RUTGERS–NEW BRUNSWICK
School of Engineering

Combustion Experiments in Microgravity

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Committee on Biological and Physical Sciences in Space
National Academies, Space Studies Board
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My microgravity combustion background (35 years)

- Undergrad: Flame balls (Prof. Paul Ronney, Princeton)
- Grad: Smoldering combustion (Prof. A. Carlos Fernandez-Pello, U.C. Berkeley)
- Post-doc: Spherical diffusion flames (Prof. C.K. Law, Princeton)
- Professor: ISS ACME spherical diffusion flames

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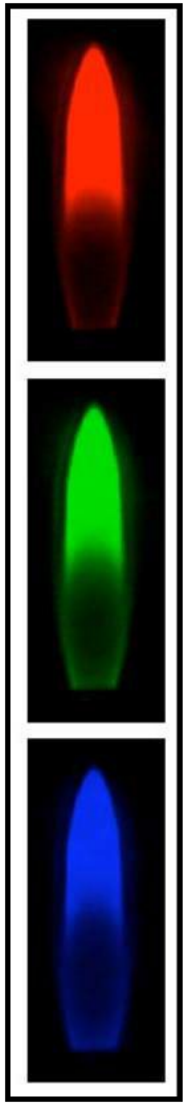
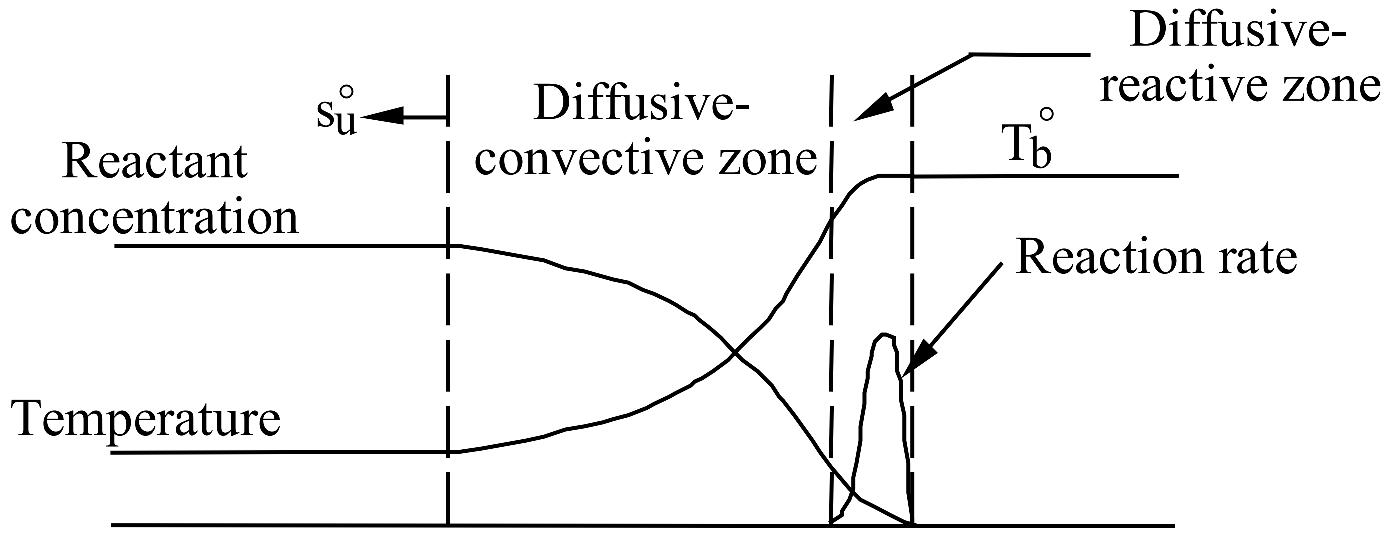
Why Study Combustion?

- **Energy**
  - While we might associate fire with the Stone Age, we still make extensive use of combustion in our daily lives.
    - Electricity – about 70% in the U.S. from combustion
    - Heating of buildings, water, food, and in manufacturing processes
    - Transportation, propulsion (rocket & air-breathing)
  - Our reliance on imported fuel contributes to our national trade deficit and affects our national security.
- **Environment**
  - Combustion is a major source of greenhouse gases.
  - Soot contributes to global warming and is a health problem.
- **Fire Safety**
  - Materials flammability, smoldering with transition to flaming, gaseous explosions
- **Materials Synthesis**
  - Carbon black, carbon nanotubes, graphene



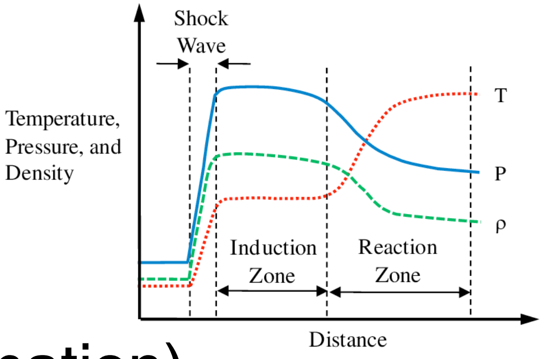
Given its pervasive use ***with annual U.S. fuel costs on the order of a trillion dollars*** **even small improvements in combustion technology can significantly reduce fuel needs and pollution production!**

Laminar Premixed Flame (deflagration)



Flame structure

- Laminar flame speed embodies the basic diffusive and reactive information about the combustible
- Validation of reaction mechanisms
- Flammability limits (lean & rich)
- Dual nature for same mixture (deflagration v. detonation)



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Centrally-Ignited Premixed Flame

H_2/Air, 1atm, $\phi = 4.00$
(high-speed schlieren)

Chemical Kinetic Mechanisms

Table I H_2/O_2 Reaction Mechanism. Units Are cm^3-mole-sec-kcal-K; $k = AT^n \exp(-E_a/RT)$

