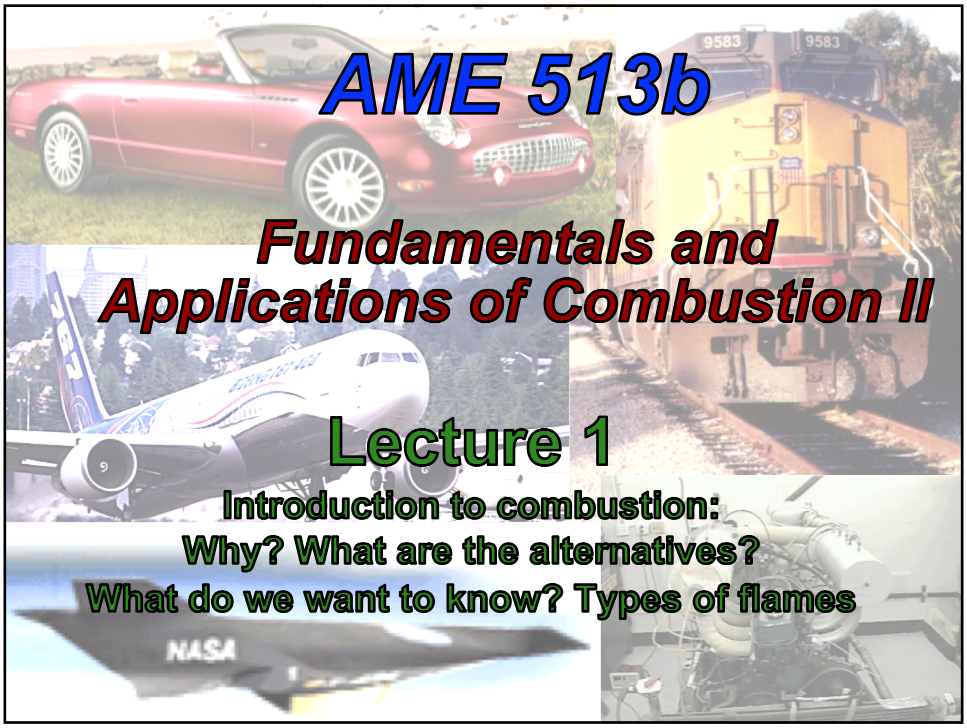

Nomenclature (summary for whole course)

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Symbol	Meaning (units)
A	Cross-section area (m^2)
A^*	Throat area (m^2)
A_e	Exit area (m^2)
B	Pre-exponential factor in reaction rate expression (AME 513a) = Z in 513b ($[moles/m^3]^{1-n}K^{-a}/s$) (n = order of reaction)
B	Transfer number for droplet burning (---)
c	Sound speed (m/s)
C	Duct circumference (m)
C_D	Drag coefficient (---)
C_f	Friction coefficient (---)
CO	Carbon monoxide (compound having 1 carbon and 1 oxygen atom)
C_P	Heat capacity at constant pressure (J/kgK)
C_v	Heat capacity at constant volume (J/kgK)
D	Mass diffusivity (m^2/s)
D	Drag force (N)
DORF	Degree Of Reaction Freedom
E	Energy contained by a substance = U + KE + PE (J)
E_a	Activation Energy (J/mole)

Nomenclature (summary for whole course)

Symbol	Meaning (units)
f	Fuel mass fraction in mixture (---)
FAR	Fuel to air mass ratio (---)
g	Acceleration of gravity (m/s^2)
g	Gibbs function ≡ h - Ts (J/kg)
H	Enthalpy ≡ U + PV (J)
h	Enthalpy per unit mass = u + Pv (J/kg)
h	Heat transfer coefficient (usually W/m^2K, dimensionless in AirCycles.xls files)
$\tilde{h}_i$	Enthalpy of chemical species i per mole = $[\tilde{h}(T)-\tilde{h}_{298}]_i + \Delta\tilde{h}^o_{f,i}$ (J/mole)
$[\tilde{h}(T)-\tilde{h}_{298}]_i$	Thermal enthalpy of chemical species i per mole (J/mole)
I_{SP}	Specific impulse (sec)
K_i	Equlibrium constant of chemical species i (---)
k	Thermal conductivity (W/mK)
k	Reaction rate constant ($[moles/m^3]^{1-n}/sec$) (n = order of reaction)
K	Droplet burning rate constant (m^2/s)
K	Stretch rate (1/s) (in 513a notation; = Σ in 513b)
Ka	Karlovitz number (= $0.157\, Re_L^{-1/2} (u'/S_L)^2$ for premixed flames in turbulent flows)
KE	Kinetic energy (J or J/kg)
L	Lift force (N)
L_f	Jet flame length (m)
L_I	Integral length scale of turbulence (m)
LOMA	Law Of Mass Action

