



Aerospace Combustion

Lecture 1:

Introduction into Combustion and Aerospace Applications

This lecture series uses slides and material from the following individuals:
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**Please ask questions
throughout the lecture**



Lecture Organization

Lecture

Time : Tuesdays, 15:30-17:00

Location: MW 0608m

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Exercise

Time : Wednesdays, 17:30-18:30

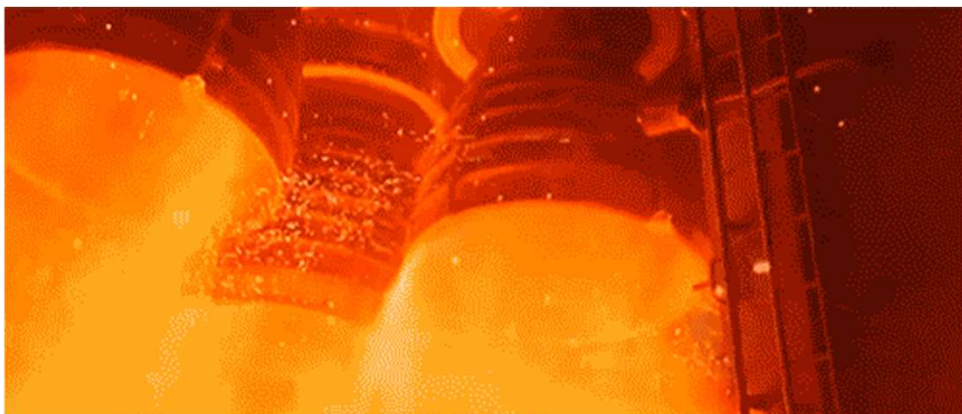
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We encourage you to use to the Moodle Forum for organizational and learning/content questions.



Course Structure

Lecture

- Introduction
- Propellants
- Rocket Engines
- Aero Engines
- Combustion chamber and injector design
- Combustion Instabilities
- Fluid Mechanics
- Combustion theory
- Combustion Modeling
- Spray Combustion

Exercise

- Introduction
- Laminar Flame Theory
- Propulsion Engines
- Combustion chamber design
- Turbulence
- Turbulent Premixed Flames
- Turbulent non-premixed flames



Sample Aerospace Applications



Airbus A 380-800

MTOW: ~ 620 to
Fuel: ~ 260 to
Dry weight: ~ 260 to
Payload: ~ 100 to

Ariane 5

MTOW: ~ 780 to
Fuel: ~ 680 to
Dry weight: ~ 90 to
Payload: ~ 10 to





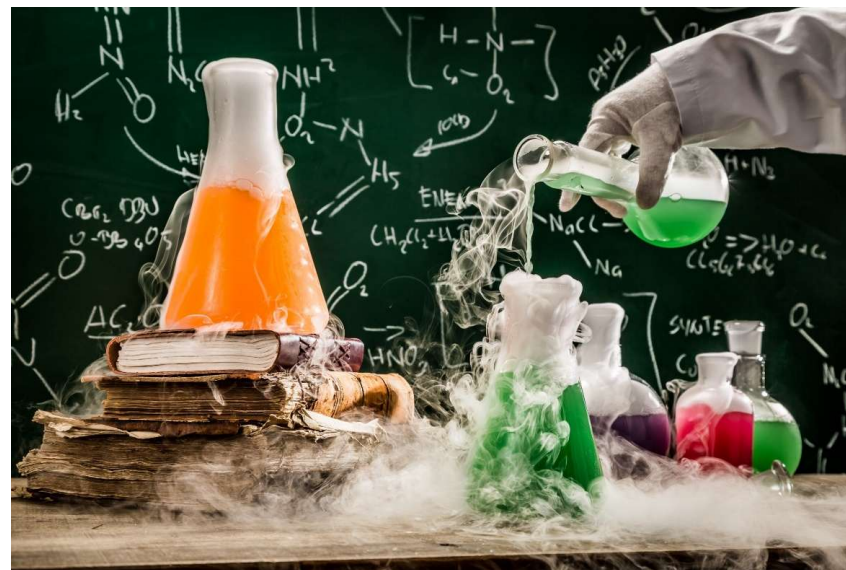
General Introduction into Combustion and Aerospace Applications

- What is Combustion and Why do we need to study it ?
- Global Energy and Transportation Sector Consumption
- Aerospace Engines and Applications
 - Air-breathing Engines
 - Turbo-fan, Turbo-jet, Turbo-prop Engines
 - RAM/SCRAM
 - Rocket Engines,
 - Solids
 - Liquid
 - Pulse Detonation, Continuous Detonation Wave Engines
- Types of Combustion
 - Pre-mixed Flames
 - Diffusion Flames

**Please ask questions
throughout the lecture**

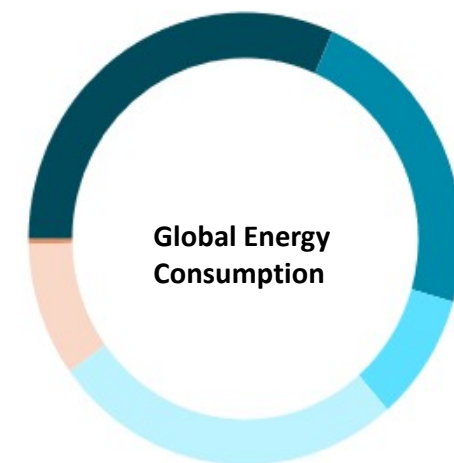
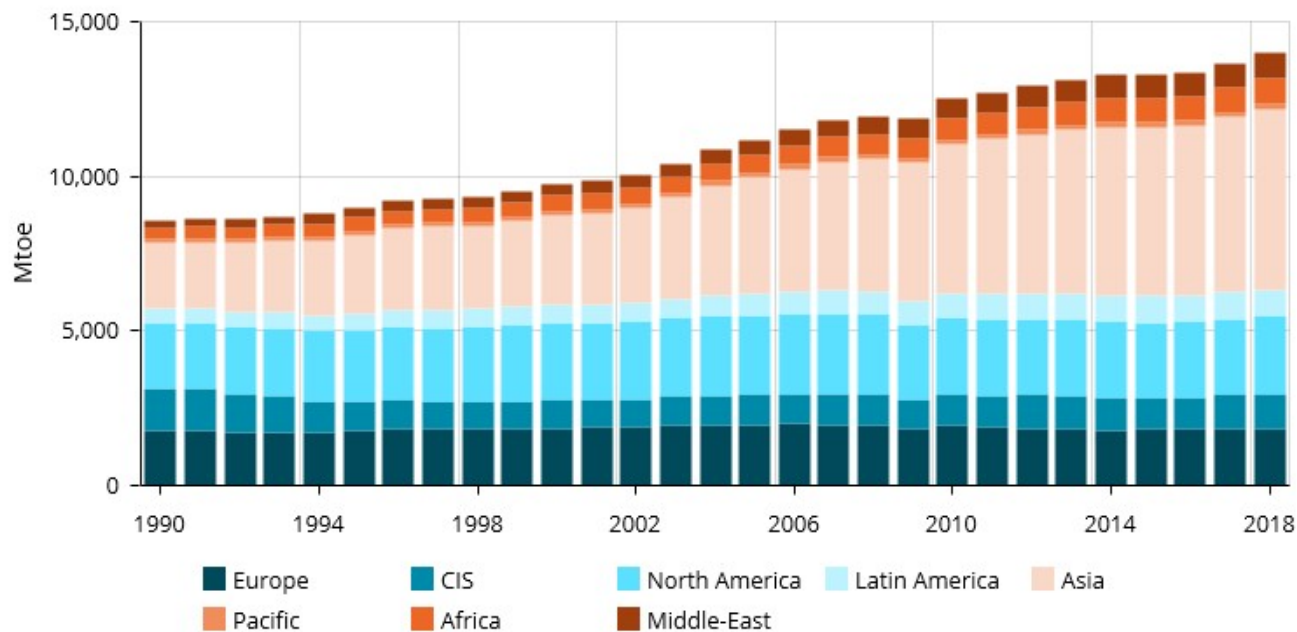
What is Combustion ?

- A specific type of chemical reaction which involves an oxidizer; typically gas mixtures or molecules which contain oxygen (air, N_2O_4 , O_2)
- Main aim is release of the energy stored in reactants and not the formation of products as in classical chemistry or pharmaceutical industry



Why do we do combustion ?