	ΔH°_{298}		A	n	E_a	Reference
H_2/O_2 Chain Reactions						
1. $H + O_2 = O + OH$	16.77		1.91×10^{14}	0.00	16.44	Pirraglia et al. [25]
2. $O + H_2 = H + OH$	1.85		5.08×10^{4}	2.67	6.29	Sutherland et al [55]
3. $H_2 + OH = H_2O + H$	−15.01		2.16×10^{8}	1.51	3.43	Michael et al. [56]
4. $O + H_2O = OH + OH$	16.88		2.97×10^{6}	2.02	13.4	Sutherland et al. [57]
H_2/O_2 Dissociation/Recombination Reactions						
5. $H_2 + M = H + H + M^a$	104.2		4.58×10^{19}	−1.40	104.38	Tsang et al. [39]
$H_2 + Ar = H + H + Ar$	104.2		5.84×10^{18}	−1.10	104.38	Tsang et al. [39]
6. $O + O + M = O_2 + M^a$	−119.1		6.16×10^{15}	−0.50	0.00	Tsang et al. [39]
$O + O + Ar = O_2 + Ar$	−119.1		1.89×10^{13}	0.00	−1.79	Tsang et al. [39]
7. $O + H + M = OH + M^a$	−102.3		4.71×10^{18}	−1.0	0.00	Tsang et al. [39]
8. $H + OH + M = H_2O + M^a$	−119.2		2.21×10^{22}	−2.00	0.00	Tsang et al. [39]
$H + OH + Ar = H_2O + Ar$	−119.2		8.41×10^{21}	−2.00	0.00	Tsang et al. [39]
Formation and Consumption of HO_2						
9. $H + O_2 + M = HO_2 + M^a$	−49.1	k_O	3.5×10^{16}	−0.41	−1.12	Mueller et al. [9]
$H + O_2 + Ar = HO_2 + Ar$	−49.1	k_O	1.5×10^{15}	0.00	−1.00	Baulch et al. [60]
$H + O_2 = HO_2^c$		k_∞	1.48×10^{12}	0.60	0.00	Cobos et al. [22]
10. $HO_2 + H = H_2 + O_2$	55.1		1.66×10^{13}	0.00	0.82	see text
11. $HO_2 + H = OH + OH$	−36.47		7.08×10^{13}	0.00	0.30	see text
12. $HO_2 + O = OH + O_2$	−52.23		3.25×10^{13}	0.00	0.00	Baulch et al. [30]
13. $HO_2 + OH = H_2O + O_2$	−70.11		2.89×10^{13}	0.00	−0.50	Baulch et al. [30]
Formation and Consumption of H_2O_2						
14. $HO_2 + HO_2 = H_2O_2 + O_2^b$	−38.53		4.20×10^{14}	0.00	11.98	Hippler et al. [40]
$HO_2 + HO_2 = H_2O_2 + O_2^b$			1.30×10^{11}	0.00	−1.63	
15. $H_2O_2 + M = OH + OH + M^a$	−51.14	k_O	1.20×10^{17}	0.00	45.5	Warnatz [58]
$H_2O_2 + Ar = OH + OH + Ar$	−51.14	k_O	1.90×10^{16}	0.00	43.0	Brouwer et al. [59]
$H_2O_2 = OH + OH^c$		k_∞	2.95×10^{14}	0.00	48.4	Brouwer et al. [59]
16. $H_2O_2 + H = H_2O + OH$	−68.05		2.41×10^{13}	0.00	3.97	Tsang et al. [39]
17. $H_2O_2 + H = H_2 + HO_2$	−16.57		4.82×10^{13}	0.00	7.95	Tsang et al. [39]
18. $H_2O_2 + O = OH + HO_2$	−14.70		9.55×10^{6}	2.00	3.97	Tsang et al. [39]
19. $H_2O_2 + OH = H_2O + HO_2^b$	−31.58		1.00×10^{12}	0.00	0.00	Hippler et al. [34]
$H_2O_2 + OH = H_2O + HO_2^b$			5.8×10^{14}	0.00	9.56	

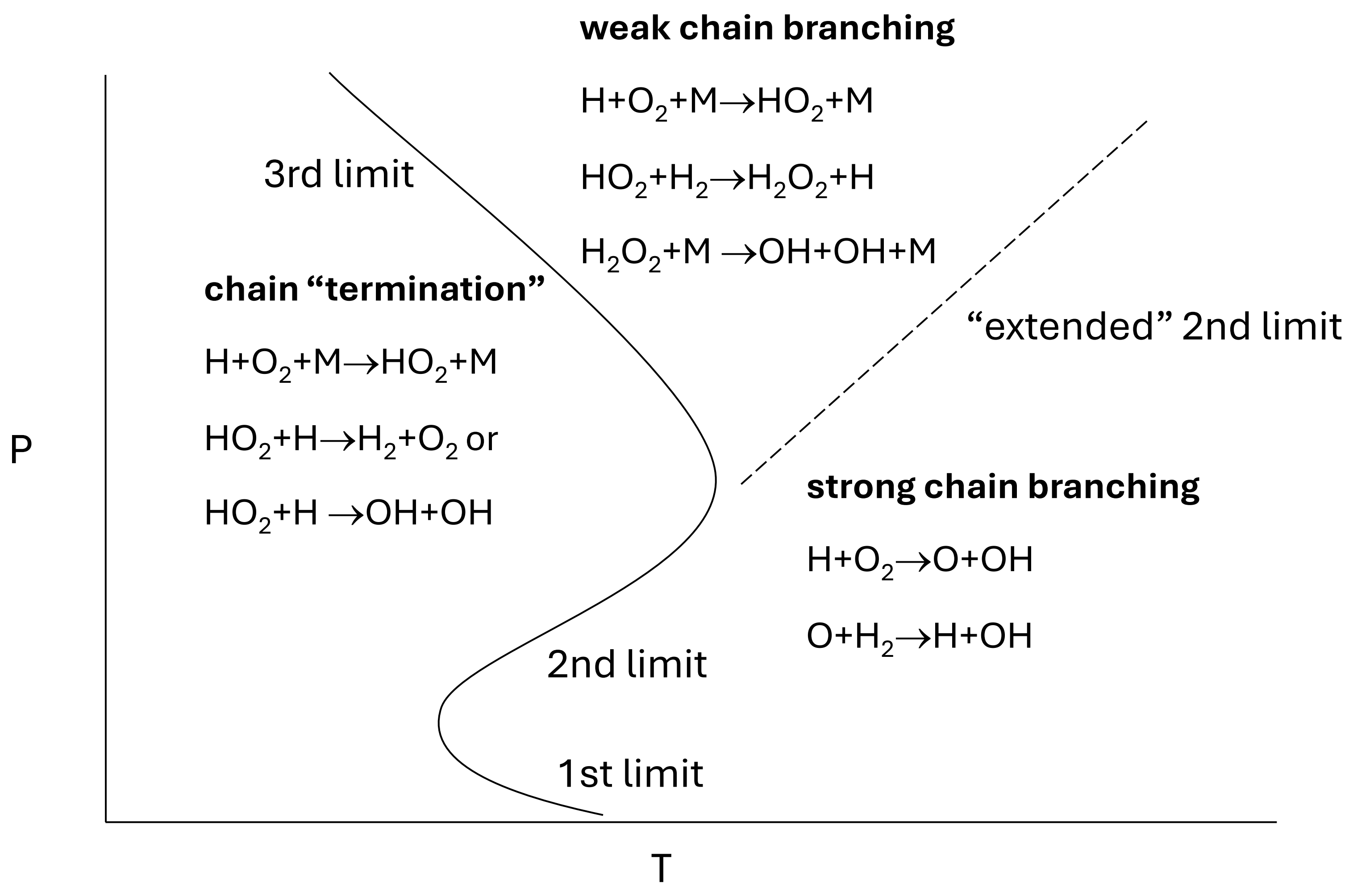
[a] Efficiency factors for the collision partners of this pressure dependent reaction are: $\epsilon_{H_2O} = 12.0$; $\epsilon_{H_2} = 2.5$; and $\epsilon_{Ar} = 0.75$. All other species have efficiencies equal to unity. When a rate constant is declared specifically for an Argon collision partner, the efficiency of Argon is set to zero when determining M for the same reaction.

[b] Reactions 14 and 19 are expressed as the sum of the two rate expressions.

[c] Reaction 9 is given as a true fit with $F_c^{N_2} = 0.5$ and $F_c^{Ar} = 0.45$. Reaction 15 is given as a true fit with $F_c = 0.5$.