Nomenclature (summary for whole course)

Symbol	Meaning (units)
M_i	Molecular weight of chemical species i (kg/mole)
M	Mach number (---)
m	mass (kg)
$\dot{m}$	Mass flow rate (kg/sec)
$\dot{m}_a$	Air mass flow rate (kg/s)
$\dot{m}_f$	Fuel mass flow rate (kg/s)
n	Order of reaction (---)
n	Exponent on T term in expression for reaction rate constant k
n_i	Number of moles of chemical species I
N	Number of chemical species in a mixture
NO	Nitric oxide (compound having 1 nitrogen atom and 1 oxygen atom)
NO_x	Oxides of Nitrogen (any compound having nitrogen and oxygen atoms)
O_3	Ozone
P	Pressure (N/m^2)
P_a	Ambient pressure (N/m^2)
P_e	Exit pressure (N/m^2)
P_{ref}	Reference pressure (101325 N/m^2)
P_t	Stagnation pressure (N/m^2)
PE	Potential Energy (J or J/kg)
Q	Heat transfer (J or J/kg)
$\dot{Q}$	Heat transfer rate (Watts or Watts/kg)
Q_R	Fuel heating value (J/kg)

Nomenclature (summary for whole course)

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Symbol	Meaning (units)
R	Gas constant = $\Re$/M (J/kgK)
R	Flight vehicle range (m)
r or r_c	Compression ratio $\equiv (V_c+V_d)/V_c$ (---)
r_e	Expansion ratio (---)
Re_L	Reynolds number of turbulence $\equiv u' L_I/\nu$ (---)
$\Re$	Universal gas constant = 8.314 J/moleK
S	Entropy (J/K)
s	Entropy per unit mass (J/kgK)
S_L	Laminar burning velocity (m/s)
S_T	Turbulent burning velocity (m/s)
ST	Specific Thrust
T	Temperature (K)
TSFC	Thrust Specific Fuel Consumption
T_{ad}	Adiabatic Flame Temperature (K)
T_t	Stagnation temperature (K)
T_w	Wall temperature
T_∞	Ambient Temperature (K)

Nomenclature (summary for whole course)

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Symbol	Meaning (units)
U	Internal energy (J)
u	Internal energy per unit mass (J/kg)
u	Velocity (m/s) (most easily confused nomenclature – internal energy vs. velocity)
u_e	Exit velocity (m/s)
u_1	Flight velocity (m/s)
u'	Turbulence intensity (m/s)
UHC	Unburned hydrocarbons
V	Volume (m^3)
v	Specific volume = $1/\rho$ (m^3/kg)
W	Work transfer (J or J/kg)
$\dot{W}$	Work transfer rate (Watts or Watts/kg)
X_f	Mole fraction fuel in mixture (---)
X_i	Mole fraction of chemical species i (---)
Y_f	Mass fraction of fuel in mixture (---)
Z	Pre-exponential factor in reaction rate expression (AME 513b) = B in 513a ($[moles/m^3]^{1-n}K^{-a}/s$) (n = order of reaction)
z	Elevation (m)

Nomenclature (summary for whole course)

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Symbol	Meaning (units)
$[\ ]_i$	Concentration of species i (moles/m^3)
$(\ )^*$	Property at reference state (Mach number = 1 for all cases considered in this course)
α	Thermal diffusivity (m^2/s)
β	Non-dimensional activation energy $\equiv E/\Re T$ (---)
δ	Flame thickness (m)
$\Delta\tilde{h}^o_{f,i}$	Enthalpy of formation of chemical species i at 298K and 1 atm (J/mole)
$\Delta\tilde{s}^o_i(T)$	Entropy of chemical species i at temperature T and 1 atm (J/mole K)
ϕ	Equivalence ratio (---)
γ	Gas specific heat ratio $\equiv C_P/C_v$ (---)
η	Efficiency (thermal efficiency unless otherwise noted)
η_b	Burner (combustor) efficiency for gas turbine engines (---)
η_d	Diffuser efficiency for propulsion engines (---)
η_e	Expansion efficiency for reciprocating engines (---)
η_n	Nozzle efficiency for propulsion engines (---)
η_o	Overall efficiency (---)
η_p	Propulsive efficiency (---)
η_{th}	Thermal efficiency (---)