- Power generation (coal, natural gas)
- Transportation (land, air, sea vehicles)
- Heating & Cooking (1/3 of the world's population still uses biomass fueled open fires)
- Weapons (rapid production of high-pressure gas) & hazardous waste & chemical warfare agent destruction
- Lighting
- Production of new materials, e.g. nano-materials



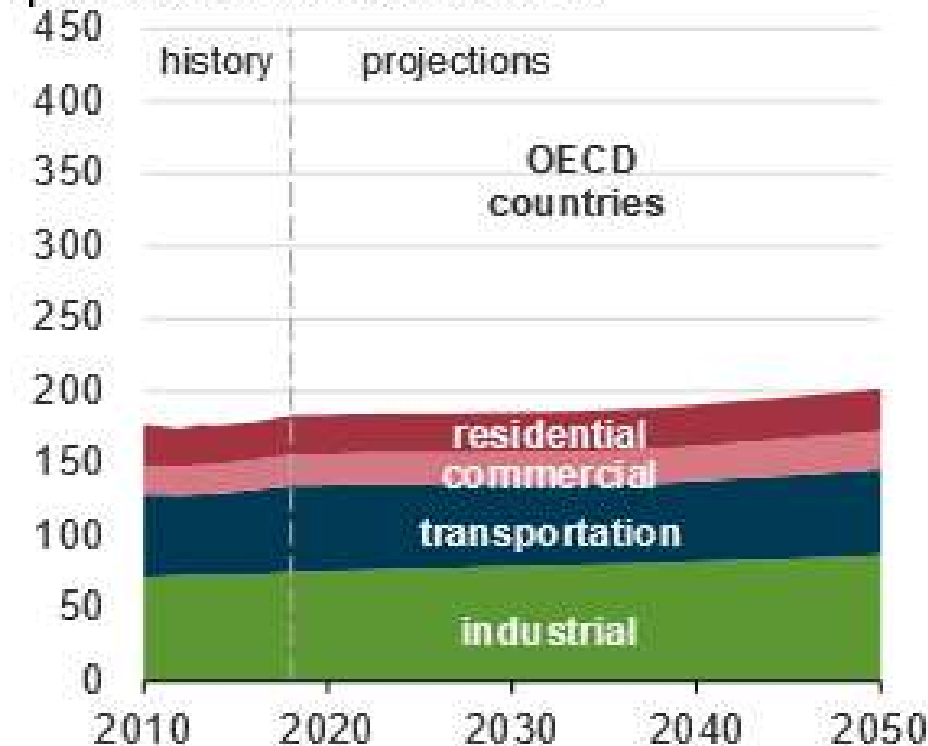


More Facts

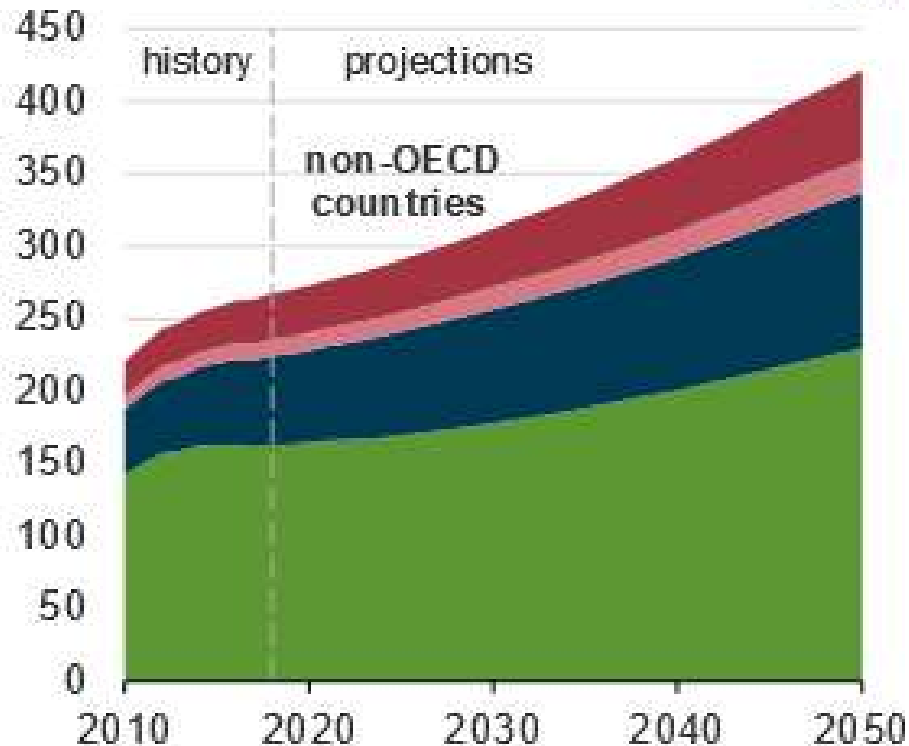
- About $\frac{3}{4}$ of world energy production results from combustion of fossil fuels
- Energy sector accounts $\sim 2\%$ of German Gross Domestic Product
- Continuous burning things and quest to find more things to burn has resulted in
 - Economic booms and busts
 - Political and military conflicts
 - Global warming (or the need to deny its existence)
 - Human health issues
- Unintended / undesired consequences
 - Fires and explosions (residential, urban, wildland, industrial)
 - Pollutants; NO_x (brown skies, acid rain), CO (poisonous),
 - Unburned Hydro-Carbons (UHCs, photochemical smog), formaldehyde, particulates, Sox
 - Global warming from CO₂ & other products



Global energy consumption by sector (2010-2050)
 quadrillion British thermal units



1 Btu = 1.055 Wh →
 1 quadrillion Btu = 1.055 x 10¹² kWh



Source: U.S. Energy Information Administration, *International Energy Outlook 2019* Reference case

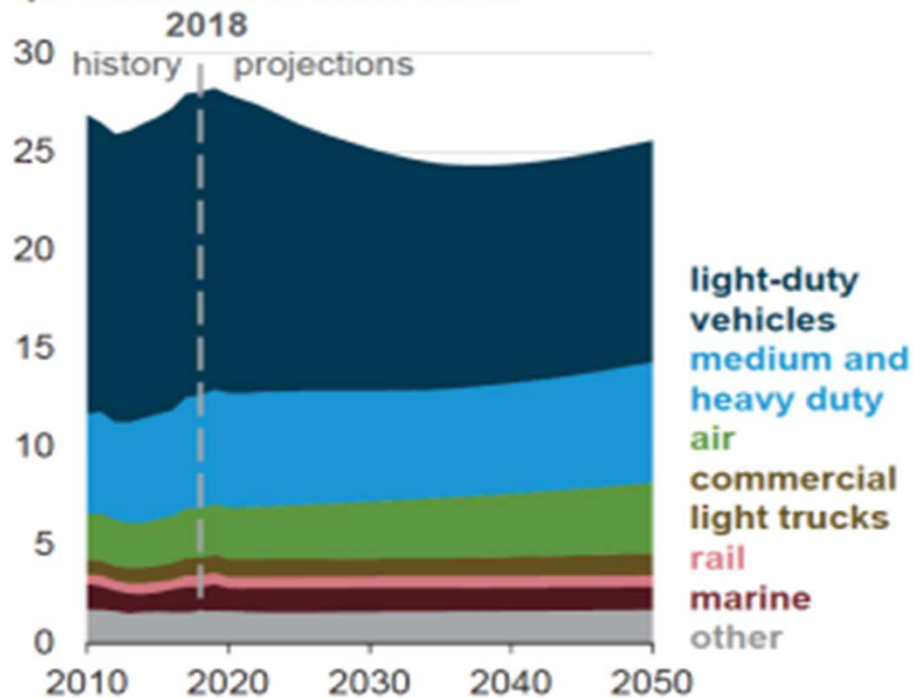


Introduction



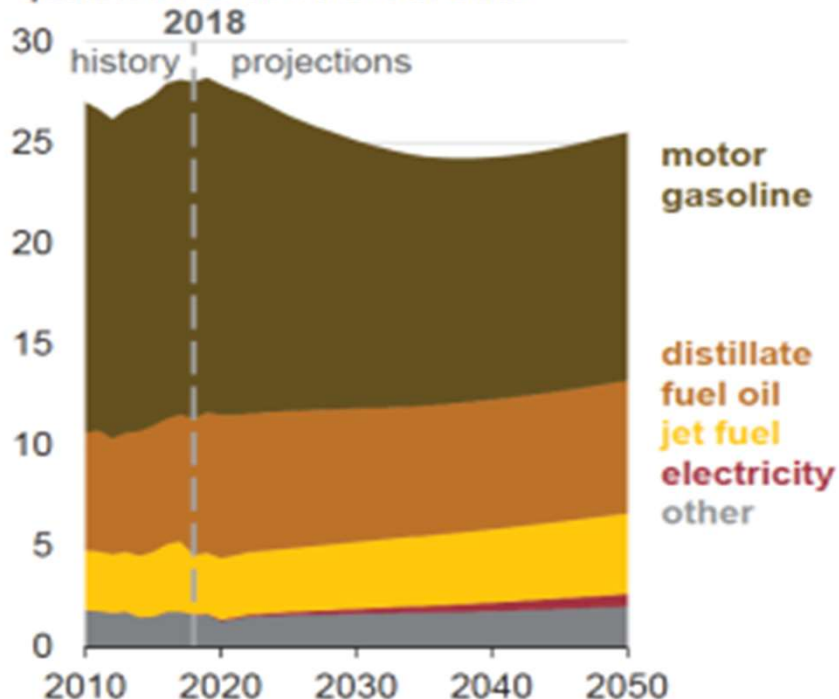
Transportation sector consumption (by type) (Reference case)