Mueller, M.A., Kim, T.J., Yetter, R.A., and Dryer, F.L., *Int. J. Chem. Kinet.* 31:113-125 (1999)

Hydrogen/Oxygen Explosion Limits



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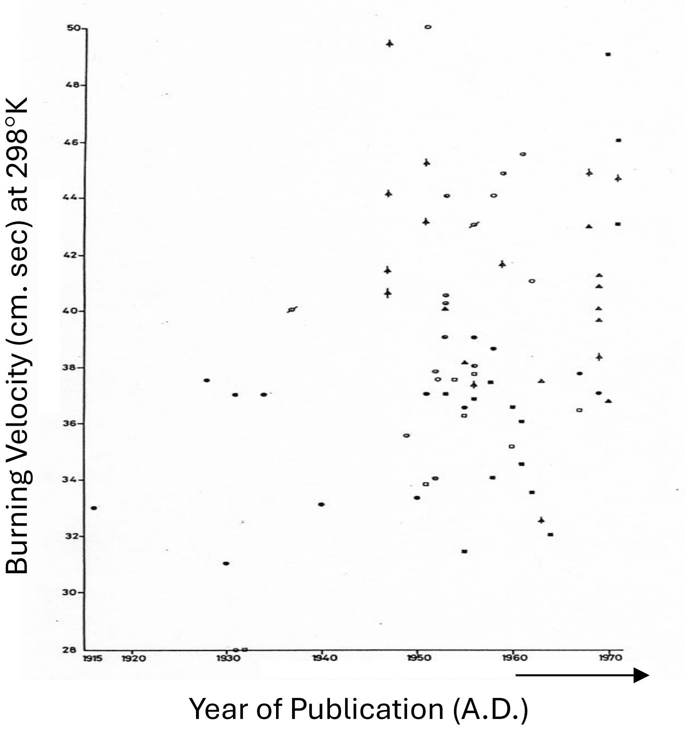
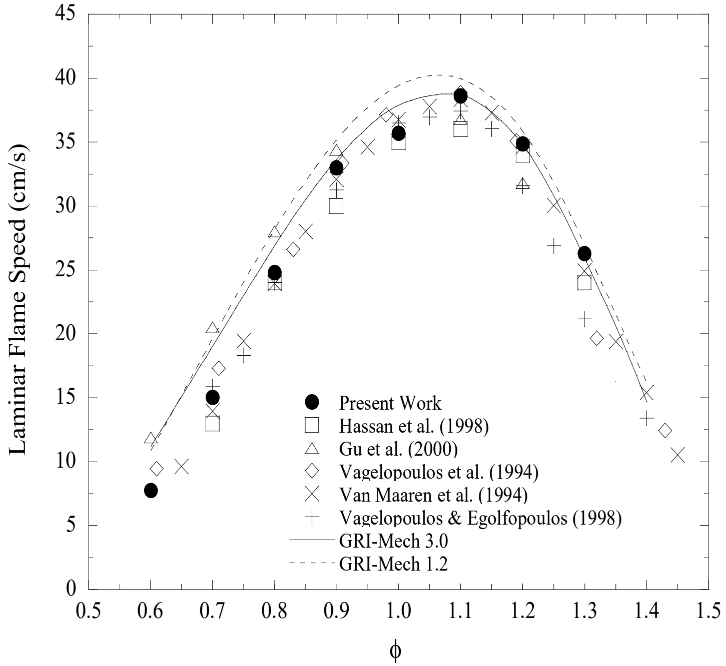
Importance of Data Fidelity: Methane-Air Flame Speeds





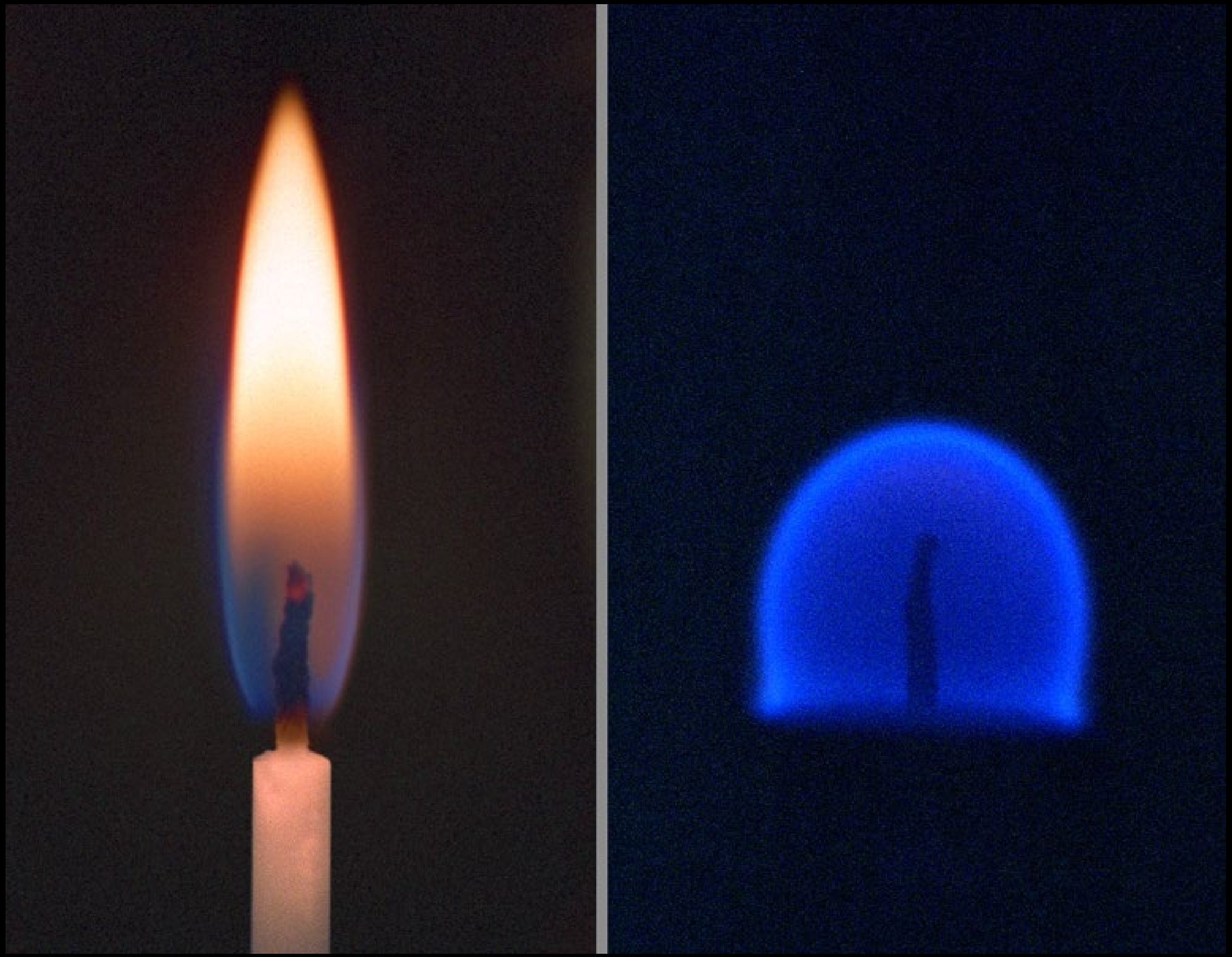
ϕ=1 data by 1970s;

Stretch contaminated

1 atm data after 1980s;

