Aalto University
School of Engineering

Lecture 6:
Laminar premixed flames

(related : Warnatz, Ch. 3, 5 & 8)

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Combustion Course, Spring 2018

1st April 2019, Otaniemi
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Me?

- M.Sc. at Aalto : engineering physics & mathematics
- Ph.D. graduation 2019 : supervisor Prof. Vuorinen
- Fields of research and interests:

  - Fluid dynamics
  - CFD
  - Combustion physics
  - Aerospace engineering
  - Numerical modeling

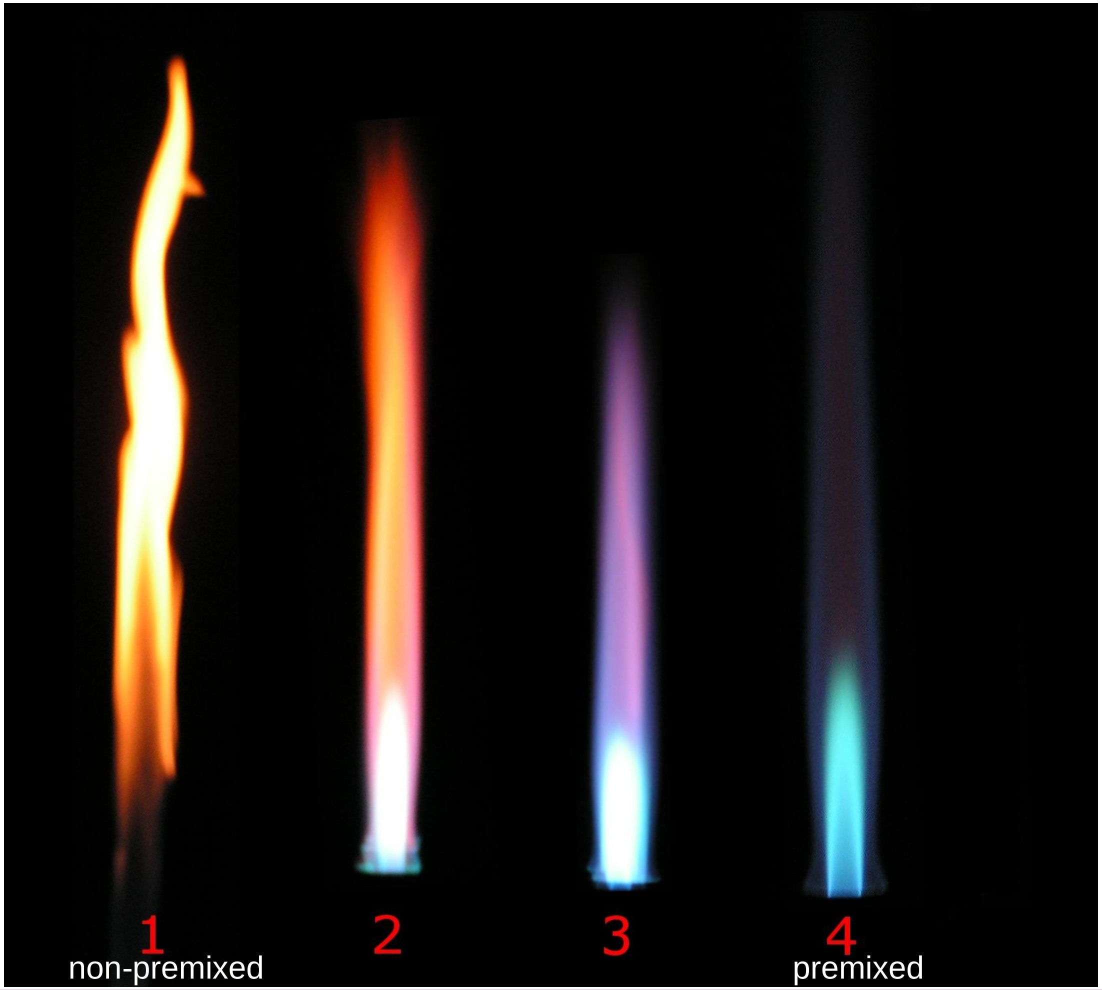
Upcoming Sessions

- Lecture 6: Laminar premixed flames
- Lecture 7: Details of laminar premixed flames
- Exercise 4 on theory and practice of laminar flame computations with complex chemistry
- My Course web interface for discussions and questions: https://mycourses.aalto.fi/