Nomenclature (summary for whole course)

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Symbol	Meaning (units)
μ	Dynamic viscosity (kg/m s)
ν	Stoichiometric coefficient (---)
ν	Kinematic viscosity $\equiv \mu/\rho$ (m^2/s)
π_i	Stagnation pressure ratio across component i (i = diffuser (d), burner (b), or nozzle (n))
π_r	$= P_{1t}/P_1$ ("recovery pressure" ratio) $= \{1 + [(\gamma-1)/2]M^2\}^{\gamma/(\gamma-1)}$ if γ = constant
ρ	Density (kg/m^3)
Σ	Stretch rate (1/s) (= K in 513a notation)
τ	Torque (N m)
τ_λ	$= T_{4t}/T_1$ (ratio of maximum allowable turbine inlet temperature to ambient temperature)
τ_r	$= T_{1t}/T_1$ ("recovery temperature" ratio) $= 1 + [(\gamma-1)/2]M^2$ if γ = constant
ω	Chemical reaction rate (mole s^{-1} m^{-3})

Outline of 1st lecture

- What do we do with combustion? Who cares?
- World & US energy usage
- Global warming
- Alternatives to combustion engines
- What do we want to know about combustion?
- Types of combustion

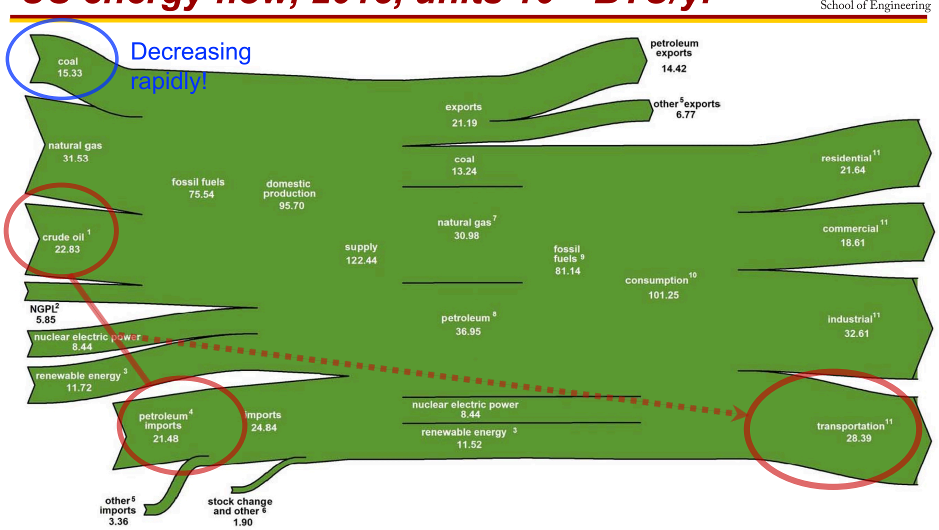
What do we do with combustion?

- Power generation (coal, natural gas)
- Transportation (land, air, sea vehicles)
- Weapons (rapid production of high-pressure gas)
- Heating
- Lighting
- Cooking (1/3 of the world's population still uses biomass-fueled open fires)
- Hazardous waste & chemical warfare agent destruction
- Production of new materials, *e.g.* nano-materials
- (Future?) Portable power, e.g. battery replacement
- Unintended / undesired consequences
  - Fires and explosions (residential, urban, wildland, industrial)
  - Pollutants – NO_x (brown skies, acid rain), CO (poisonous), Unburned HydroCarbons (UHCs, catalyzes production of photochemical smog), formaldehyde, particulates, SO_x
  - Global warming from CO_2 & other products