Stretch effect eliminated

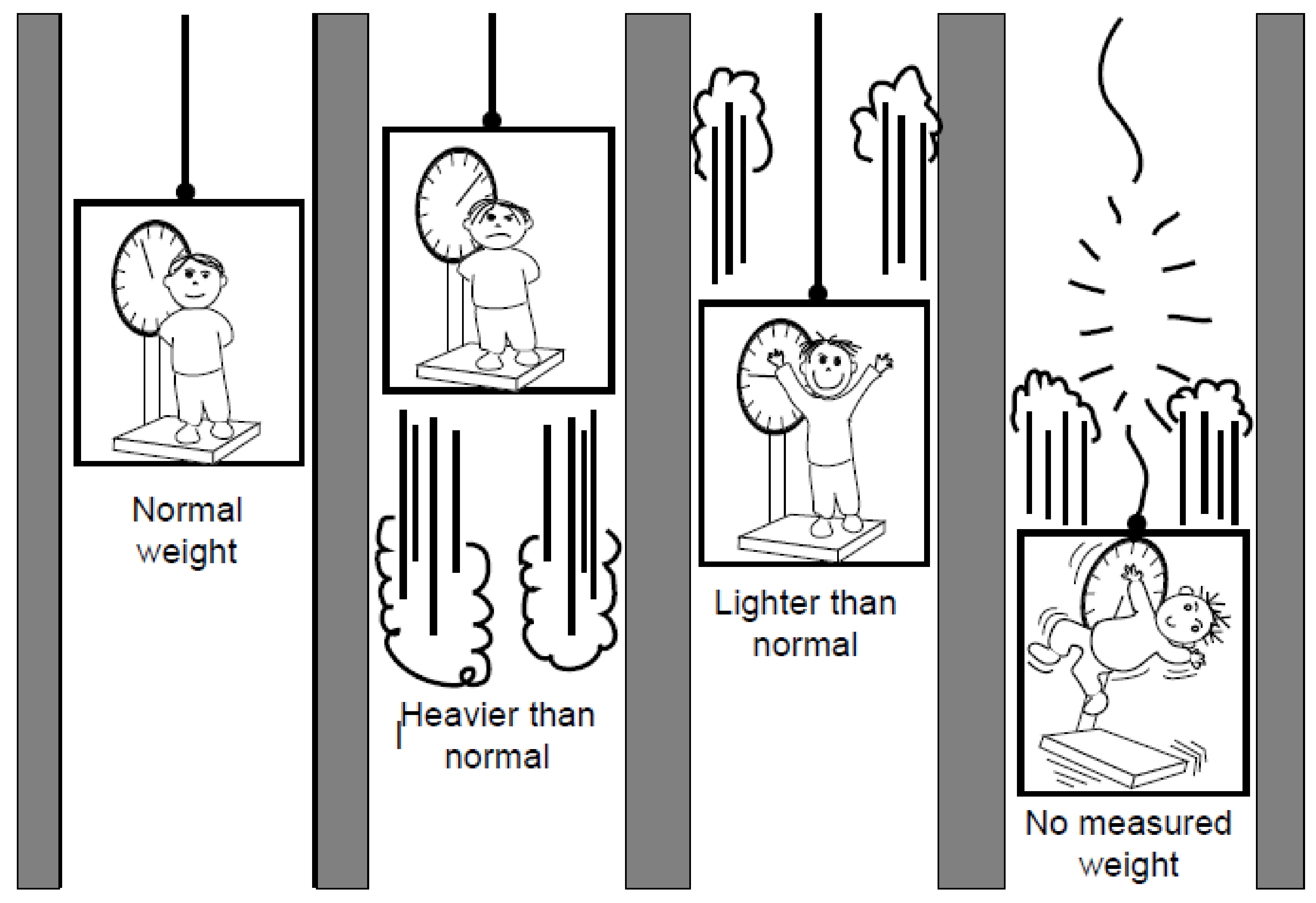
Combustion and Buoyancy (shape & chemistry)



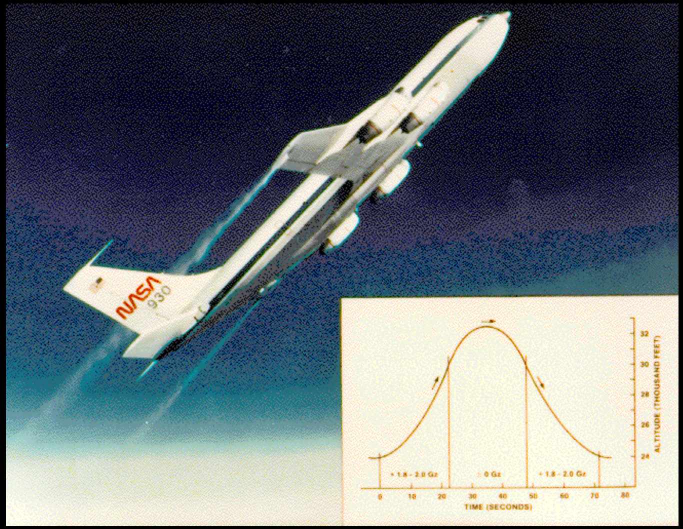
- Combustion of solids, liquids, droplets, gases
- Soot (incandescence)
- Spacecraft fire safety
- Supercritical reacting fluids

- Non-premixed

How to Achieve Microgravity?

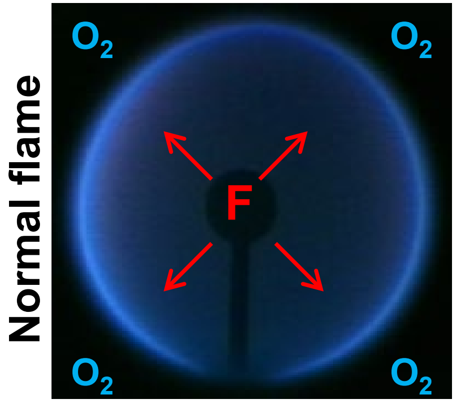


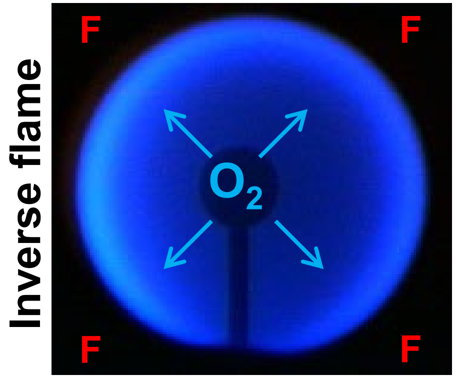
Microgravity Facilities



Gaseous Laminar Diffusion Flames

- **Gaseous**
  - fuel is a gas, e.g., methane, ethylene
- **Laminar**
  - flow is smooth and not turbulent
    - i.e., without swirling vortices
- **Diffusion, i.e., non-premixed**
  - fuel and oxidizer (e.g., air) are on opposite sides of the reaction sheet
    - where they meet, react, and emit products
      - including heat and light





Merits of One-Dimensional Flames for Fundamental Studies

- Flame structure fundamentally affected by aerodynamics.
- Simple flow and flame configuration facilitate experimentation, computation, analysis, and comparison, with enhanced accuracy and reliability.
- Reduced effort in describing flows allows more detailed study of other aspects of flames such as chemistry.
- A one-dimensional flame is the simplest possible configuration.