quadrillion British thermal units



Transportation sector consumption (by fuel) (Reference case)

quadrillion British thermal units



U.S. Energy Information Administration

#AEO2019 | www.eia.gov/aeo

Aerospace Combustion

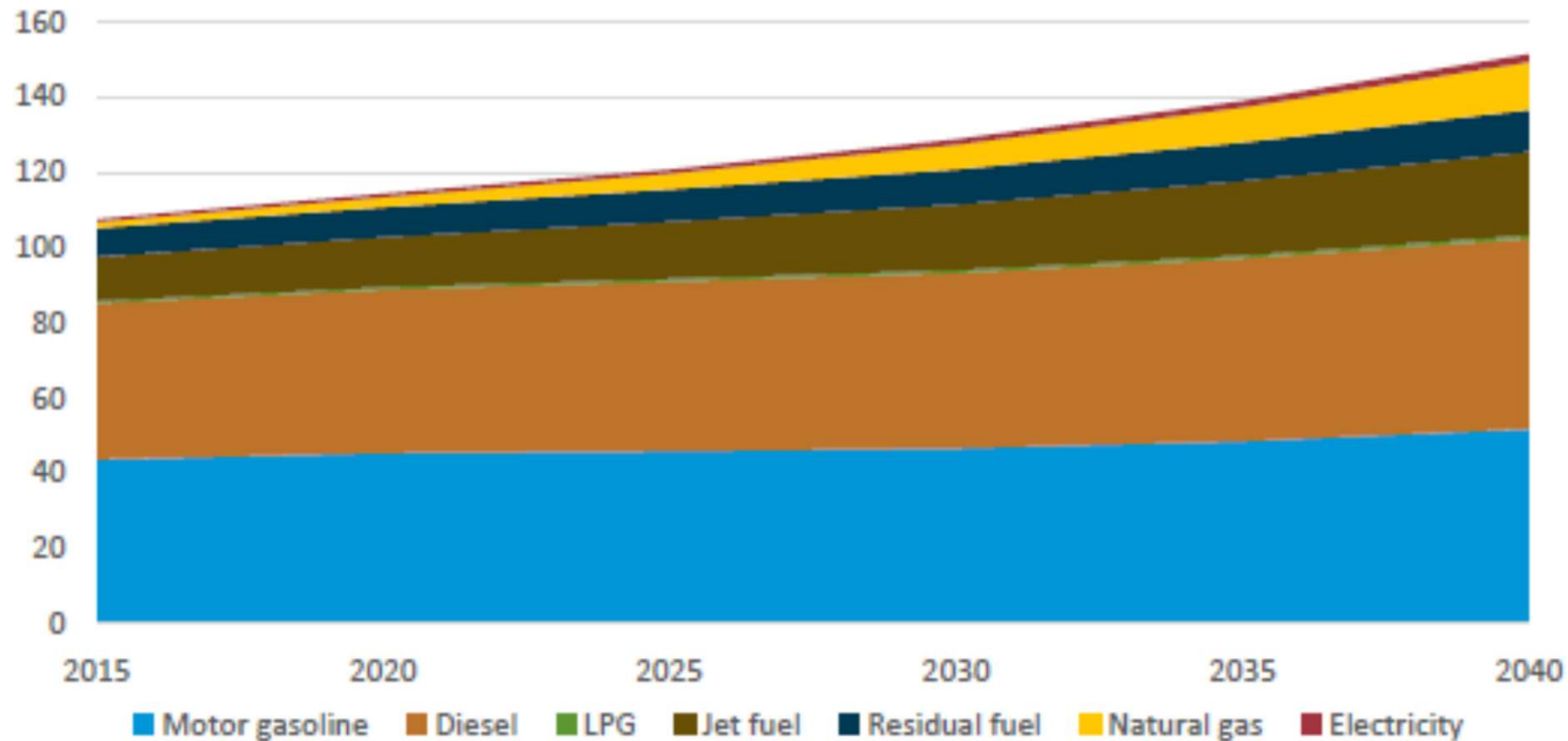
Prof. Dr.-Ing. O. J. Haidn, Dr. -Ing Daniel Martínez Sanchis, Dr. -Ing Andrej Sternin



Introduction



Total Transportation Energy Consumption Forecast (quadrillion Btu, 2017)



Source: U.S. Energy Information Administration

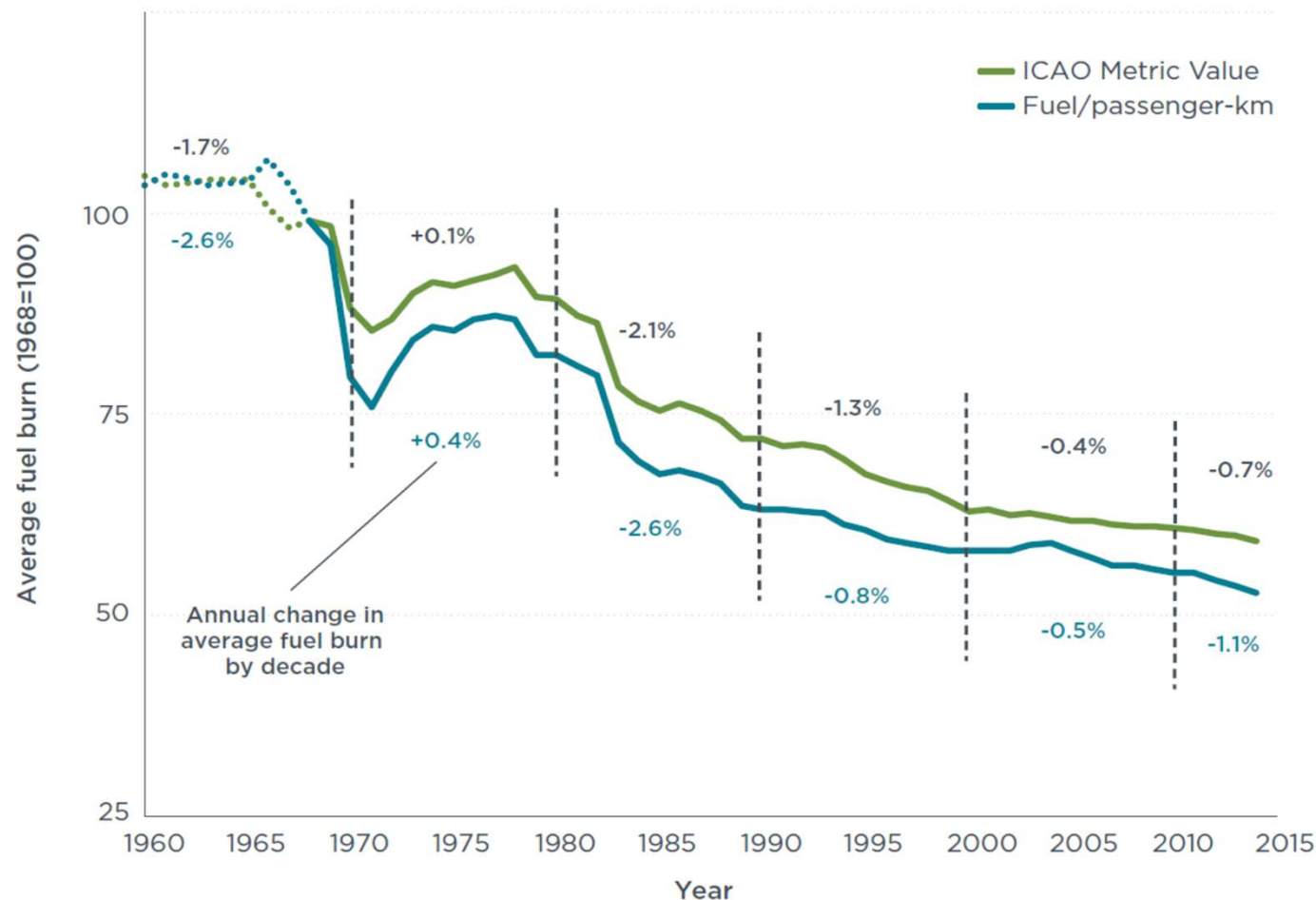




Averaged Aviation Fuel Consumption

Continuous development of energy efficient aircraft engines yielded a continuous and significant reduction of fuel consumption