Flame – Where *fuel* and *oxygen* meet *heat* and *radicals*

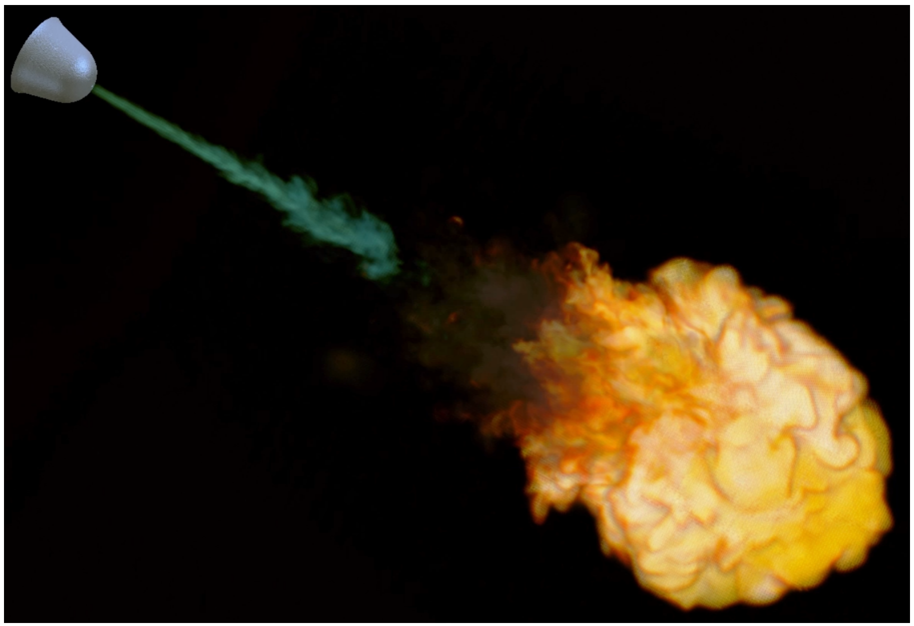
World of different flames

World of different flames

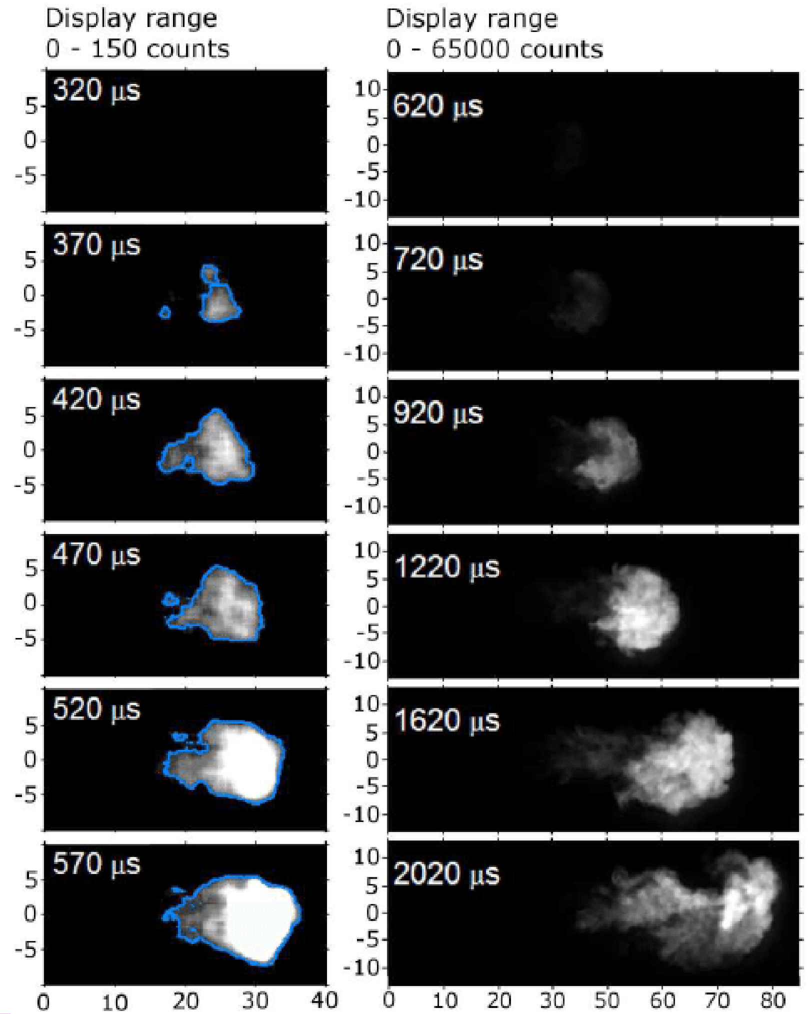


World of different flames

Flames in diesel engines

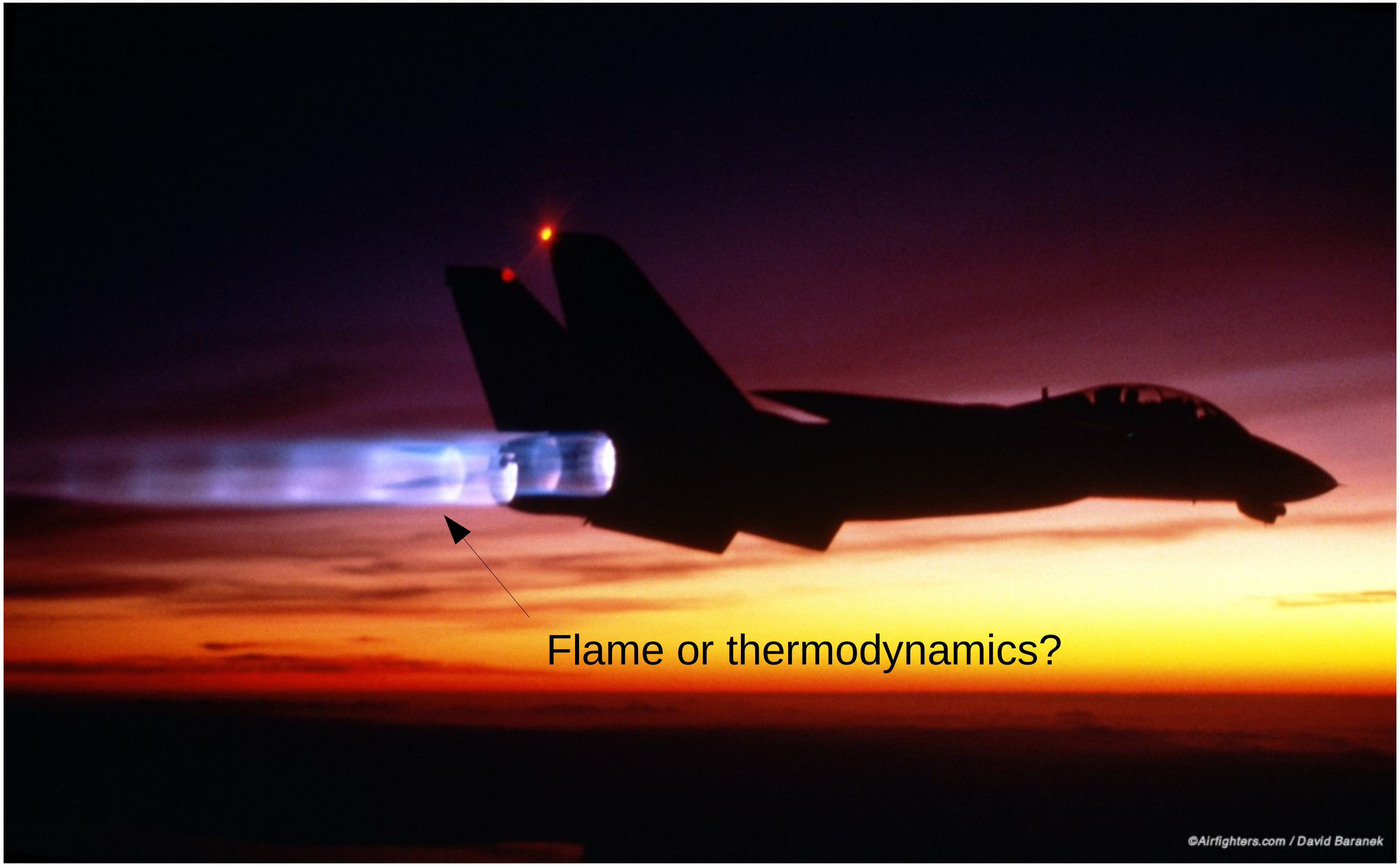


Wehrfritz et al., Comb. Flame 2016.



Bardi et al. 2012 Atomization and Sprays 22(10):807-842

World of different flames



https://s-media-cache-ak0.pinimg.com/originals/73/e2/84/73e2842d87505c77cffc8ad10f9dbc41.jpg

World of different flames

Different?

NASA: http://www.spd.org/2011/05/texas-monthly-dan-winters-disc.php

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World of different flames

https://commons.wikimedia.org/wiki/File:USAF_EOD_explosion.jpg

Some names in combustion science

Lavosier (1743-1794)

Bunsen (1811-1899)

Le Chatelier (1850-1936)

Chapman (1869-1958)

Jouguet (1871-1943)

Zel’dovich (1914-1987)

Landau (1908-1968)

Damköhler (1908-1944)

What is a flame?

- Understanding flames needs a definition for combustion
- Combustion:
  - a process of heat release in exothermal reactions
    - Chemical source
    - Thermonuclear source (fission, fusion)
    - Includes mass and heat transfer
  - Fuel can be solid, liquid or gaseous
    - solid rocket propellants
    - liquid droplets in diesel engines
    - gaseous combustion in burners and Otto engines

What is a flame?