World energy usage

- ≈ 80% of world energy production results from combustion of fossil fuels
- Energy sector accounts for ≈ 10% of US Gross Domestic Product
- Our continuing habit of burning things and our quest to find more things to burn has resulted in
  - Economic booms and busts
  - Political and military conflicts
  - Deification of oil - "the earth's blood"
  - Global warming (or the need to deny its existence)
  - Human health issues

US energy flow, 2018, units 10^{15} BTU/yr



Each 10^{15} BTU/yr = 1 "Quad"/yr = 33.4 gigawatts

"Renewable energy": hydroelectric, biomass, geothermal, solar, wind

http://www.eia.gov/totalenergy/data/monthly/pdf/flow/total_energy.pdf

US energy demand

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2.25 gigawatt coal power plant (Page, AZ), 34% coal-to-electricity efficiency

In 2013, Los Angeles DWP received 40% of its electricity from here and a similar plant, but plans to be coal-free by 2025 (most major CA utilities already are)

US total energy demand (not just electrical) ≈ 500 of these, running continuously 24/7

Inflation-adjusted gasoline prices

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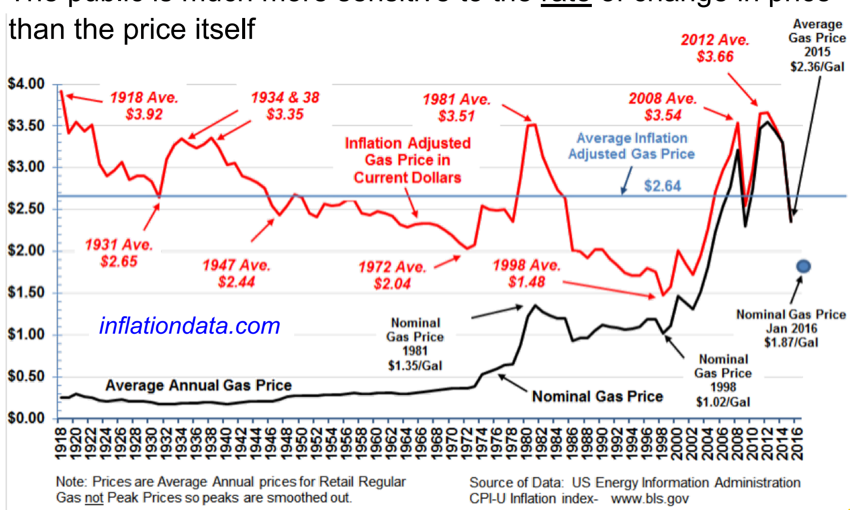
- $2.64/gal ± 50% for last 100 years
- Even during energy "crises" prices didn't change that much
- The public is much more sensitive to the rate of change in price than the price itself



Global warming

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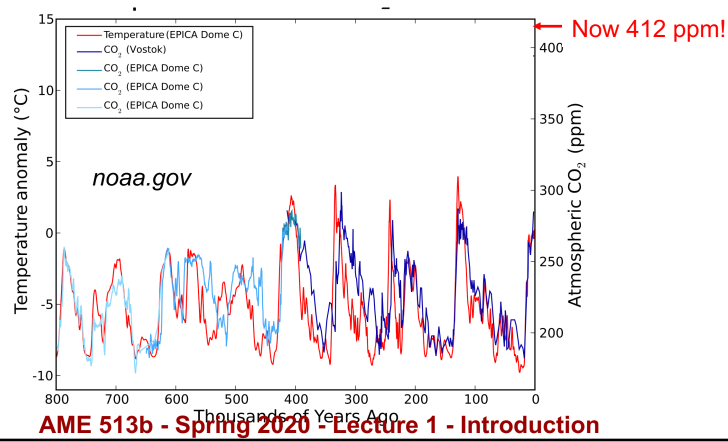
- Intergovernmental Panel on Climate Change (> 800 scientists selected from > 3500 nominations) in 2013 http://www.ipcc.ch/report/ar5/wg1/

"It is extremely likely [>95%] that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together"