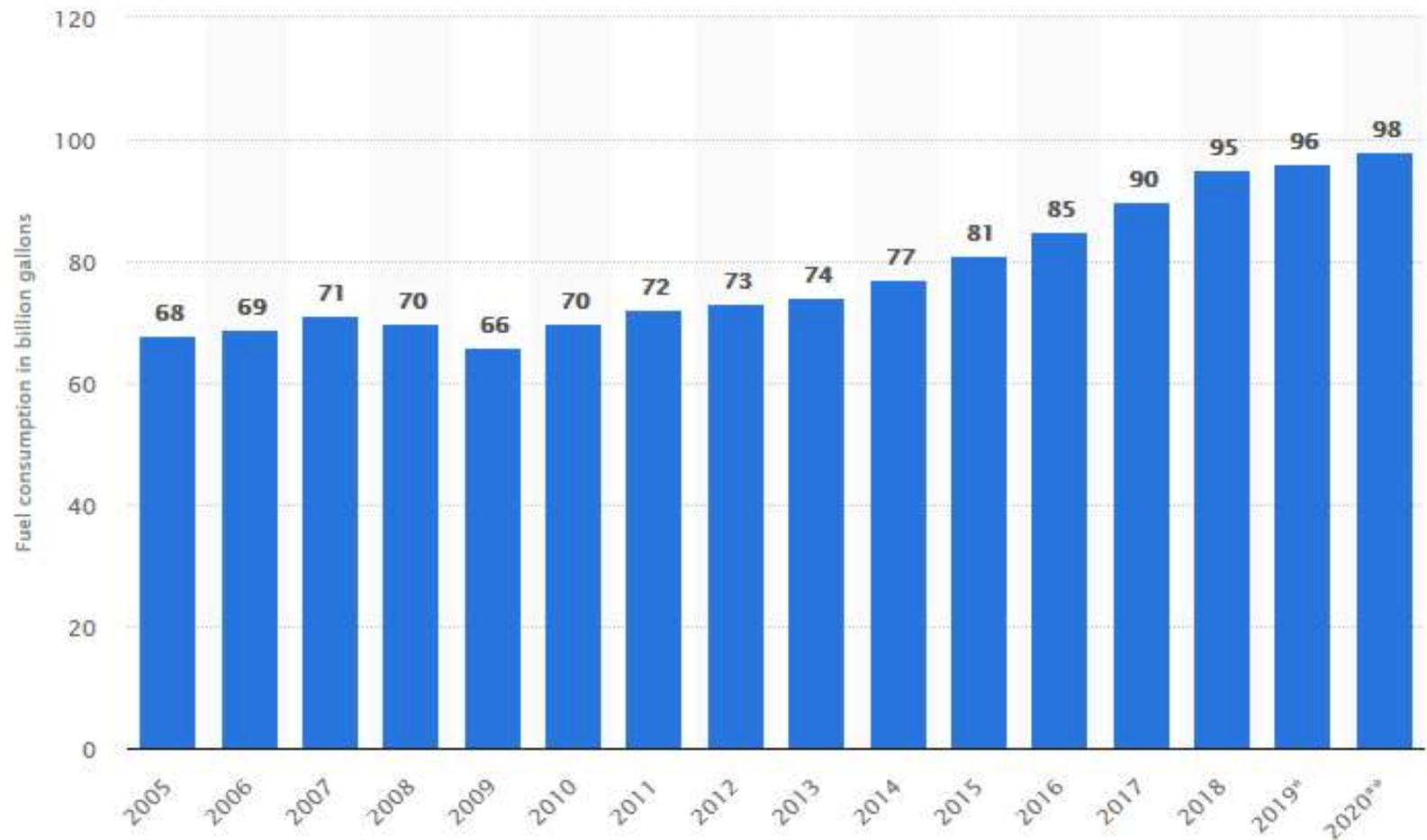
→ However, total fuel consumption has increased





Total Global Consumption of Aviation Fuel

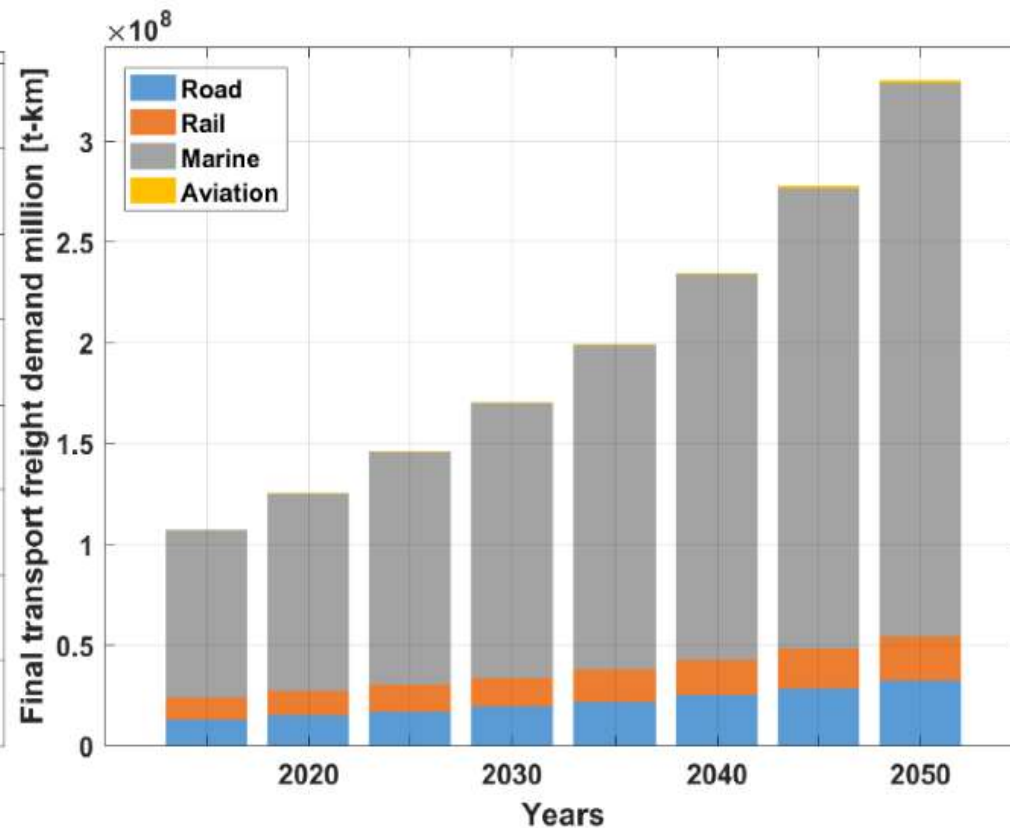
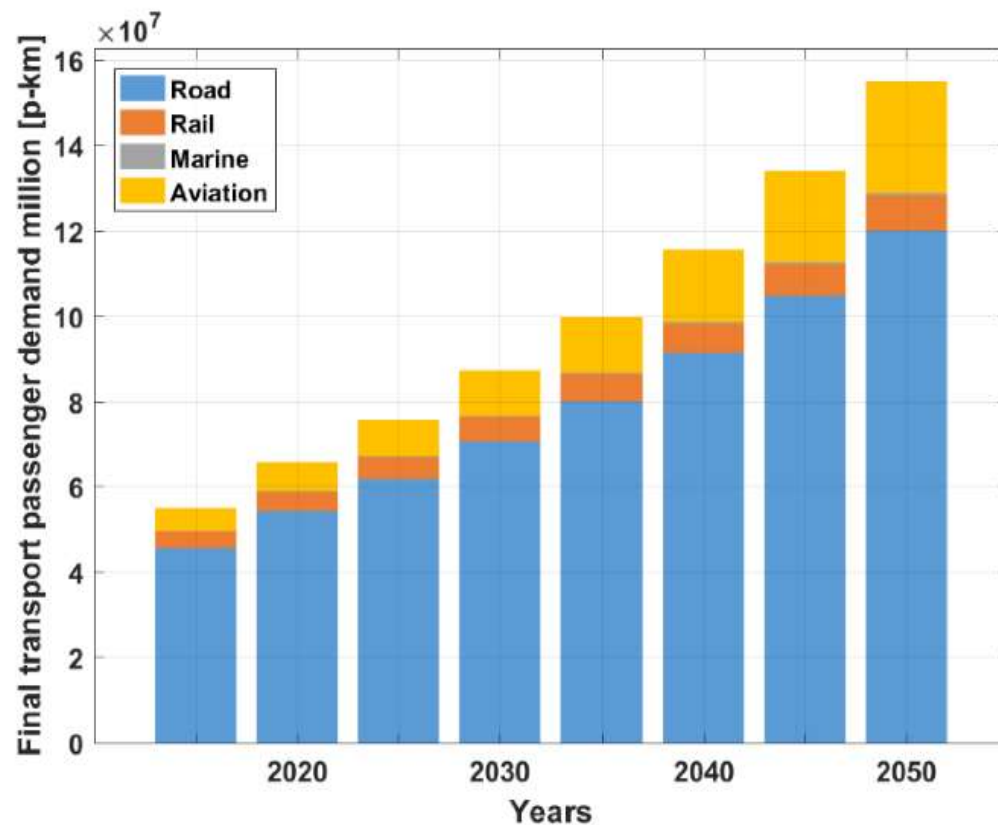
Engine efficiency couldn't compensate increased demand for air traffic





Global Transportation Demand Growth Forecast

Energies **2019**, 12(20), 3870;
<https://doi.org/10.3390/en12203870>





We need to study Combustion

Chemical thermodynamics only tells us the end states, i.e. what has happened if we wait infinitely long for chemical reactions to occur.