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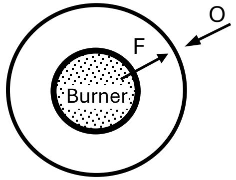
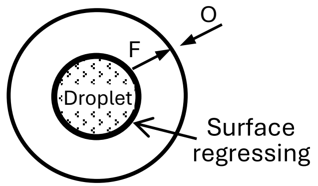
Merits of Burner-Generated Spherical Diffusion Flames

- Only spherical (vs. planar and cylindrical) configuration admits steady-state 1D behavior in semi-infinite domain.
- Spherically symmetric droplet combustion complicated by transient effects due to droplet heating and surface regression. Kinetics of large HC fuels also less well established.
- Burner generation assures steady-state surface boundary conditions.

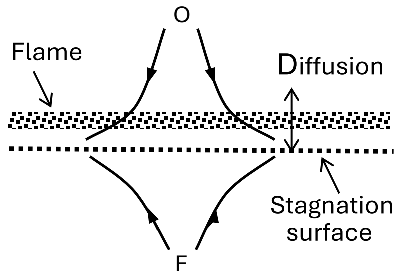


Spherical Burner Flame



Droplet Flame

- Planar flame in counterflow is not 1D in terms of diffusion-convection as well as radiation misalignment.



Counterflow Flame

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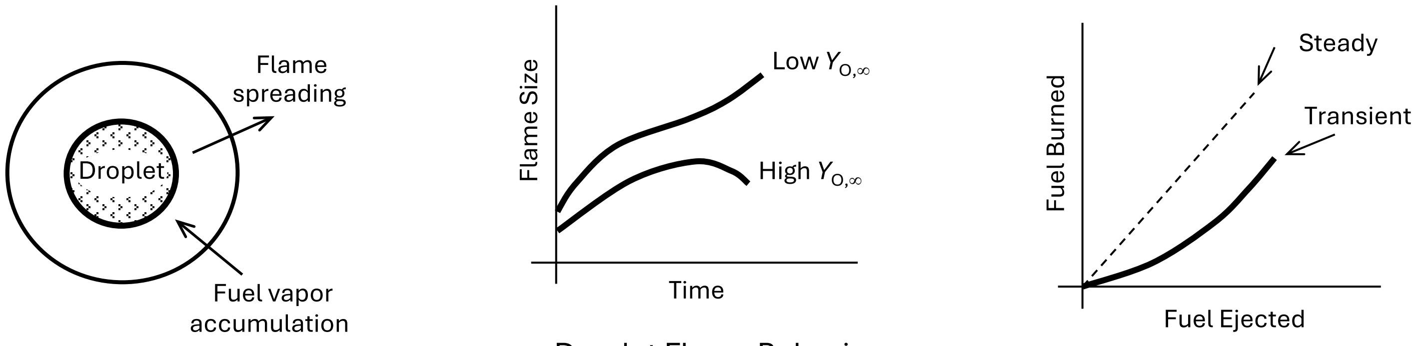
Spreading of Diffusion Flame Sheets: Phenomenology

- Steady-state assumption ignores initial conditions (**transient effects**).
- An important process is fuel accumulation, i.e. scalar profile buildup, leading to spreading of the flame sheet from the fuel source.
- Relevant for all non-planar processes!



Droplet Flame Behavior

- Previous observation of droplet flame complicated by far field diffusion and surface regression.
- Insensitive to chemistry, allows focus on diffusion.
- Coupling to density and hence temperature fields allows assessment of radiation effects.

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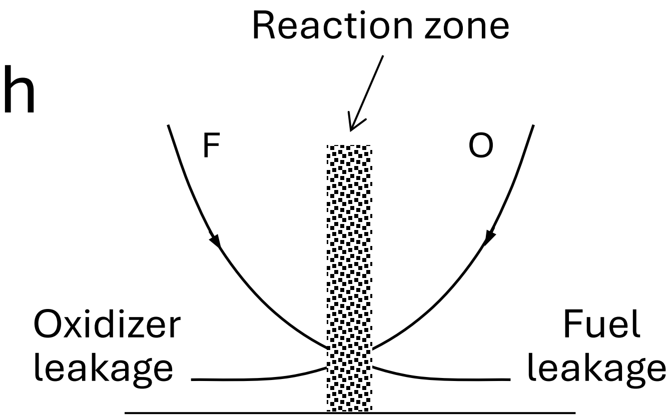
Flame Extinction: Phenomenology

- Unlike premixed flames, reactant leakage is the root cause of diffusion flame extinction.
- For thin reaction zones, effects of other loss processes (radiation, diffusional stratification, unsteadiness, multi-dimensional)

can all be folded into reactant leakage through flame temperature reduction.

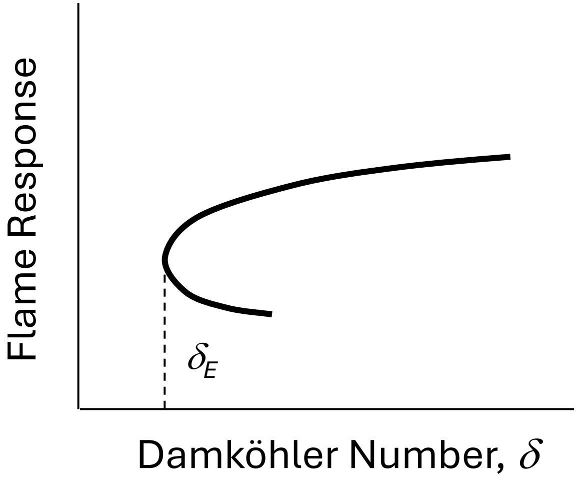


Flame Extinction: Phenomenology

- Consequently practically all diffusion flame extinction phenomena have been found to be described by Lĩnán's canonical extinction criterion:

$$\delta < \delta_E$$

where δ is (Linán's) flame Damköhler number and
$\delta_E \sim e(1-|\gamma|)$,
$\gamma = \gamma$(freestream energy parameters).



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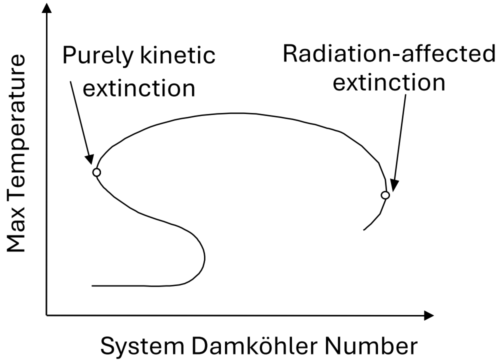
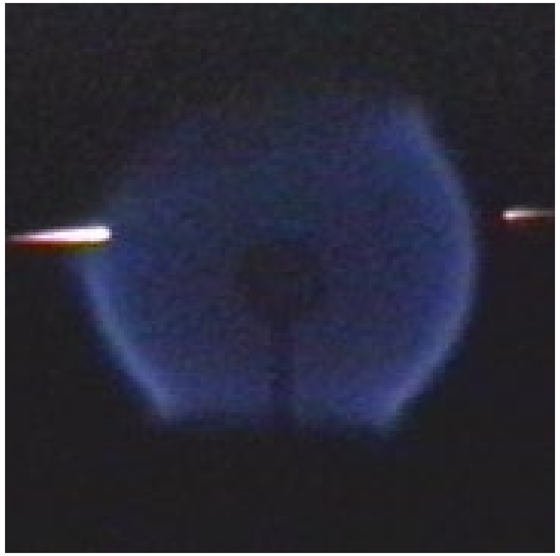
Flame Extinction: Phenomenology