Global warming

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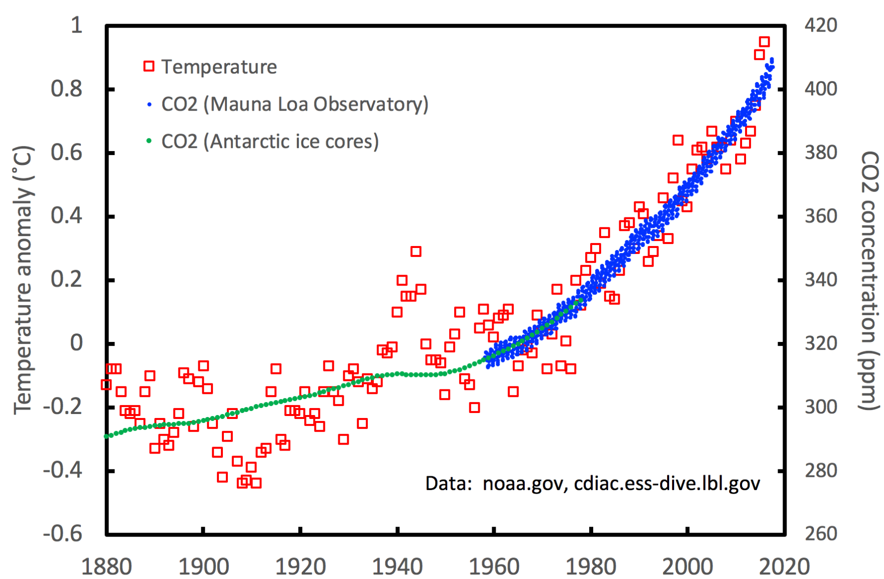

Alternatives to Internal Combustion engines

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- More information: http://ronney.usc.edu/AME436/Lecture1
- No energy technology is without economic and environmental consequences
- Hard to beat liquid-fueled internal combustion engines for
  - Power/weight & power/volume of engine
  - Energy/weight (4.3×10^7 J/kg assuming only fuel, not air, is carried) & energy/volume of liquid hydrocarbon fuel
  - Recharging / refueling rate
  - Low materials cost
    - » ICEs: steel & aluminum
    - » Fuel cells: platinum catalyst, exotic polymer membranes, gold contacts
    - » Batteries: lead, nickel, lithium, gold contacts, …
  - Distribution & handling convenience of liquids
  - Relative safety of hydrocarbons compared to hydrogen or nuclear energy

Alternatives to Internal Combustion engines

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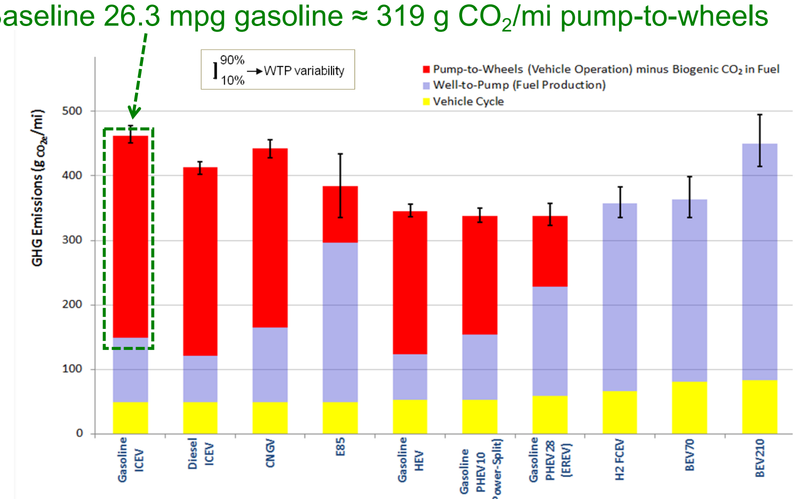
- Total "cradle to grave" greenhouse gas (GHG) emissions ≈ same for all propulsion methods and energy sources
- Baseline 26.3 mpg gasoline ≈ 319 g CO_2/mi pump-to-wheels



http://www.hydrogen.energy.gov/pdfs/14006_cradle_to_grave_analysis.pdf

Practical alternatives…

- Conservation!
- Aerodynamic, lightweight vehicles (e.g., http://edison2.com/very-light-car-overview/)
- Combined cycles
  - Use hot exhaust from ICE to heat water for conventional steam cycle
  - Can achieve > 60% efficiency
  - Not practical for vehicles - too much added volume & weight
- Natural gas (NG)
  - 3.6 cents / kW-hr (electricity 13.3, gasoline 8.0) (latest bls.gov data)
  - Somewhat cleaner than gasoline or diesel, but no environmental silver bullet
  - Low energy storage density when stored as a compressed gas at ≈ 3000 lb/in^2 - 5x lower than gasoline or diesel
  - Lowest CO_2 emissions of any fossil fuel source
  - Problem: greenhouse effect of unburned NG (escaping from production wells, filling stations, etc.) ≈ 8x that of burned NG