- Typical features of a flame:
  - Visible
  - Colorful: red, yellow, blue, green (case dependent)
  - Appears as a propagating “combustion wave front“
  - Very thin
  - In certain cases (combustion) self-sustainable → hazardous
  - Includes often turbulent structures
- Flame is often something we see :
  - Excited specie are formed which emit light
  - Colors seem to depend on fuel and/or final species
  - Colors seem to depend on how much oxygen we have available
  - Unburned fuel and solid particles radiate strongly → bright flame in a fire

Definition of a flame

Typically a narrow region in space at which combustion takes place in it’s characteristic form

Categories of flames

Fuel/Oxidizer Mixing	Fluid Motion	Examples
premixed	turbulent	spark-ignited gasoline engine low NO_x stationary gas turbine
	laminar	flat flame Bunsen flame (followed by a nonpremixed candle for $\Phi > 1$)
nonpremixed	turbulent	pulverized coal combustion aircraft turbine Diesel engine H_2/O_2 rocket motor
	laminar	wood fire radiant burners for heating candle

Warnatz Table 1.2

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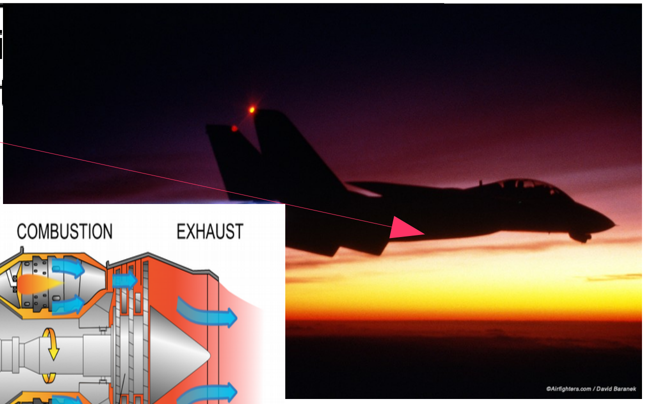
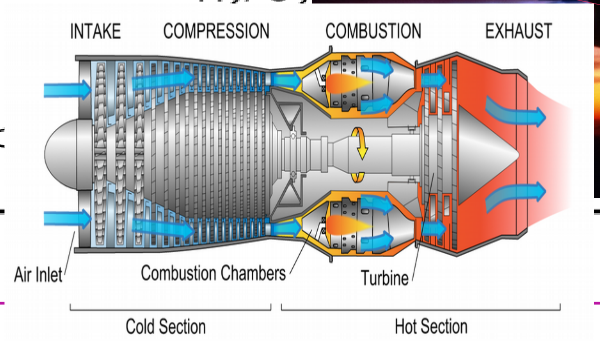
	laminar	





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Warnatz Table 1.2

Non-premixed flames

- Fuel and oxidizer separated → physical mixing and molecular diffusion needed
- Rate of combustion is governed by the rate of molecular diffusion (a.k.a diffusion flames)
- Fuel rich combustion → soot and particles
- Typically bright yellowish flames
  - High luminosity origins from soot radiation (black body)
  - BUT, non-premixed flame can be invisible (H2 combustion)
- Hot combustion temperatures → typically high Nox
- Non-premixed flames applied when safety and reliability are obligatory (aircraft engines, gas turbines, industrial furnaces etc.)

Premixed (PM) flames

- Reactants are perfectly premixed prior to ignition

  → all components necessary for the reaction are present in the fuel

  → to initiate reaction one has only to ignite the mixture

  → complete combustion

- Formation of a propagation front
  - Front separates unburned from fully burned
  - self-sustaining

- Targeted to lean conditions

  → complete combustion → “no” soot → no bright yellowish flame

  → Visibility depends on fuel: e.g. blue glow of the premixed bunsen flame originates from excited states of CH and C_2 (intermediate species in oxidization)

  → Lower combustion temperatures → lower Nox

- Applications : Gasoline and natural gas engines, modern gas turbines, explosions

From ignition to premixed flame

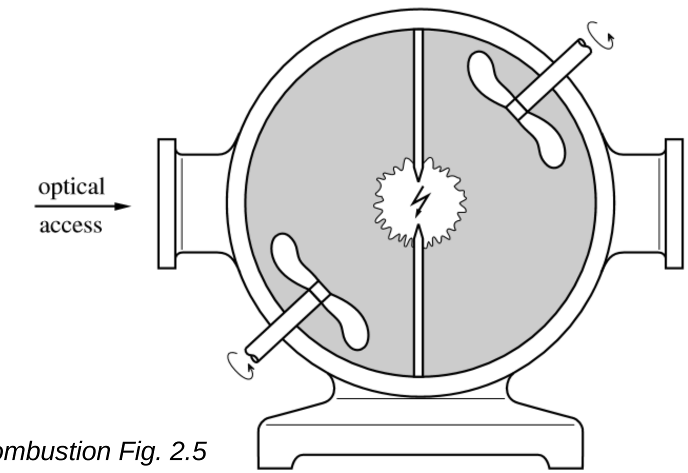
- Auto-ignition within flammability limits
  - $T > T_{crit}$ (temperature)
  - $\lambda_{low} < \lambda < \lambda_{high}$ (air-fuel equivalence ratio)
  - T_{crit} is fuel, mixture and pressure dependent
  - reaction rate ~ exp(T) (Try out with Cantera)
  - Thermal stratification → non-uniform ignition

- External energy source
  - Light a gas stove by a matchstick
  - Electric spark : Gasoline engines and gas grill at summer cottage

From ignition to premixed flame

https://www.youtube.com/watch?v=IwjiVdk_msA

https://www.youtube.com/watch?v=xg3Ri1-1rCE



Peters. N. Turbulent combustion Fig. 2.5

Laminar premixed flames

- **Why to study laminar flames?**

  - "*The test of all knowledge is experiment. Experiment is the sole judge of scientific "truth"*". (Feynman)

    The most detailed experiments are in laminar conditions

  - Observations from laminar flames give the basis for the principles in combustion physics

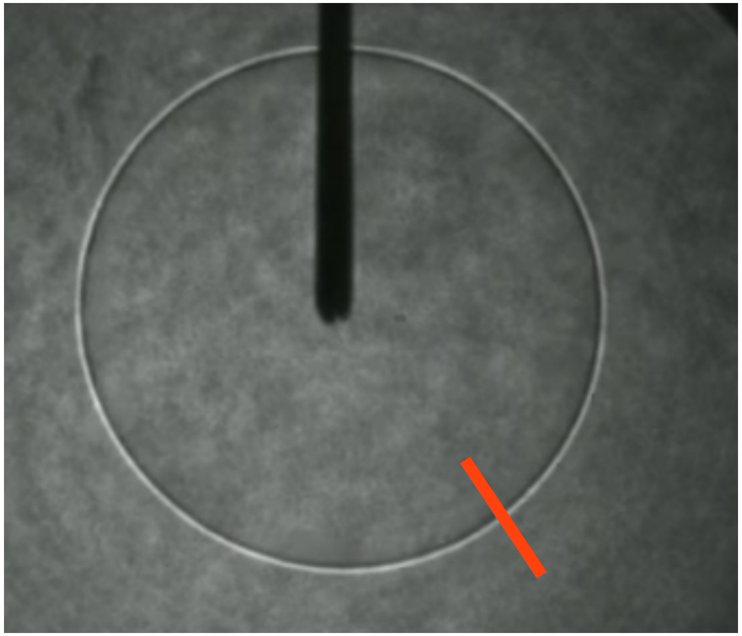
  - Often theoretical approaches, derived for laminar flames, extend to turbulent cases