- We need to know how fast reactions occur and this depends on both the inherent reaction rates and the rates of heat and mass transport to and from the reaction zone.

Combustion \leftrightarrow Coupling of Chemical Reactions + Heat & Mass Transport

- Thermo-physical properties of all species involved, even intermediates
- Rates of individual reactions
- Boundary conditions of temperature, pressure and species concentrations
- Flammability limits, ignition delays, heat release,



What do we need to know ?

- Type of Combustion Device / Application
 - Power (thermal, electrical, shaft, propulsive)
 - Efficiency (% fuel burned, % fuel converted to power)
- Combustion Process Data
 - Rates of consumption of
 - Reactants
 - Intermediates
 - Rates of formation of
 - Intermediates
 - Products
- Global properties
 - Rates of flame propagation
 - Rates of heat generation (more precisely, rate of conversion of chemical enthalpy to thermal enthalpy)
- Initial Conditions of Temperature, Pressure and Mixture Ratio

Combustion Applications / Devices / Operating Modes

Air-breathing Propulsion

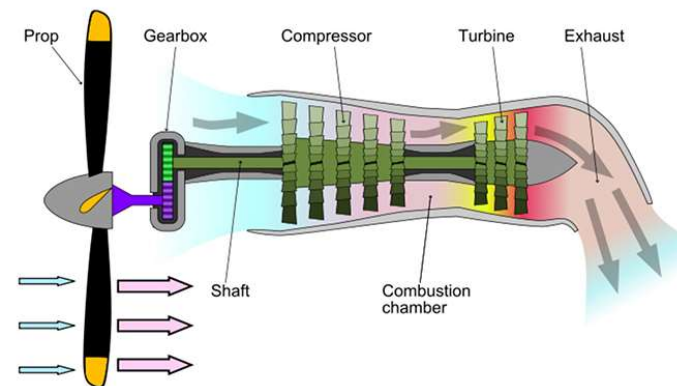
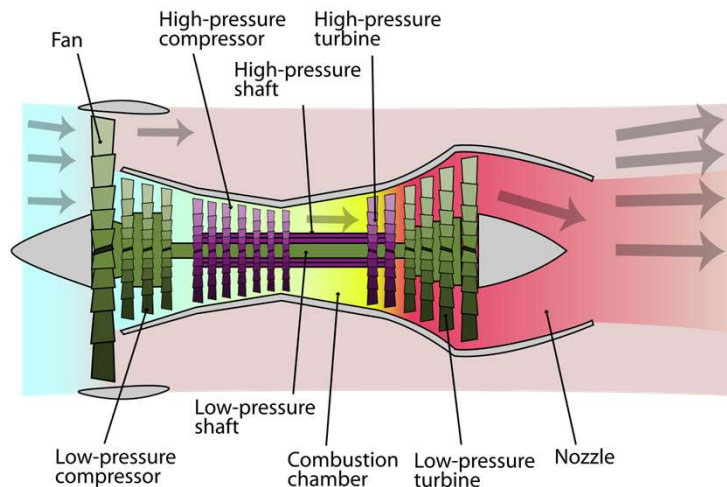
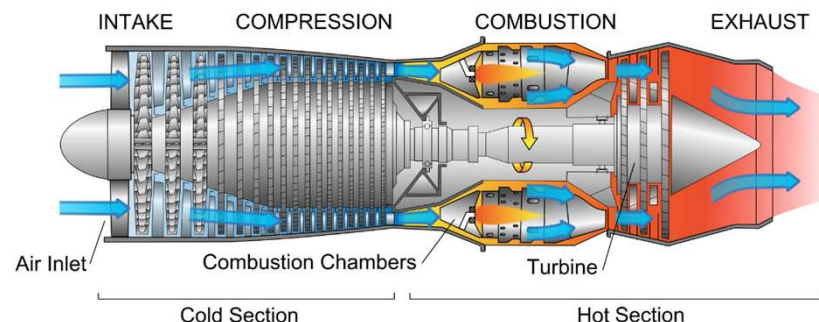
- Turbofan / Turbojet / Turboprop Engines
- Ramjet / Scramjet Engines
- Pulsejet (Detonation) Engines

Commonalities:

Compressor, Combustor, Turbine

Differences:

- Jet rides on the exhaust jet (all air goes through combustor)
- Fan gets its performance on bypass flow (only a small amount of air goes through combustor)
- Prop drives propeller



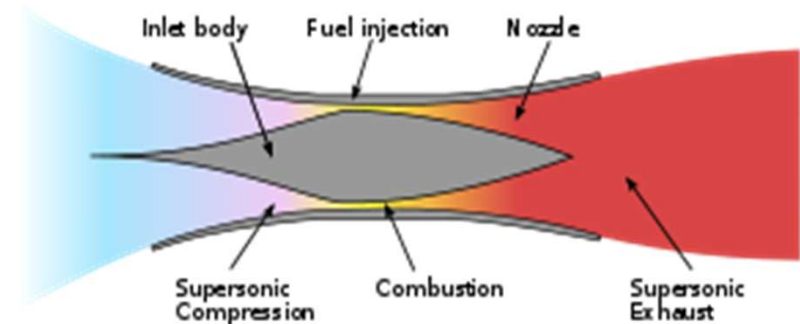
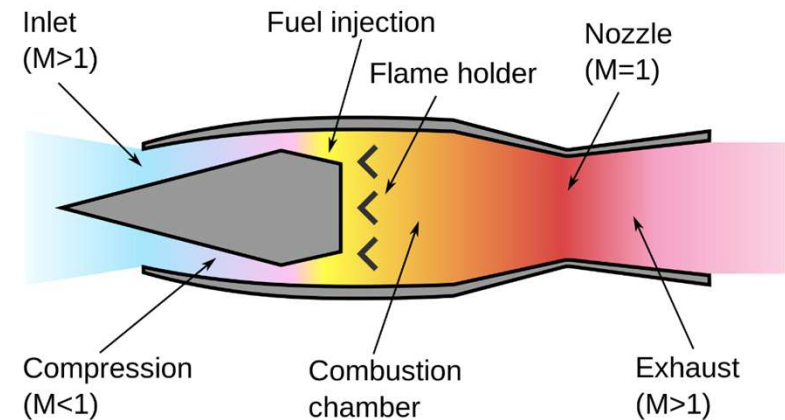
Combustion Applications / Devices / Operating Modes

Air-breathing Propulsion

- Turbofan / Turbojet / Turboprop Engines
- Ramjet / Scramjet Engines
- Pulsejet (Detonation) Engines

In a ramjet the flow inside the combustor is entirely subsonic and thus their flight Mach number is limited (losses).

Although the volume inside the scramjet combustor is subsonic, the rest of the flow is supersonic and thus way higher flight Mach number can be achieved.