Practical alternatives…

- Fischer-Tropsch fuels - liquid hydrocarbons from coal or NG
  - Coal or NG + O_2 → CO + H_2 → liquid fuel
  - Competitive with ≈ $75/barrel oil
  - Cleaner than gasoline or diesel
  - … but using coal increases greenhouse gases!

    Coal : oil : natural gas ≈ 2 : 1.5 : 1
  - Can use biomass (e.g. agricultural waste) instead of coal or natural gas as "energy feedstock"

Why do we need to study combustion?

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- Chemical thermodynamics only tells us the end states - what happens if we wait "forever and a day" for chemical reaction to occur
- We need to know how fast reactions occur
  - How fast depends on both the inherent rates of reaction and the rates of heat and mass transport to the reaction zone(s)
  - Chemical reactions + heat & mass transport = combustion
  - Some reactions occur too slowly to be observed, e.g.

    $2\ NO \rightarrow N_2 + O_2$

    has an adiabatic flame temperature of 2650K but no one has ever made a flame with NO because reaction rates are too slow!
- Chemical reaction leads to gradients in temperature, pressure and species concentration
  - Results in transport of energy, momentum, mass
- Combustion is the study of the coupling between thermodynamics, chemical reaction and transport processes

What do we want to know about combustion?

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- From combustion device
  - Power (thermal, electrical, shaft, propulsive)
  - Efficiency (% fuel burned, % fuel converted to shaft, electrical and/or propulsive power)
  - Emissions
- From combustion process itself
  - Rates of consumption
    - » Reactants
    - » Intermediates
  - Rates of formation
    - » Intermediates
    - » Products
  - Global properties
    - » Rates of flame propagation
    - » Rates of heat generation (more precisely, rate of conversion of chemical enthalpy to thermal enthalpy)
    - » Temperatures
    - » Pressures

Types of combustion

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- Premixed - reactants are intimately mixed on the molecular scale before combustion is initiated; several flavors
  - Deflagration
  - Detonation
  - Homogeneous reaction
- Nonpremixed - reactants mix only at the time of combustion - have to mix first then burn; several flavors
  - Gas jet (Bic lighter)
  - Liquid fuel droplet
  - Liquid fuel jet (e.g. Kuwait oil fire, candle, Diesel engine)
  - Solid (e.g. coal particle, wood)

Type	Chemical reaction	Heat / mass transport	Momentum transport	Thermo-dynamics
Deflagration			X	
Detonation	X	X		
Homogeneous reaction		X	X	
Nonpremixed flames	X		X	X

Deflagrations

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- Subsonic propagating front sustained by conduction of heat from the hot (burned) gases to the cold (unburned) gases which raises the temperature enough that chemical reaction can occur; since chemical reaction rates are very sensitive to temperature, most of the reaction is concentrated in a thin zone near the high-temperature side
- May be laminar or turbulent
- Temperature increases in “convection-diffusion zone” or “preheat zone” ahead of reaction zone, even though no heat release occurs there, due to balance between convection & diffusion
- Reactant concentration decreases in convection-diffusion zone, even though no chemical reaction occurs there, for the same reason
- How can we have reaction at the reaction zone even though reactant concentration is low there? (See diagram…) Because reaction rate is much more sensitive to temperature than reactant concentration, so benefit of high T outweighs penalty of low concentration