  - Chemical mechanism validation

  - Turbulent flame can be interpreted to assemble from many pieces of laminar flames (flamelets)

Lecture exercise

- Sketch profiles along the line for
  T, ρ, velocity, O2, fuel, CH

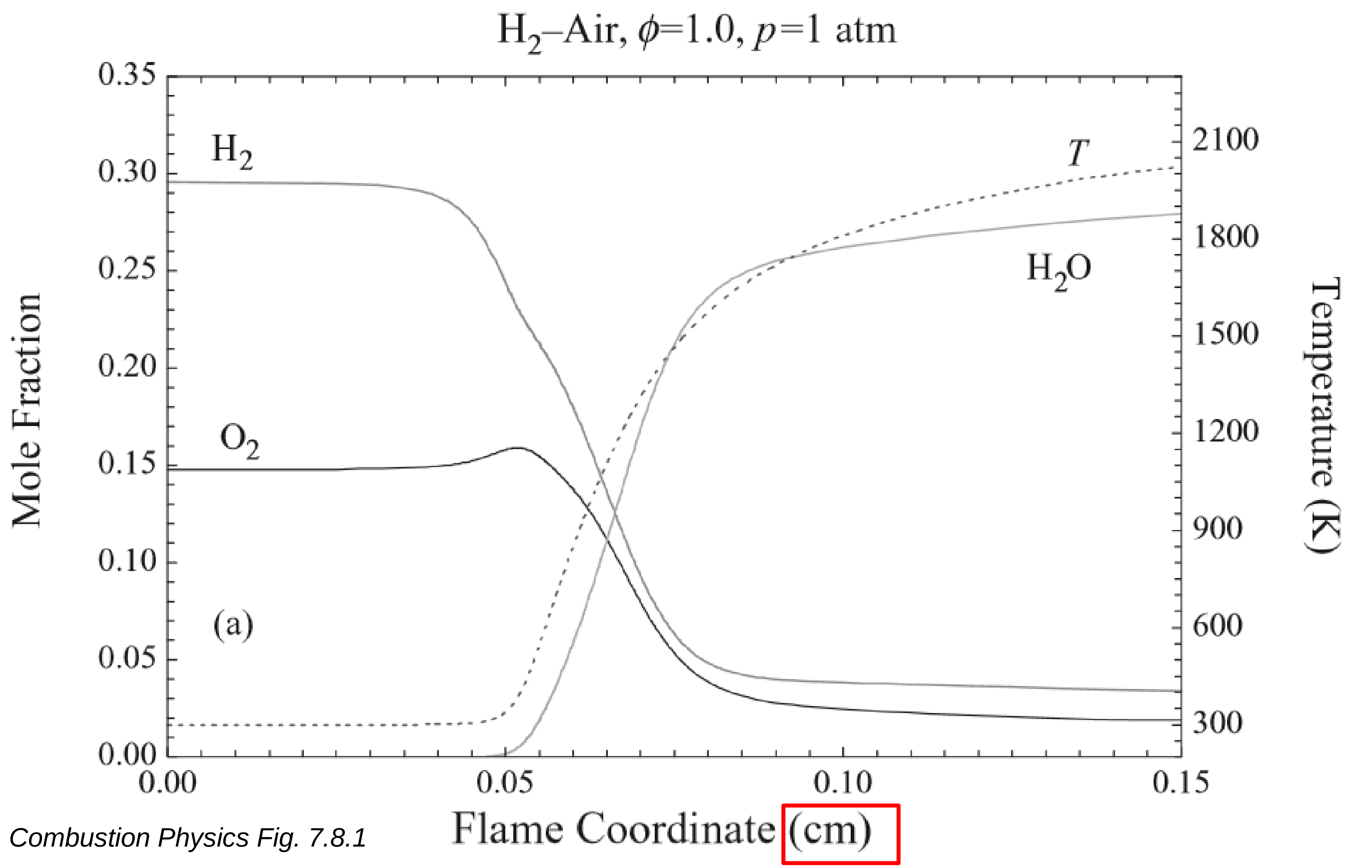


https://www.youtube.com/watch?v=IwjiVdk_msA

https://upload.wikimedia.org/wikipedia/commons/e/e3/Blow_Torch_(3257353199).jpg