- Flame can extinguish at both small & large Damköhler numbers
- Kinetically limited extinction occurs for small Da.
- Increasing Da implies longer residence time or large system dimension, leading to increased radiation loss, reduced flame temperature, and eventually extinction through excessive leakage



- Liñán’s extinction criterion applies at both limits
- Dual extinction observed in μg droplet burning (?)
- Present experiment further facilitates interpretation (*e.g.* no droplet heating, simpler fuels)



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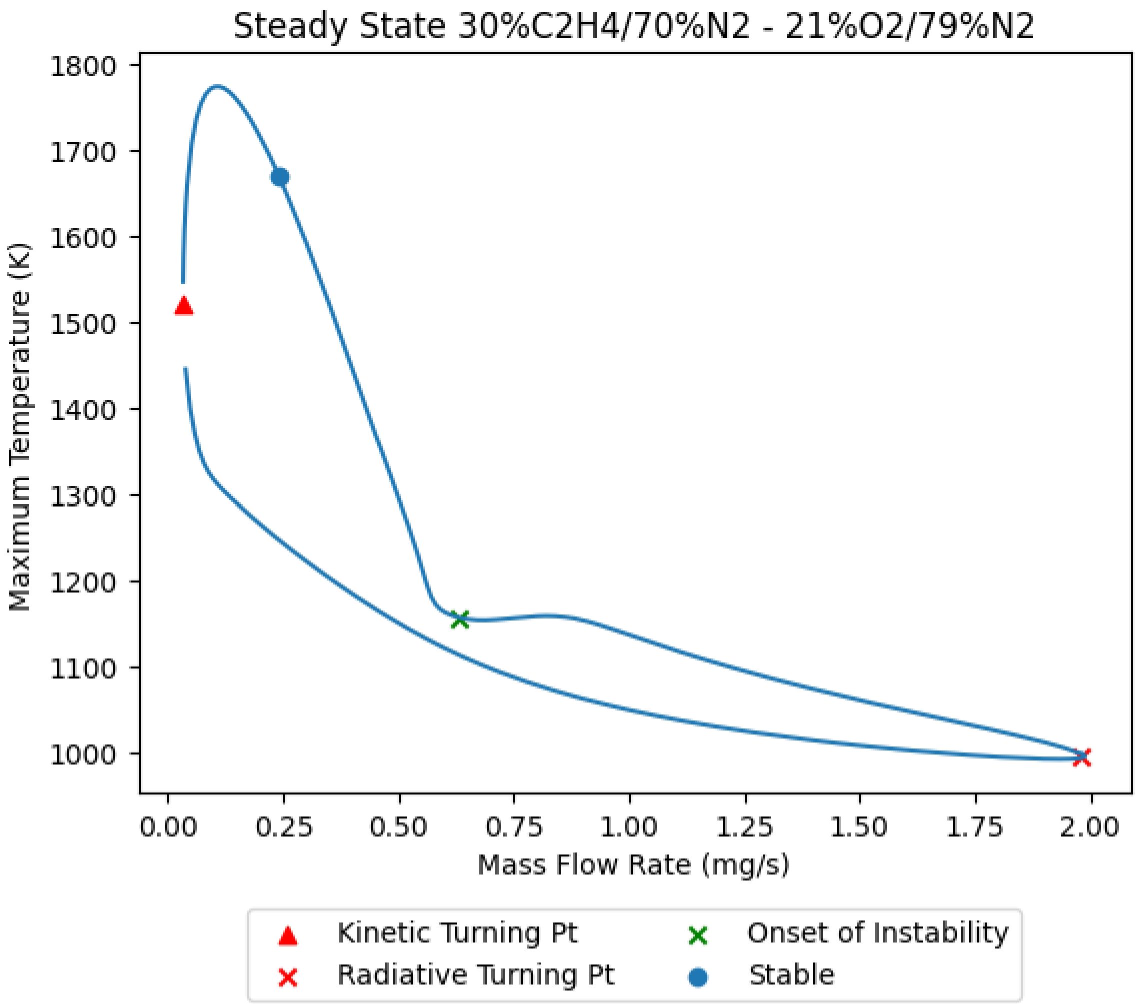
Steady State Mapping (S/Isola)

Optically Thin Radiation Model
Quasi-Steady-State Curve

Le ~ 0.9-1.2 for C_2H_4/N_2
Le=0.94 Fuel side
Le=1.11 Oxidizer side
Evaluated at free stream

For radiative extinction (opically thin) for



Flamefront Instabilities: Phenomenology

- Stoichiometry constraint and lack of chemistry render diffusion flame sheets absolutely stable.
- However, chemistry becomes important for near-limit burning. Will flame become unstable?
- Recent theories & experiments show instability characteristics similar to those of premixed flames for near-limit burning
- Since (positive) stretch suppresses cellular instability while promotes pulsating instability, the (stretchless) spherical flame is well suited for such studies.

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Cellular Instability in Premixed Flames

$H_2/N_2/O_2$, α = 0.125, 5atm, ϕ = 0.70
(transition to turbulence to detonation?)