Combustion Applications / Devices / Operating Modes

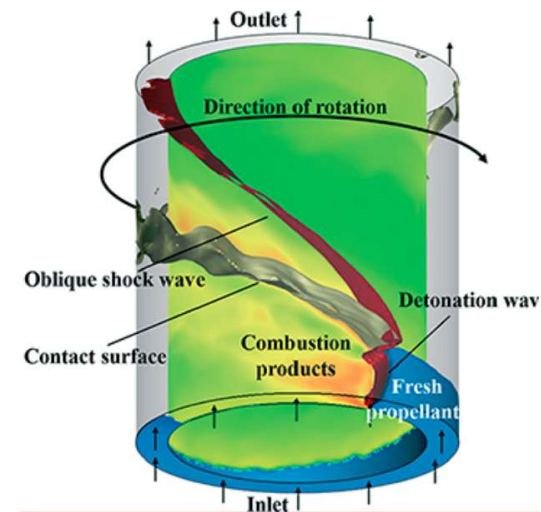
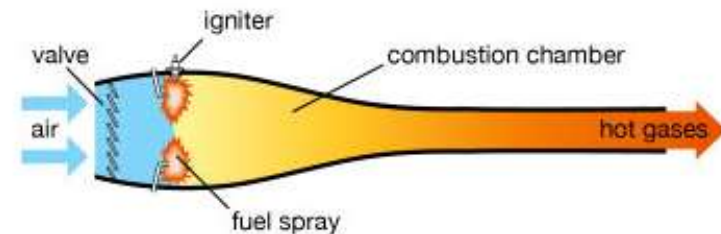
Air-breathing Propulsion

- Turbofan / Turbojet / Turboprop Engines
- Ramjet / Scramjet Engines
- Pulsejet Engines

Here are two detonation engines concepts which theoretically have performance advantage, however: there is no free lunch:

- Pulsed detonation engine (PDE)
 - Several tubes arranged in parallel and fired sequentially to generate an almost homogeneous thrust level
- Continuous detonation wave engines (CDWE)
 - Depending on engine diameter one or more detonation wave propagate along the gap and generate a continuous thrust.

Problems are severe noise and vibration levels as well as boundary layer effects and thermal loads



Combustion Applications / Devices / Operating Modes

Rocket Propulsion

- Liquid Propellant Engines
- Solid Propellant Engines
- Hybrid Engines

Liquid:

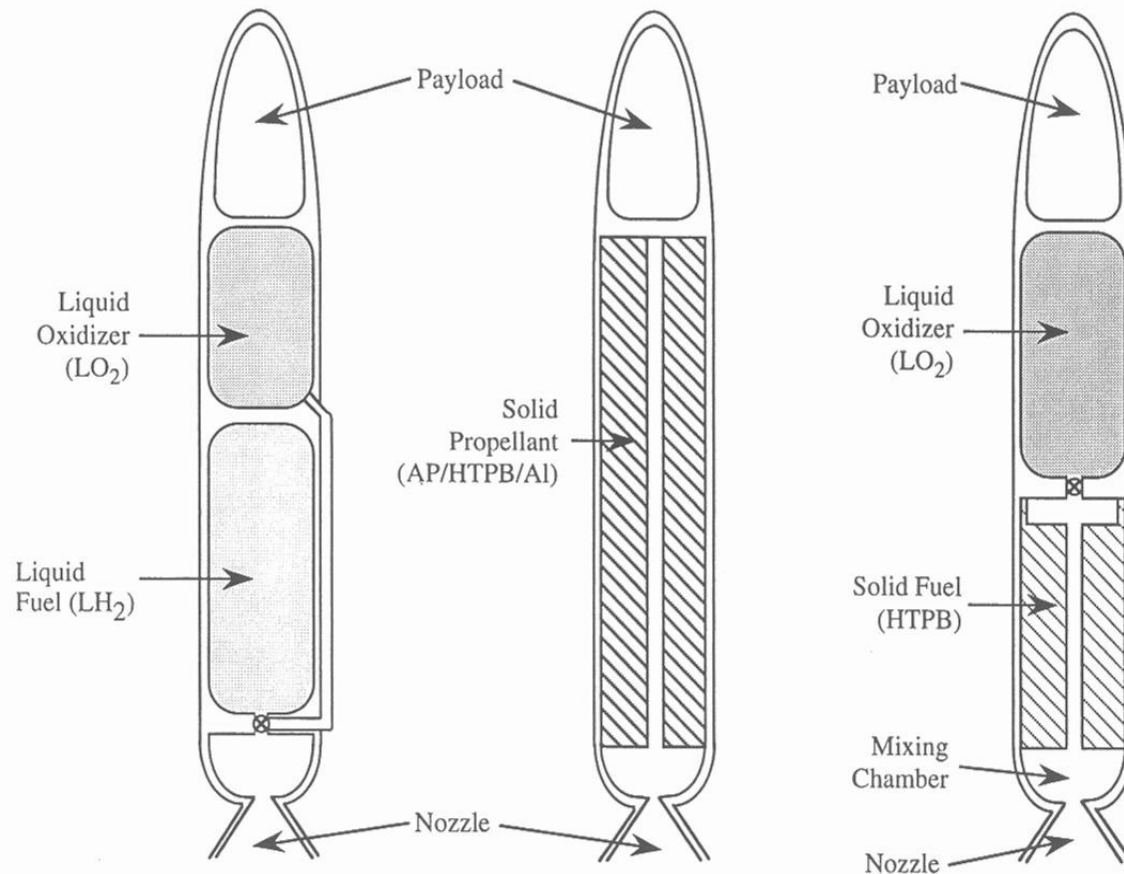
- 'volumetric' Heat Release
- Tank pressure usually \ll smaller than chamber pressure

Solid:

- Boundary Layer Heat Release
- Tank = combustion chamber (pre-mixed)

Hybrid:

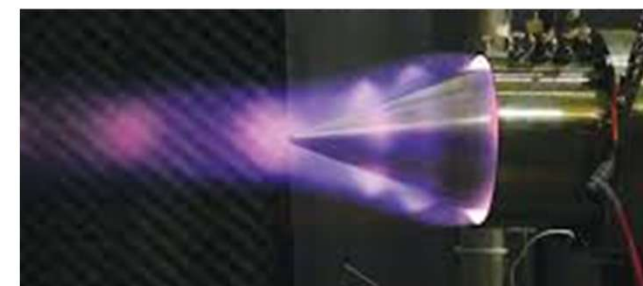
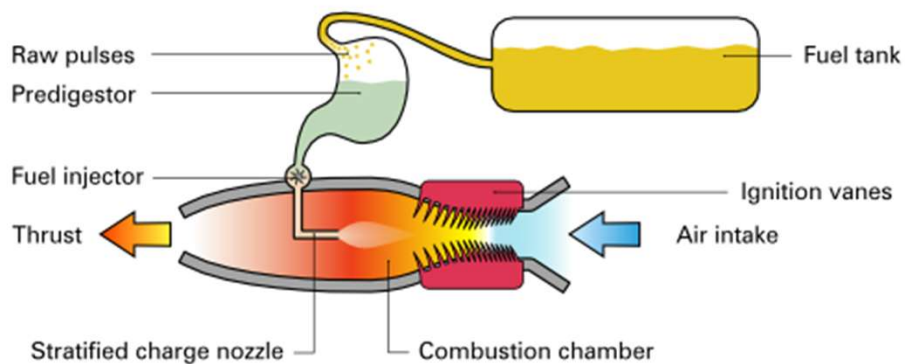
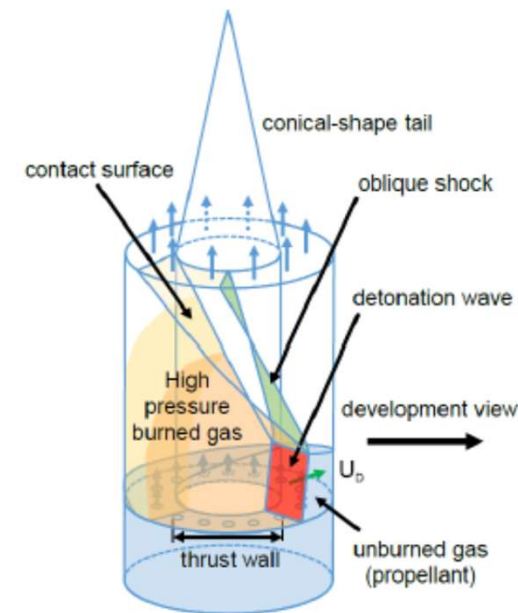
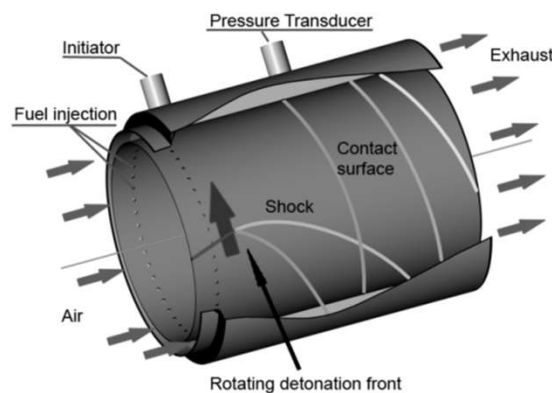
- Boundary Layer Heat Release
- Diffusion Flame