Chemical structure of PM flames

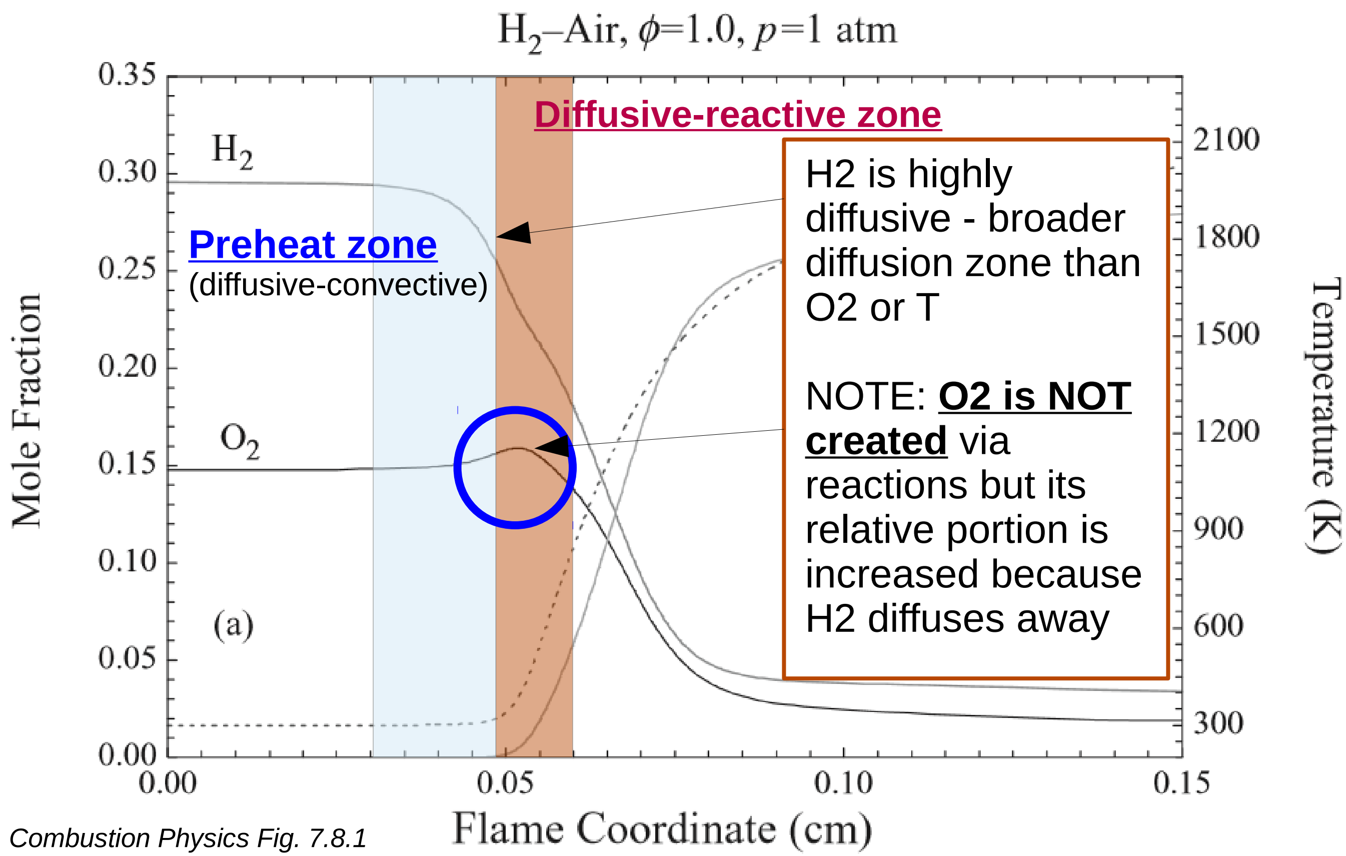
- Stoichiometric hydrogen flame



C. K. Law. Combustion Physics Fig. 7.8.1

Chemical structure of PM flames

- Stoichiometric hydrogen flame



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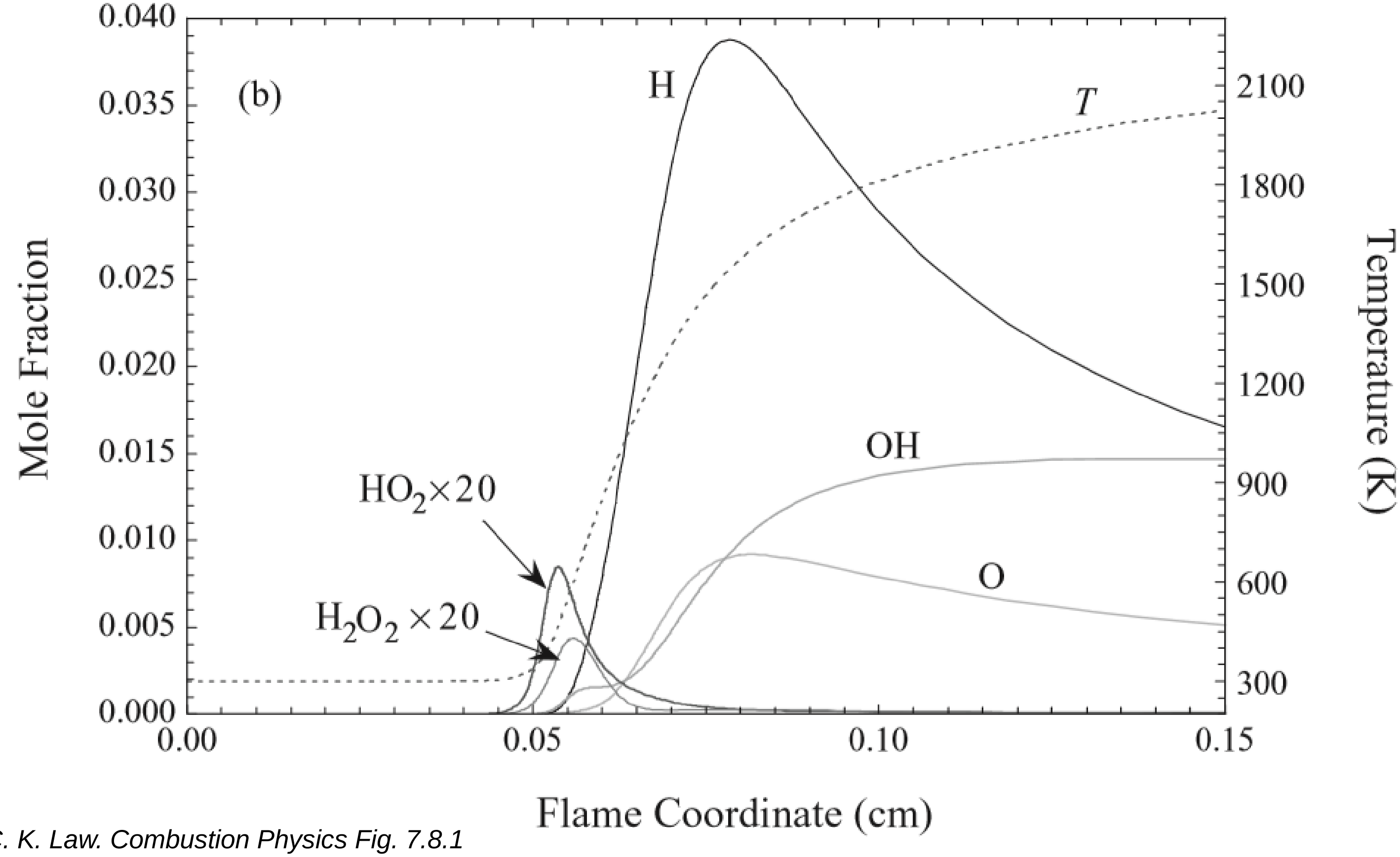