Schematic of deflagration

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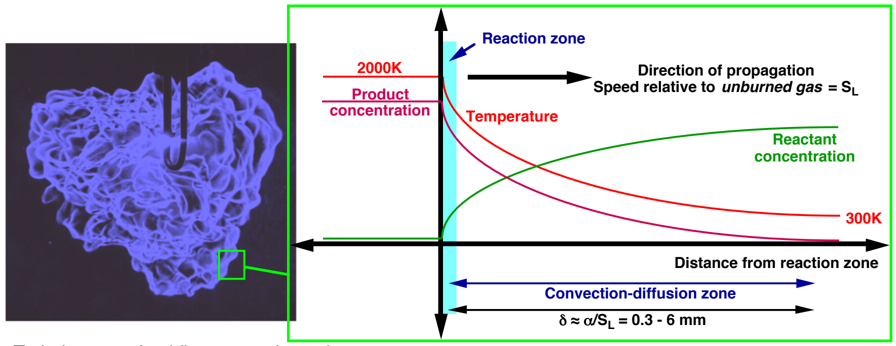

Turbulent premixed flame experiment in a fan-stirred chamber (http://www.mech-eng.leeds.ac.uk/res-group/combustion/activities/Bomb.htm)

Flame thickness (δ) ~ α/S_L
(α = thermal diffusivity)

Premixed flames - detonation

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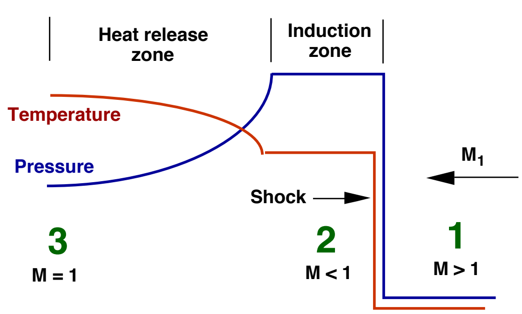
- Supersonic propagating front sustained by heating via shock wave
  - After shock front, need time (thus distance = time x velocity) before reaction starts to occur ("induction zone")
  - After induction zone, chemical reaction & heat release occur
  - Pressure & temperature behavior coupled strongly with supersonic/subsonic gasdynamics
  - Ideally only M_3 = 1 "Chapman-Jouget detonation" is stable

    (M = Mach number = u/c; u = velocity,
    c = sound speed = $(\gamma RT)^{1/2}$ for ideal gas)



CJ detonation:

$$M_1 = \left[1 + \frac{H(\gamma^2-1)}{2\gamma}\right]^{1/2} + \left[\frac{H(\gamma^2-1)}{2\gamma}\right]^{1/2}$$

$$H = \frac{q}{RT_1} \text{ (heat release parameter)}$$

$$q = C_P(T_{3t} - T_{2t}) = fQ_R$$

Premixed flames - homogeneous reaction

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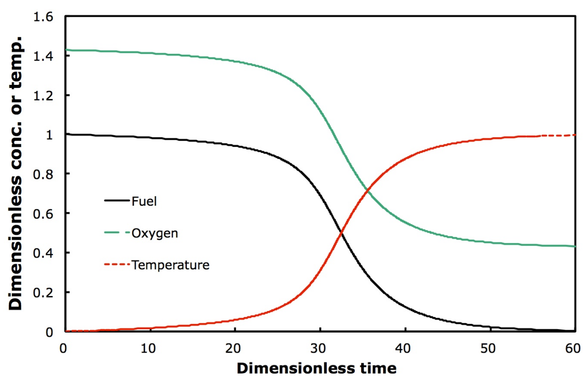
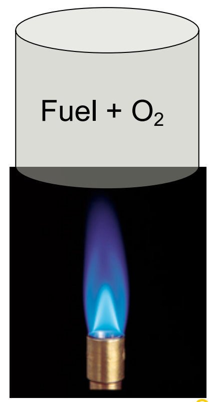
- Model for knock in premixed-charge engines
- Fixed mass with uniform (in space) T, P, composition
- No "propagation" in space but propagation in time
- In laboratory, could heat chamber to a certain T and measure time to react; in engine, compression of mixture (increases P & T, thus reaction rate) initiates reaction





"Non-premixed" or "diffusion" flames

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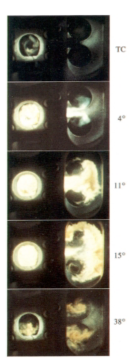
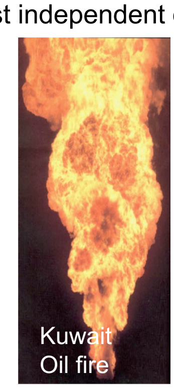
- Reaction zone where fuel & O_2 fluxes in stoichiometric proportion
- Generally "mixed is burned" - mixing slower than chemical reaction
- No inherent propagation rate (flame location determined by stoichiometric location)
- No inherent thickness (δ = mixing layer thickness ~ $(\alpha/\Sigma)^{1/2}$) (Σ = stretch rate)
- Unlike premixed flames with characteristic propagation rate S_L and thickness $\delta \sim \alpha/S_L$ that are almost independent of Σ