Combustion Applications / Devices / Operating Modes

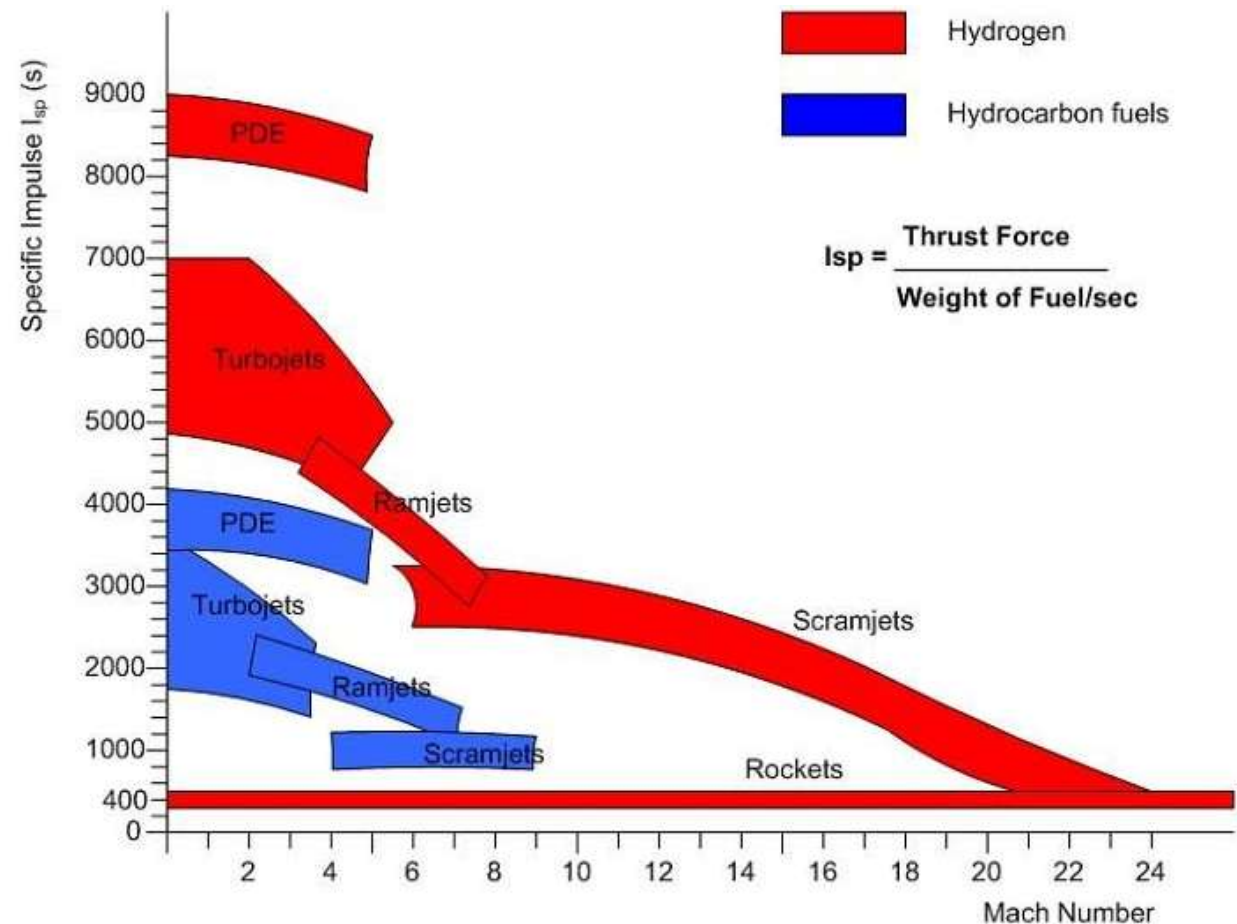
Concepts which work in both Environments

- Pulse Detonation Engines
- Continuous Detonation Wave Engines
 (Pressure Gain Combustion)



Theoretical Performances of Air-Breathing Propulsion Systems

- Variations in Design and Operational Complexity
- Aside scramjets and rocket engines all other systems have limits in feasible flight Mach number





Aerospace Propulsion: Commonalities and Differences

Both Applications strive for Optimum of performance, cost and reliability

Air-breathing Combustion

- Fuel-rich operation in rich mode (pilot burner) within an overall lean regime to reduce formation of soot and emission of unburnt propellants and increase performance
- Presence of nitrogen and as a consequence
 - lower temperatures
 - formation of Nox
- Long component life
 - minimum maintenance and overhaul
 - operation way below maximum performance
 - high cycle fatigue design
- **Most fatal failures due to human factor**
- **Main drivers are reliability, emissions, and performance**

Rocket Combustion

- Operation in fuel-rich mode to avoid oxidation of chamber liner and increase performance
- No nitrogen dilution and as a consequence
 - very high temperatures and thus as well thermal loads
 - formation of dissociated species
- Expendable or short limited reusability
 - Operation near maximum performance
 - low cycle fatigue design
- **Most fatal failures due to propulsion system**
- **Main drivers are reliability, cost, and performance**



How can we distinguish between Types of Combustion

- Gaseous, liquid (fuel or oxidizer or both), hybrid (oxidizer or fuel is liquid) or solid combustion (application-oriented)
- Subsonic, supersonic, deflagration, detonation (phenomenology-oriented)
- Pre-mixed, partially pre-mixed, diffusion dominated (process-oriented)
- Premixed: reactants are mixed on the molecular scale before combustion is initiated (studied extensively, minor relevance for applications)
 - Deflagration
 - Detonation
 - Homogeneous reaction
- Non-premixed: reactants mix only at the time of combustion have to mix first then burn (classical applications)
 - Gas jet (gas turbine, full flow cycle rocket engine)
 - Liquid fuel/oxidizer (jet engine, cryogenic rocket engine)

Pre-mixed Combustion: Deflagration

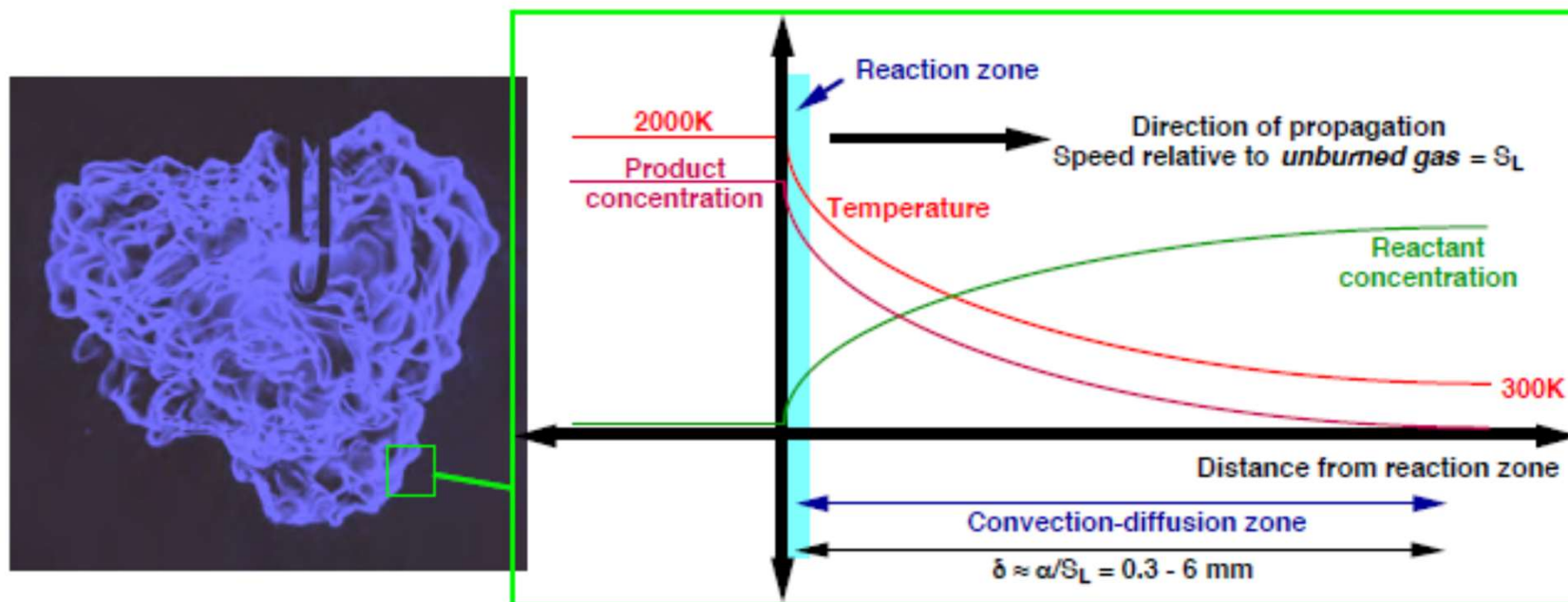
- Subsonic propagating flame front sustained by conduction of heat from burned gases to unburned gases which raises their temperature above auto-ignition temperature; chemical reaction rates are very sensitive to temperature → most of the reaction is concentrated in a thin zone near the high temperature side (laminar or turbulent)
- Temperature increase in convection-diffusion zone or preheat zone ahead of reaction zone, due to balance between convection & diffusion
- Reactant concentration decreases (**mol/m³**) in convection-diffusion zone, even though no chemical reaction occurs there
- Reaction occur even though reactant concentration is low because reaction rate is much more sensitive to temperature than reactant concentration, so benefit of high T outweighs penalty of low concentration

$$k = Ae^{-\frac{E_a}{RT}} \quad \text{or} \quad \ln k = -\frac{E_a}{RT} + \ln A$$