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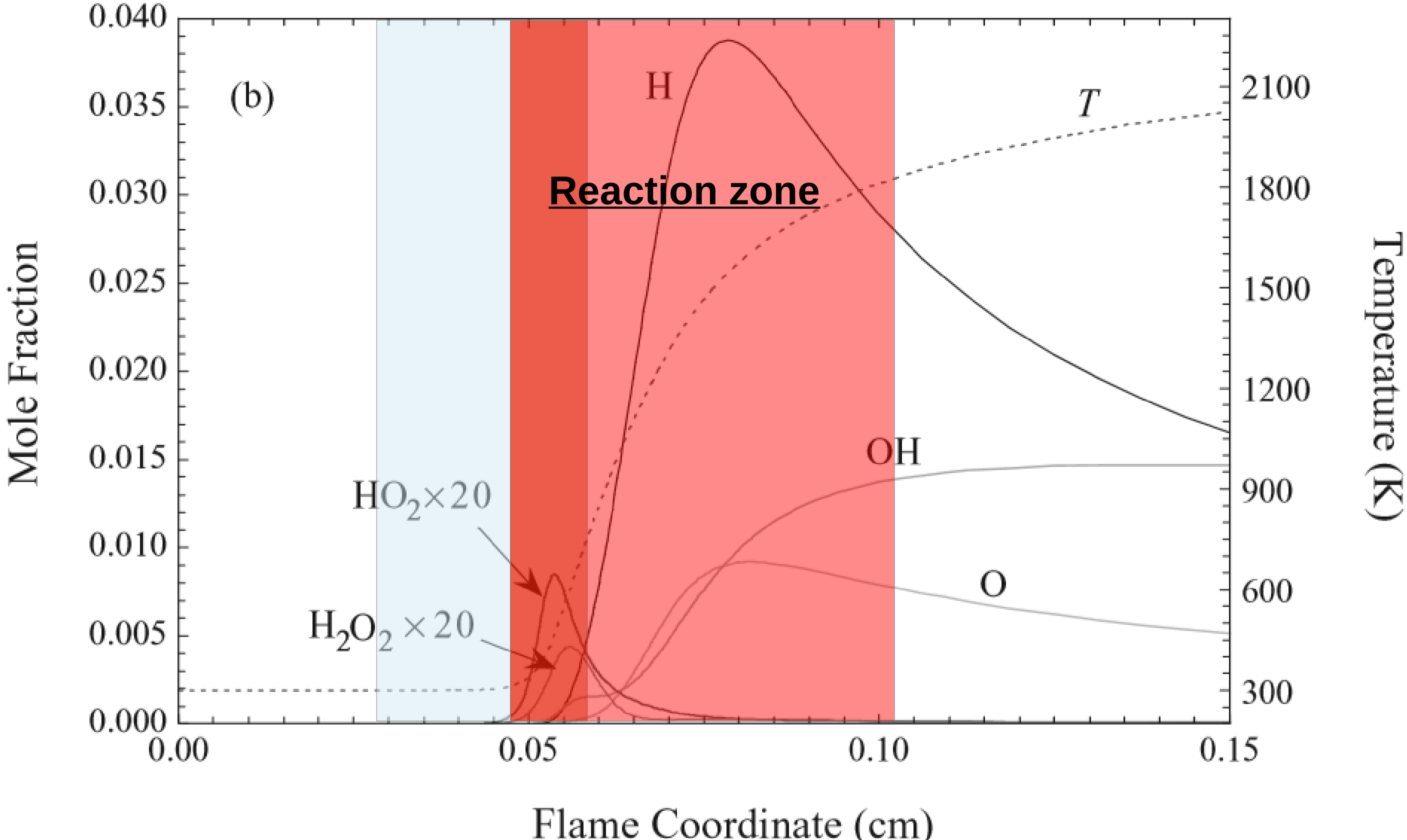

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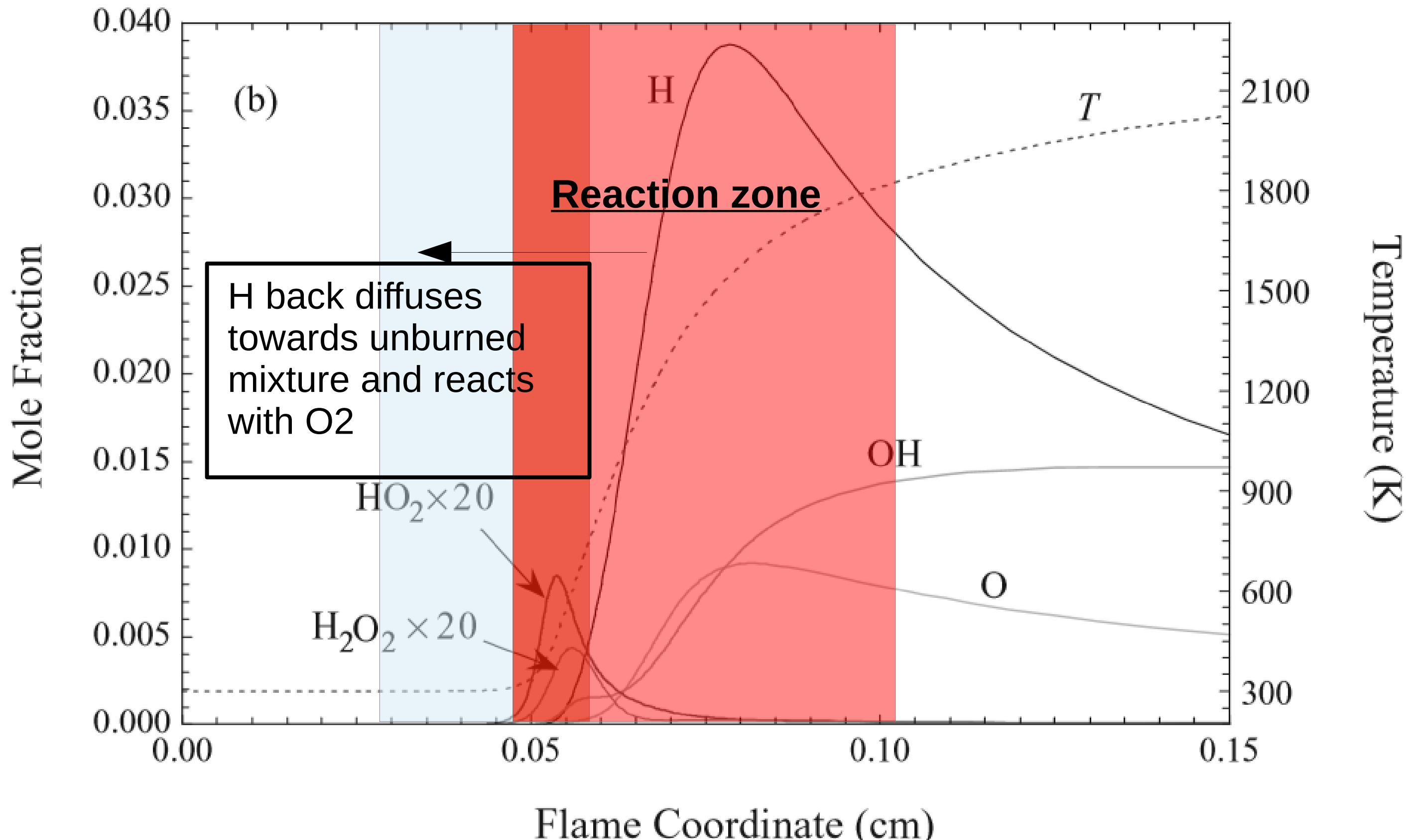
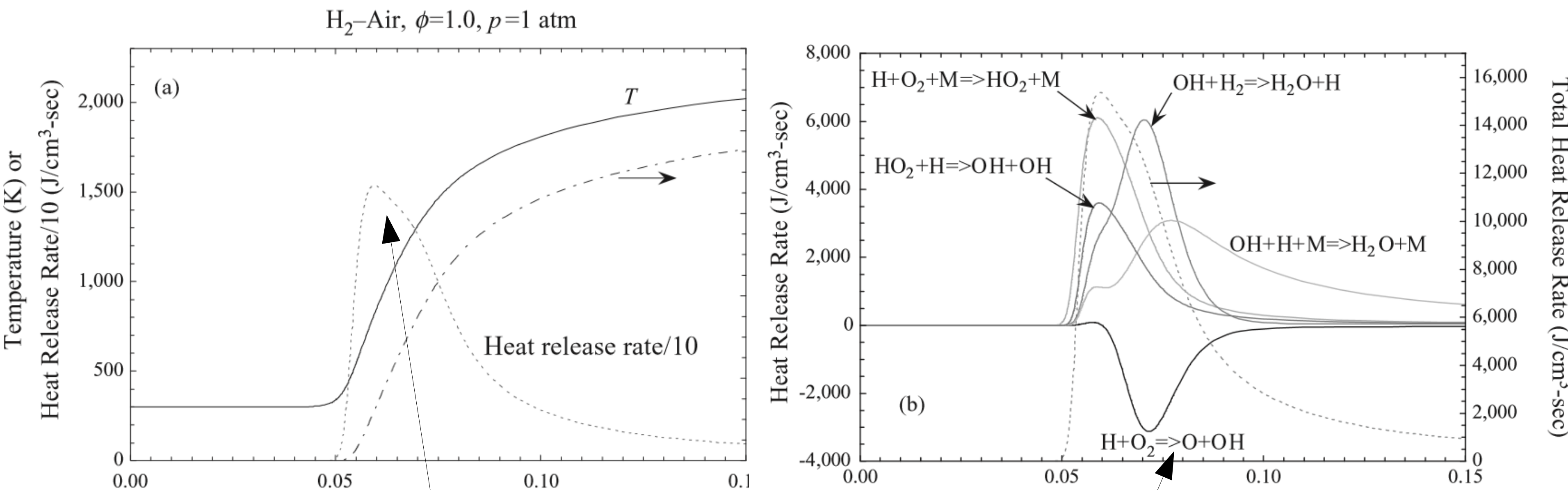