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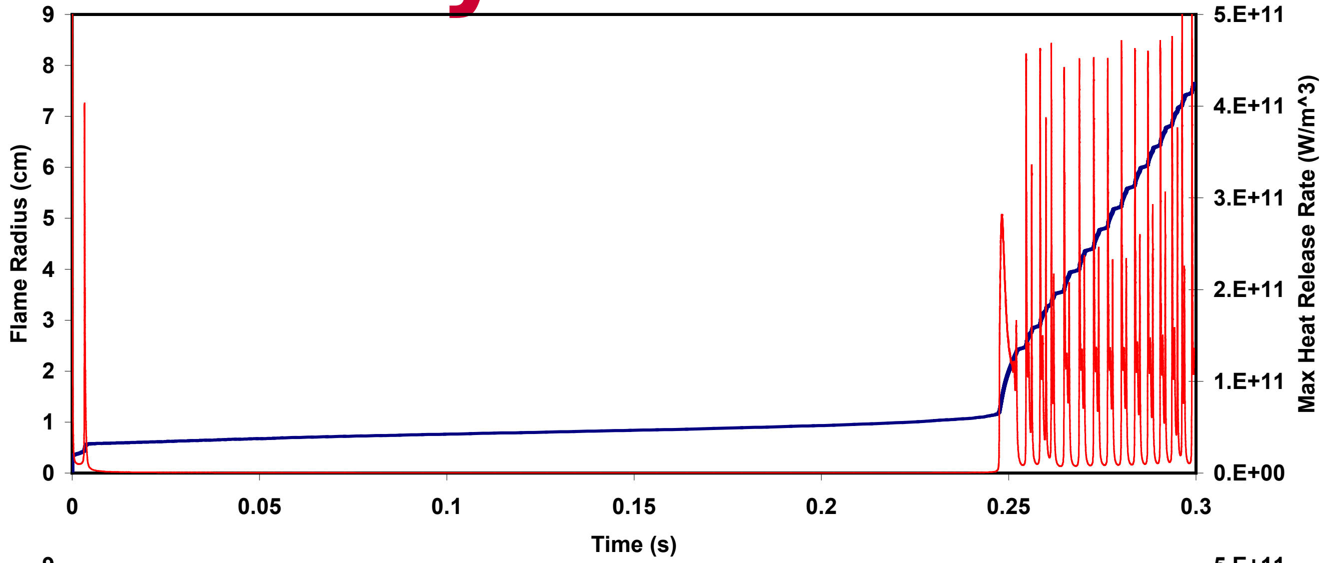
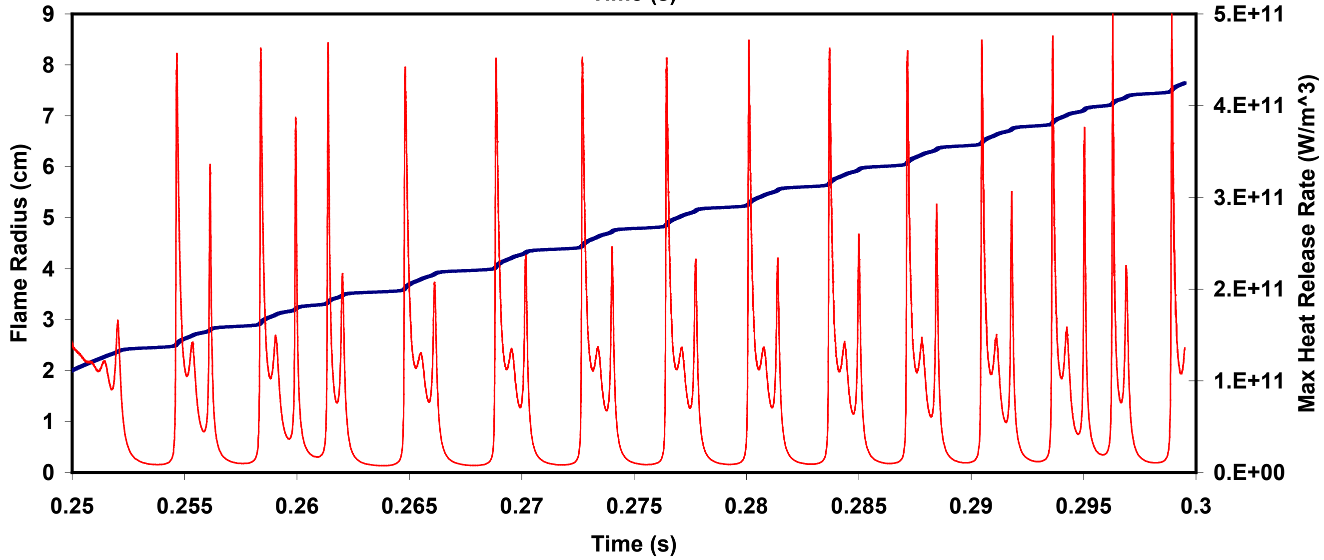
Pulsating Instability in Premixed Flames





H_2/Air, P=10atm, Phi=5.0

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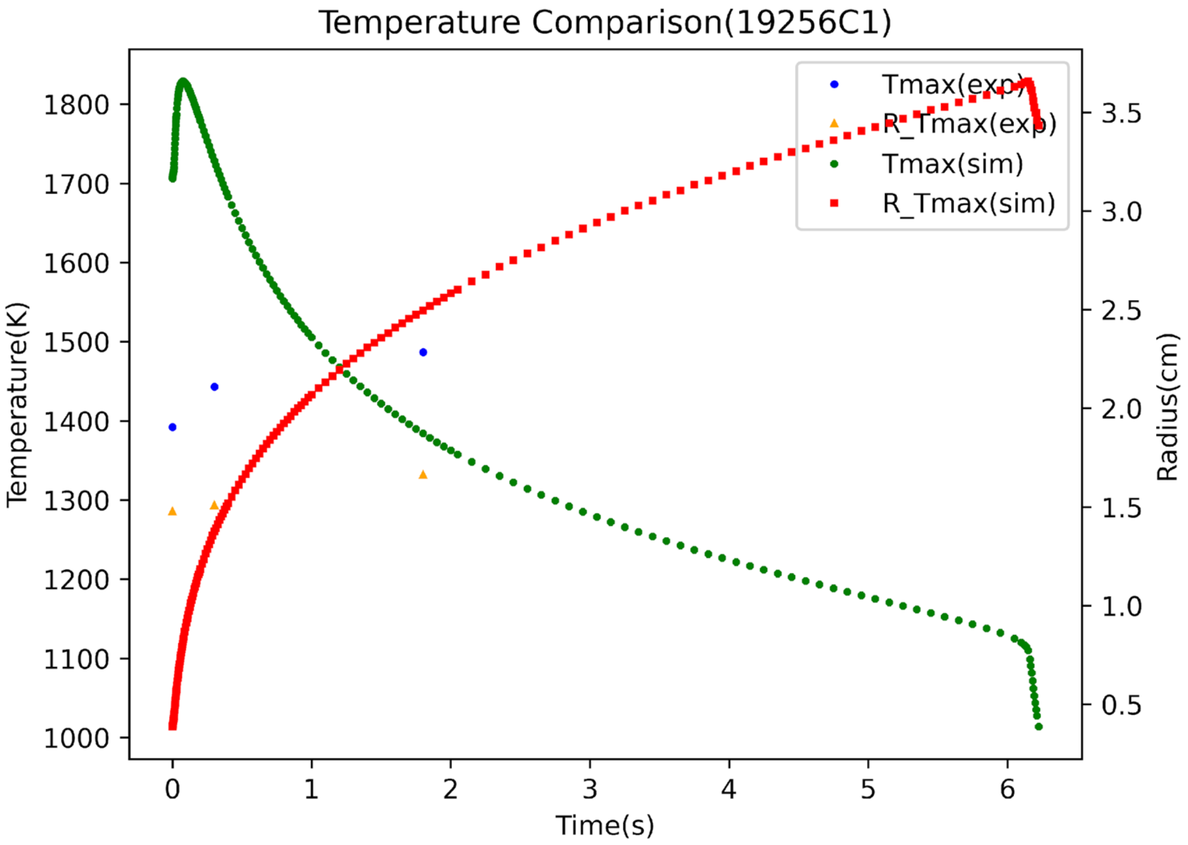
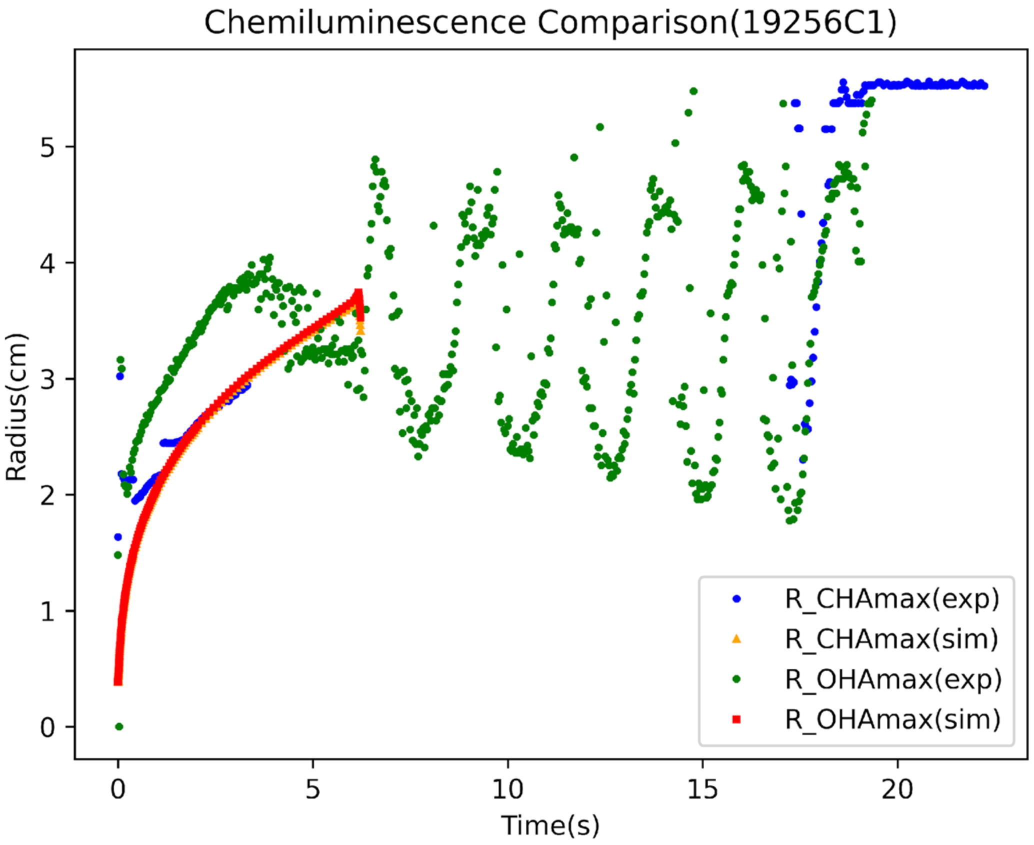
Empirical vs Simulation: Reabsorption Radiation Model