Diesel engine



Nonpremixed flame structure

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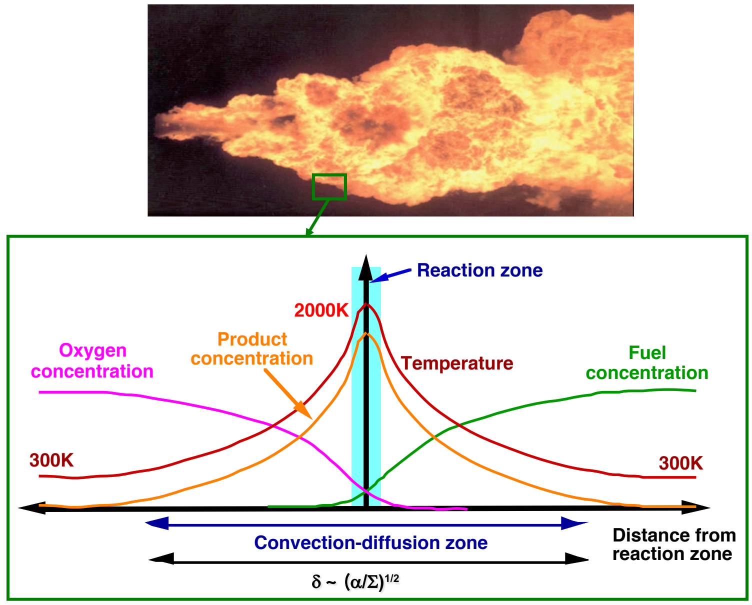

Diesel engine combustion

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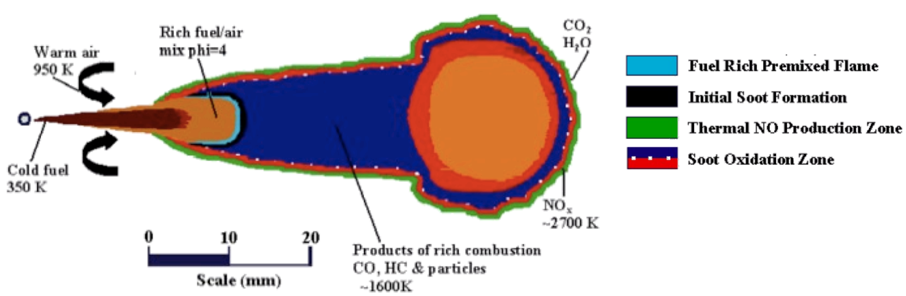
- Two extremes in practical combustors
  - Droplet combustion - vaporization of droplets is slow, so droplets burn as individuals
  - Gas-jet flame - vaporization of droplets is so fast, there is effectively a jet of fuel vapor rather than individual droplets
  - Reality is in between, but in Diesel combustion usually closer to the gas jet "with extras" – regions of premixed combustion



Flynn, P.F, R.P. Durrett, G.L. Hunter, A.O. zur Loye, O.C. Akinyemi, J.E. Dec, C.K. Westbrook, SAE Paper No. 1999-01-0509.

Summary - Lecture 1

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- Combustion is the interaction of thermodynamics, chemical reaction and heat/mass/momentum transport, but which is/are most important depends on the situation
- Combustion is ubiquitous in our everyday lives and will continue to be for our lifetimes
- Many advantages of fossil fuels over other energy sources
  - Cheap (?), plentiful (?), clean (?)
  - Energy/weight of fuel itself
  - Power/weight of engines
  - Materials costs of combustion engines (*e.g.*, compared to fuel cells)
- The most important distinction between flames is premixed vs. non-premixed, *i.e.*, whether the reactants are mixed before combustion

Discussion point

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Our current energy economy, based primarily on fossil fuel usage, evolved because it was the cheapest system. Is it possible that it's also the most environmentally responsible (or "least environmentally irresponsible") system?