C. K. Law. Combustion Physics Fig. 7.8.1

Chemical structure of PM flames

- Heat release in stoichiometric hydrogen flame



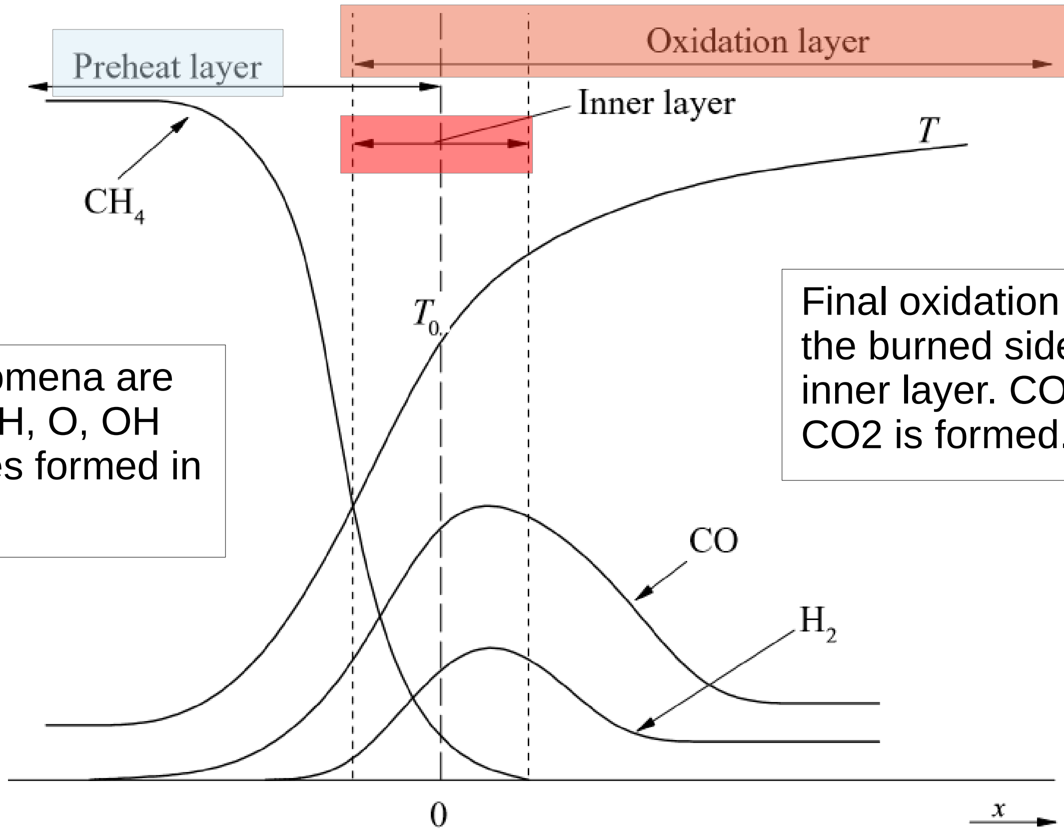
-Maximum heat release rate (HRR) at low T~800K

-HRR depends on reactions: can be even endothermic

C. K. Law. Combustion Physics Fig. 7.8.2-3

Chemical structure of PM flames

Example of **methane** flame structure and terminology



Diffusion phenomena are still important : H, O, OH etc. light species formed in the inner layer

Final oxidation takes place on the burned side of the reactive inner layer. CO decreases and CO2 is formed.

C. K. Law. Combustion Physics Fig. 7.8.7

Chemical structure of PM flames

- Important notes:

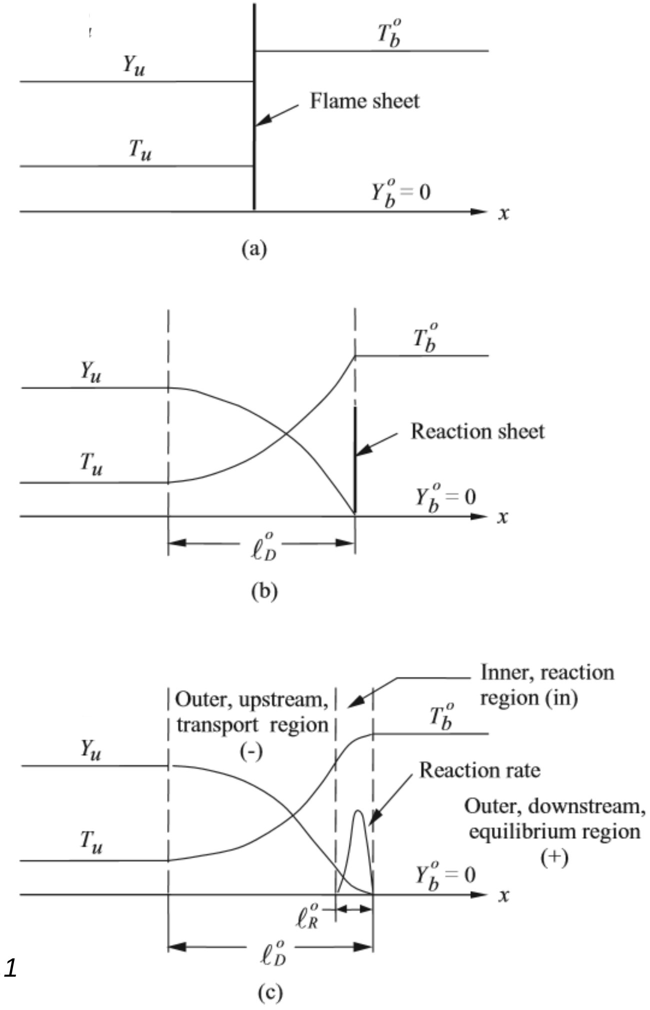
  - PM Flame has a finite thickness
  - Mass and heat diffusion are very important
  - Radicals and intermediate species can diffuse and initiate otherwise non-active reactions
  - Reactions take place throughout the flame thickness
  - Max heat release takes place at low T