Where:

k = Chemical Reaction Rate
 A = Pre-exponential Factor
 E_a = Activation Energy
 R = Gas Constant
 T = Temperature in Kelvin

Pre-mixed Combustion: Deflagration



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

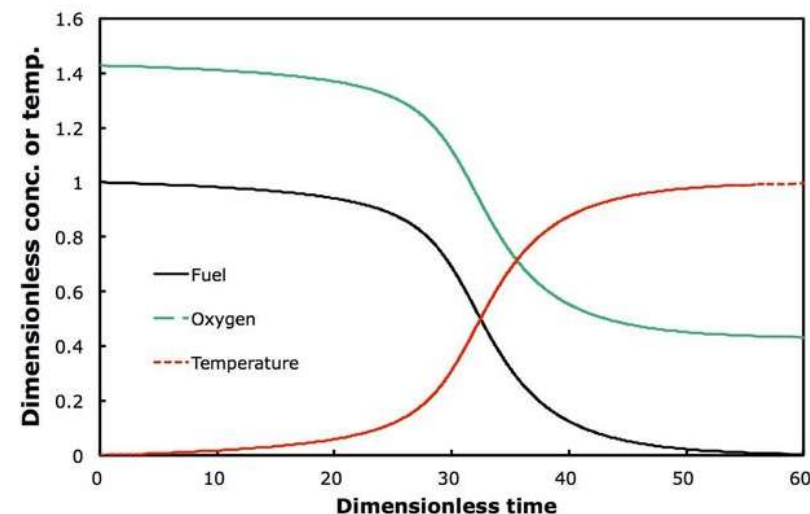
Flame thickness (δ) $\sim \alpha/S_L$
 (α = thermal diffusivity)

Pre-mixed Combustion: Homogeneous Reaction

- Model for knock in premixed-charge engines
- Fixed mass (control mass) with uniform (in space) T, P and composition

In laboratories:

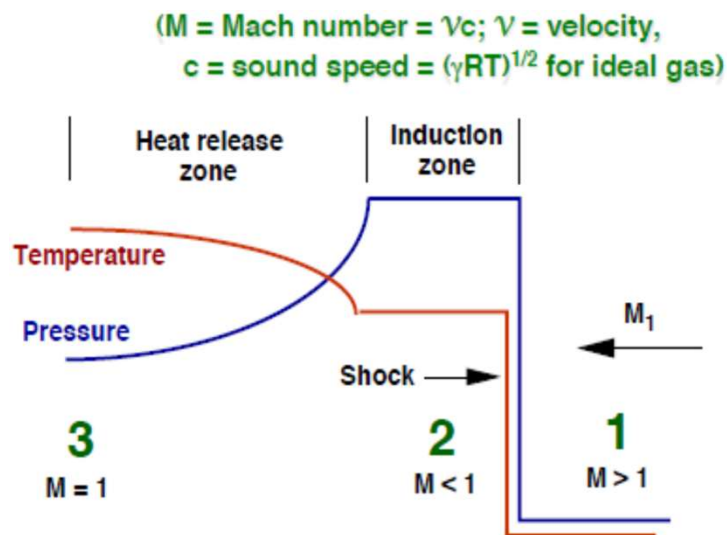
- experiments are set up such that fresh unburnt gas is provided with a velocity which is exactly the flame velocity
 - No flame propagation in space but propagation in time
- we may can the chamber to a certain T and measure reaction time, or compress mixture (increases P & T, thus reaction rate) will initiate reaction



Pre-mixed Combustion: Detonation

- 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 occurs
- Pressure & temperature behavior coupled strongly with supersonic/subsonic gas dynamics
- Ideally only $M_3 = 1$; Chapman-Jouget detonation is stable

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



CJ detonation:

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

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

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

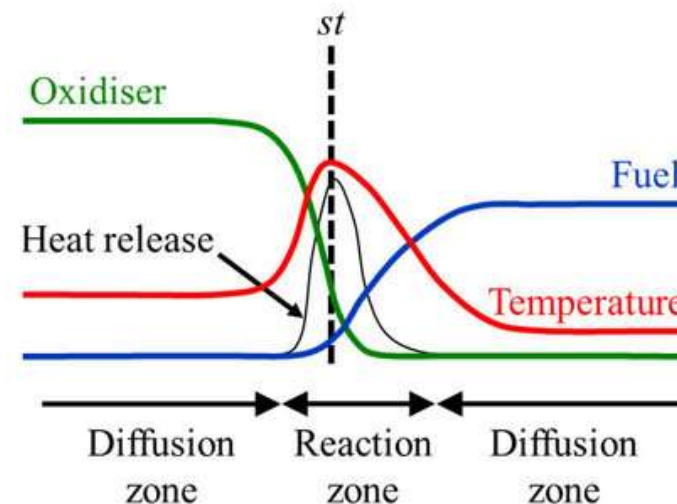
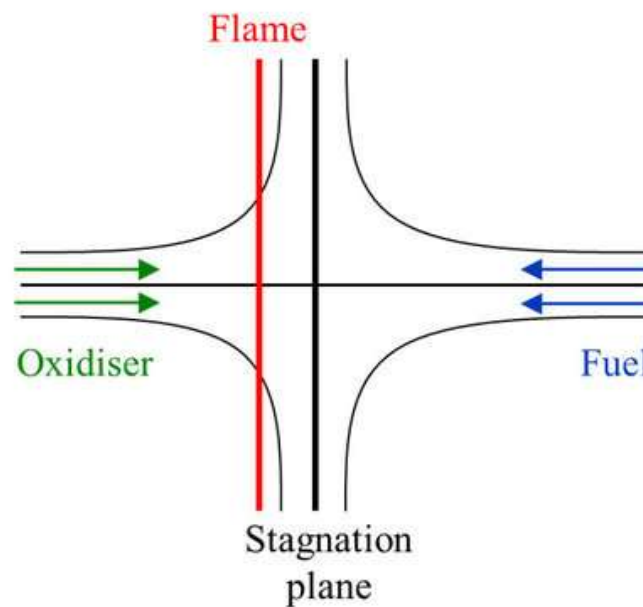
Non-Premixed Combustion / Diffusion Flames

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



Non-Premixed Combustion Counter-Flow Diffusion Flame

- Laminar flames are studied to and determine model parameters (strain rate, scalar dissipation rate) and to validate models
- Generally, industrial flames are highly turbulent but can quite often be predicted applying laminar flames models



E. Gorograptis



Real Applications (1)

Gas Turbines: Injection of liquid fuel (kerosene) in air (volumetric phenomenon):

Generally we have spray combustion, i.e. droplet vaporization, droplet drag; however depending on combustion chamber pressure we may have to consider transient trans-critical thermodynamics since kerosene is a mixture of various hydrocarbons.

Liquid Propellant Rocket Engines: Injection of liquid fuels (kerosene) or liquid oxidizers (volumetric phenomenon):

Generally we have spray combustion, i.e. droplet vaporization and combustion, droplet drag; quite often combustion chamber pressures are so high that transient trans-critical behavior has to be accounted for;

Solid Rocket Motors: Surface Phenomenon:

Quite often we have spray to consider metallic compounds, i.e. droplet melting, vaporization and combustion, droplet drag (agglomeration);

Hybrid Rocket Motors: Characteristics of liquid and solid rocket motors



Real Applications (2)

Gas Turbines:

While usually temperatures are such that cryogenic phenomena don't matter, there are issues with the required thrust variations, soot and Nox formation and quenching of chemical reactions,

A special problem are thermo-acoustic instabilities

Liquid Propellant Rocket Engines:

Quite often you have to deal with cryogenic propellants and extreme gradients in temperature, density and velocities; very high temperatures which require to consider dissociation and recombination effects;

A severe problem are combustion instabilities,

Solid Rocket Motors:

Typically very reliable but combustion stability and particle erosion are still a problem

Hybrid Rocket Motors: Characteristics of liquid and solid rocket motors



What you should not forget

- Energy Consumption in the Transportation Sector will still require combustion of fossil or renewable fuel in the foreseeable future
- Commonalities and Differences of Air-breathing and Rocket Engines
- Types of Jet Engines Propulsion Systems
- Types of Combustion Processes and their Importance in Technical Applications