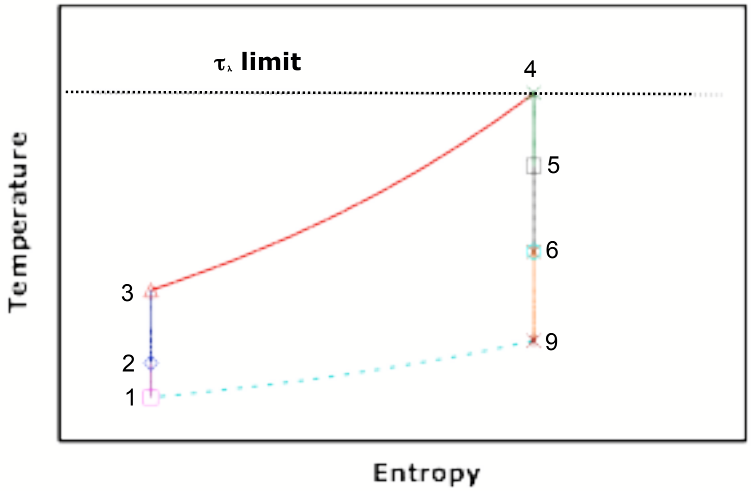
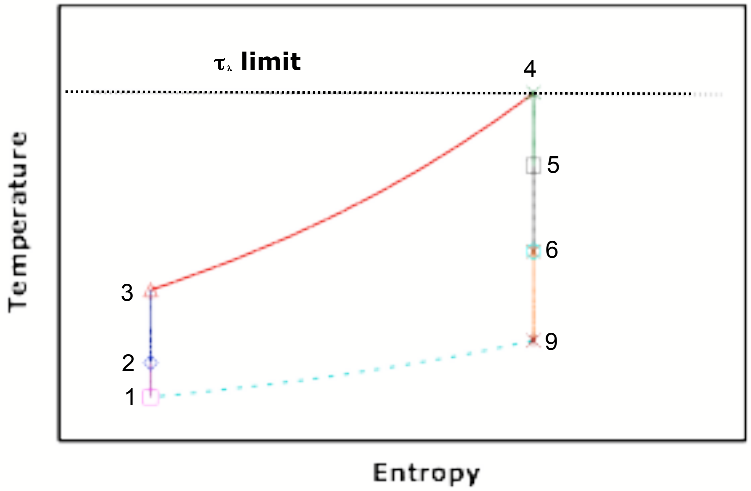
            Effects on cycle performance
    - Ramjets
        - Turbojet without compressor ($\pi_c = 1$), works only at high Mach numbers

Last year's final exam (average score was 74.9/100)

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

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

a)	
	Both the compressor and fan are irreversible but the turbine is still ideal (reversible).
b)	
	Half way though the standard (constant pressure) burn, abnormal combustion occurs which results in constant **volume** combustion. The same total amount of fuel is burned as in the baseline cycle (τ_λ limit cannot be honored in this case). All other components operate normally.

c)	
	The diffuser is terrible and has significant stagnation pressure losses. All other components operate normally.
d)	
	A new fuel is used that has 10% higher heating value.

<u>Problem #2 (Gas turbine performance)</u> **<u>(25 points total, 5 points each part)</u>** The following 5 changes to a τ_λ-limited turbofan engine flying at subsonic conditions ($M_1 = 0.8$) are being considered:

1) Use a new fuel with twice the heating value per unit mass (Q_R)
2) Increase ambient pressure (P_1) by a factor of 2 (ambient temperature T_1 not changed)
3) Increase ambient temperature (T_1) by a factor of 2 (ambient pressure P_1 not changed)
4) Increase the flight Mach number M_1 from 0.8 to 1.6
5) Use a new wing with twice the lift to drag ratio (L/D) of the original wing

All other properties of the engine, e.g. bypass ratio (α), compressor pressure ratio (π_c), fan pressure ratio (π_c'), engine size, turbine inlet temperature limit (τ_λ), etc. are held constant.

Briefly answer the following questions **(no credit without explanation!)** In some cases there might be more than one potentially "correct" answer; if so, any one of those answers are acceptable.

Do not list more than one answer for each part.

If **only one** of these 5 changes were implemented:

a) Which change would **increase specific thrust** (Thrust/$\dot{m}_a$ c_1) the most?
b) Which change would **decrease thrust** (not specific thrust) the most?
c) Which change would **increase Thrust Specific Fuel Consumption (TSFC)** the most?
d) Which change would **increase propulsive efficiency** the most?
e) Which change would **increase aircraft range** the most?

Problem #3 (gas turbine performance) (25 points total, 4 points parts a – e, 5 points part f)

The following performance parameters were measured in a turbojet-powered aircraft (no fan or afterburner):

- Flight velocity u_1 = 250 m/s; air mass flow $\dot{m}_a$ = 10 kg/s; fuel mass flow $\dot{m}_f$ = 0.3 kg/s
- Compressor pressure ratio $\pi_c = 30$
- Thrust = 10650 N
- Ambient pressure P_1 = exit pressure P_9 = 0.5 atm = 5.07×10^4 N/m^2
- Ambient temperature T_1 = 250K
- Gas constant R = 300 J/kgK, gas specific heat ratio $\gamma = 1.35$
- Fuel heating value $Q_R = 4.3 \times 10^7$ J/kg

From this information compute:

a) Flight Mach number (M_1) and recovery temperature ratio (τ_r)
b) Specific Thrust
c) Exhaust velocity (u_9)
d) Overall efficiency (η_o)
e) Propulsive efficiency (η_{prop})
f) Turbine inlet temperature T_4 (assuming an ideal cycle with no heat losses or irreversibilities)

Problem #4 (Miscellaneous) (30 points total, 5 points each part)

Ronney Oil & Gas Company claims to have developed a fuel, called PDR®, whose chemical formula is C_8H_{18} (octane) and has all the same thermodynamic properties, transport properties, etc. as C_8H_{18}. The **only** difference between C_8H_{18} and PDR® is that PDR has **10% higher heating value** than octane. If PDR® fuel were used instead of C_8H_{18}, how would each of the following be affected? In particular, state whether the property would increase, decrease or remain the same, and if there is a change, would it be by more than, less than, or equal to 10%. **No credit without explanation!**

a) **Burning velocity (S_L)** of a stoichiometric octane-air flame
b) **Soot concentration** in the products of a very rich premixed octane-air flame
c) **Indicated thermal efficiency** of an ideal diesel cycle
d) **Brake Mean Effective Pressure (BMEP)** of a premixed-charge engine operating at wide-open throttle
e) **CO emissions** from a premixed-charge engine operating at wide-open throttle
f) **Thrust Specific Fuel Consumption (TSFC)** of an afterburning turbojet with no $\tau_{\lambda,AB}$ limit in the afterburner