Simulation predicted extinction before oscillation

- 3D effects diverging from 1D simulation
- Possibly from non-uniform gas velocity gradient

Fuel: 25% C_2H_4/75% N_2
Environment: 21%O_2 / 79% N_2
Fuel Flow Rate: 15 cc/s





Development of Fundamental Physical & Chemical Database

- Detailed fuel oxidation mechanisms
- Reduced fuel oxidation mechanisms
- Diffusion coefficients
- Radiation models

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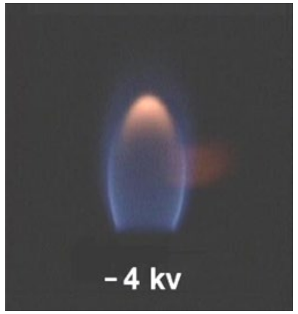
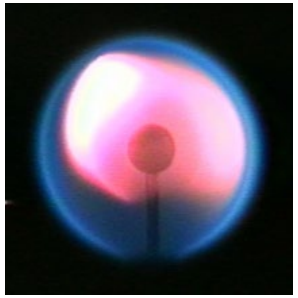
ACME Experiments

- **CLD Flame**
  - **Coflow Laminar Diffusion Flame**
  - PI Marshall Long (Yale U.)
  - Co-I Mitchell Smooke (Yale U.)

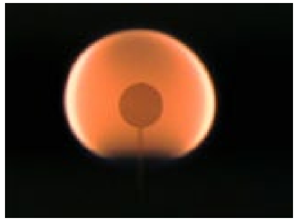
- **E-FIELD Flames**
  - **Electric Field Effects on Laminar Diffusion Flames**
  - PI Derek Dunn-Rankin (UC Irvine)
  - Co-Is Felix Weinberg (Imperial College)
    Zeng-Guang Yuan (NCSER @ NASA Glenn)



- **Flame Design** - ***a novel approach to clean, efficient diffusion flames***
  - PI Richard L. Axelbaum (Washington U. in St. Louis)
  - Co-Is Beei-Huan Chao (U. Hawaii),
    Peter B. Sunderland (U. Maryland),
    David L. Urban (NASA Glenn)



- **s-Flame**
  - **Structure and Response of Spherical Diffusion Flames**
  - PI C.K. Law (Princeton U.)
  - Co-Is Stephen D. Tse (Rutgers U.)
    Kurt R. Sacksteder (NASA Glenn)



ACME Approach

- ACME is not a technology demonstration, but is seeking to improve life on Earth via the path below.

ACME

Improved understanding of combustion fundamentals

↓

Improved numerical models of combustion processes

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Improved design tools

↓

Improved practical combustion devices

from ACME

Numerical prediction of flame structure

Instagram

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We've recently created flames on the space station as a part of the s-Flame experiment. The study takes advantage of microgravity to gather information about combustion that could allow researchers to predict the structure and dynamics of flames. The results may help develop more efficient and less polluting engines.

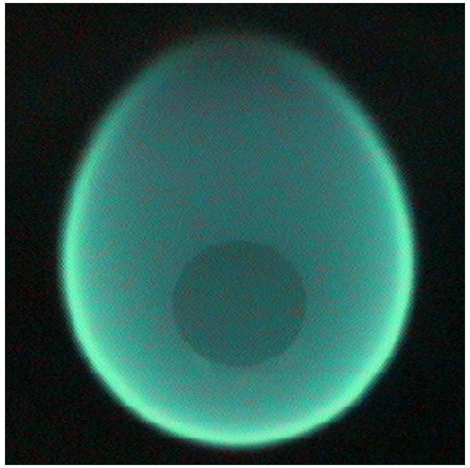
#nasa #research #flame #combustion #science #microgravity #international #space #station

254,637 views

July 22, 2020

Needed further studies

- Partial gravity studies, i.e., Lunar, Martian
- Flammability, extinction limits, instabilities
- Supercritical / trans-critical phenomena
- Dimensional effects
- Fire scaling, confined environments, e.g., habitats
- Smoldering with transition to flaming
- Ignition (intertwined with extinction, e.g., flame balls)
- Need enhanced test capabilities (e.g., zero to variable gravity drop towers)



Low Gr Flames

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- Grants from NASA
  - Mr. Jonathan Shi
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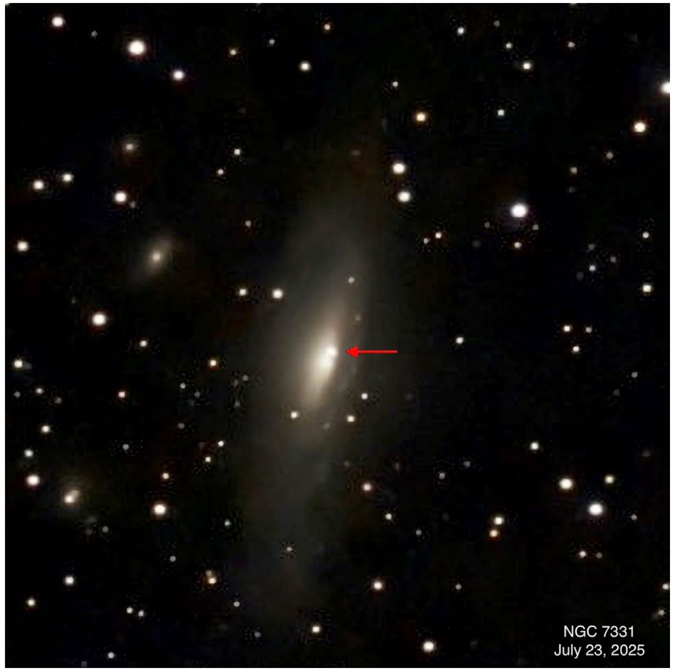
- NASA Glenn
  - Mr. Dennis Stocker
  - Dr. Daniel Dietrich
  - Dr. David Urban



Y.B. Zeldovich – supernova theory
($500 smart telescope accidental capture of recent supernova)

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