Three levels of detail

- Flame sheet
  - Discontinuity
  - Conservation of mass and energy
  - Rankine-Hugoniot
  - Analytical analysis + combustion models

- Reaction sheet level
  - Includes the preheat zone
  - Finite thickness
  - Discontinuous reaction sheet
  - Analytical analysis + combustion models

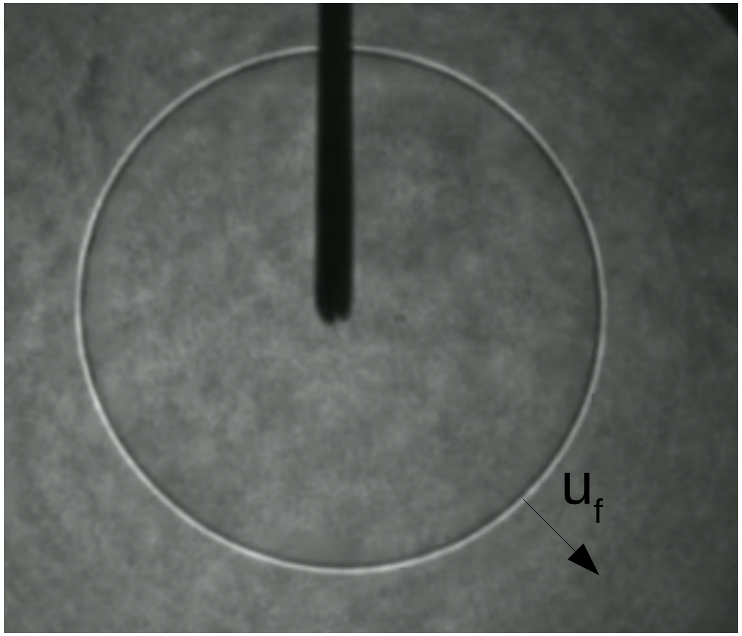
- Complete structure
  - Fundamental understanding
  - Combustion models



C. K. Law. Combustion Physics Fig. 7.2.1

Laminar flame propagation

- Propagating flame front is an intrinsic feature of PM flames
- What influences to the propagation velocity ?
- How can we estimate this **"laminar flame speed" ?**



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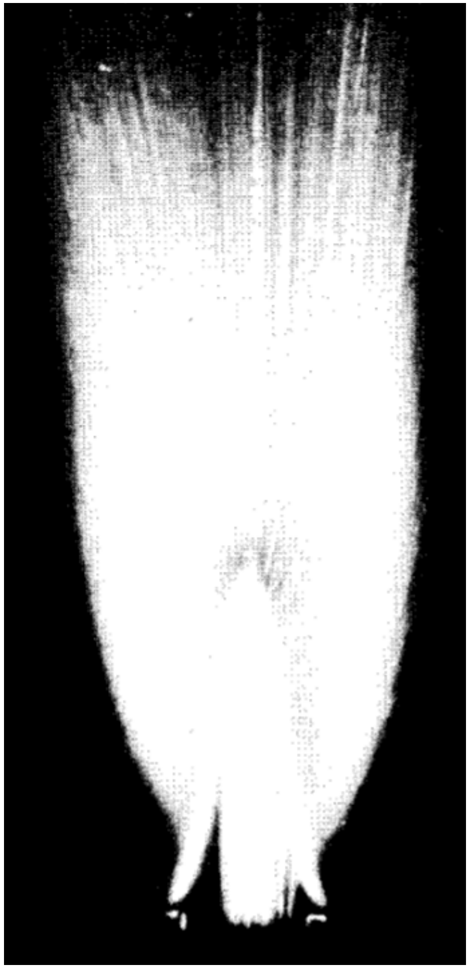
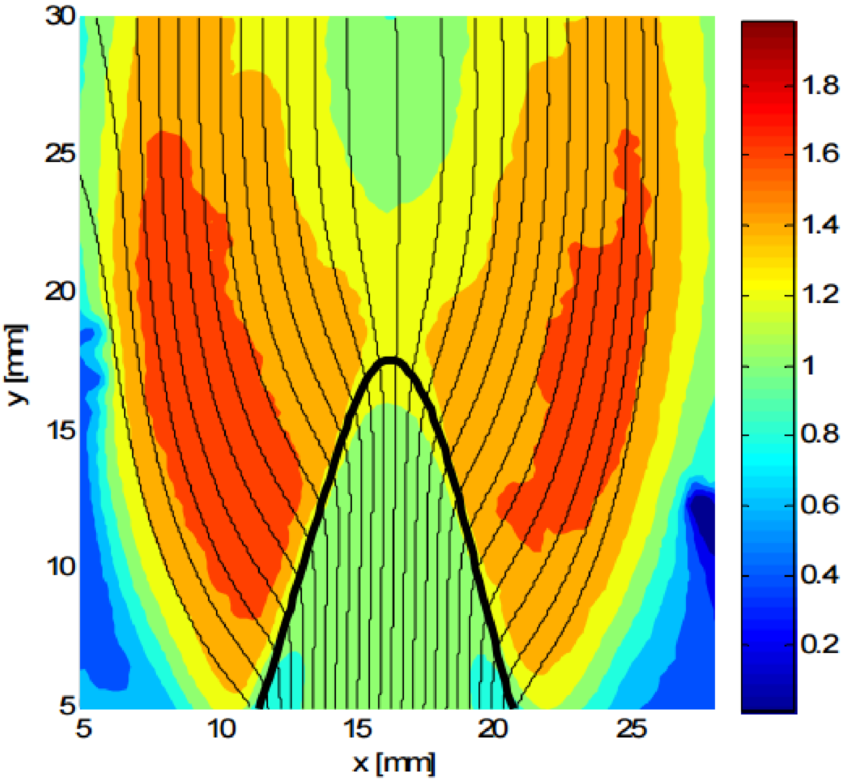
Laminar flame propagation



Williams. Combustion Theory Fig. 5.2



Kurtulus et al. : Characterisation of Lean Premixed Laminar Flames in High Pressure using PIV.

Upcoming Session

- Deflagration vs. detonation
- Reacting conservation equations
- Expressions for laminar flame speed
- Turbulent flame speed correlations
- Expressions for flame thickness
- Details of mass diffusion
- Sensitivity of flames to ambient conditions