Understanding Combustion Processes Through Microgravity Research

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Why study microgravity combustion?

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- Gravity influences combustion through
  - Buoyant convection
  - Deformation / dropping of liquid droplets
  - Sedimentation in multi-phase systems
- Eliminating gravity enables observation of processes overwhelmed by gravity on earth
- Applications
  - Spacecraft fire safety
  - Better understanding of combustion at earth gravity

Time scales – premixed-gas flames

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- Chemical time (t_{chem}) ≈ $\delta/S_L \approx (\alpha/S_L)/S_L \approx \alpha/S_L^2$
  - α = thermal diffusivity
  - S_L = laminar flame speed ≈ 40 cm/s for stoichiometric hydrocarbon-air; ≈ 5 for near-limit mixtures
- Buoyant transport time ≈ d/U; $U \approx (gd(\Delta\rho/\rho))^{1/2} \approx (gd)^{1/2}$ (g = gravity, d = characteristic dimension)
  - Inviscid: $t_{inv} \approx d/(gd)^{1/2} \approx (d/g)^{1/2}$
  - Viscous: $d \approx \nu/U \Rightarrow t_{vis} \approx (\nu/g^2)^{1/3}$ (ν = viscosity)
- Conduction time (t_{cond}) ≈ $T_f/(dT/dt) \approx d^2/16\alpha$
- Radiation time (t_{rad}) ≈ $T_f/(dT/dt) \approx T_f/(\Lambda/\rho C_p)$
  - Optically thin: $\Lambda = 4\sigma a_p(T_f^4 - T_\infty^4)$ (radiative loss rate / volume)
    (a_p = Planck mean absorption coefficient)
    $\Rightarrow t_{rad} \sim P/\sigma a_p(T_f^4 - T_\infty^4) \sim P^0$, P = pressure

Time scales (hydrocarbon-air, 1 atm)

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Time scale	Stoich. flame	Limit flame
Chemistry (t_{chem}) or diffusion (t_{diff})	0.00094 s	0.25 s
Buoyant, inviscid (t_{inv})	0.071 s	0.071 s
Buoyant, viscous (t_{vis})	0.012 s	0.010 s
Conduction (t_{cond}), d = 5 cm	0.95 s	1.4 s
Radiation (t_{rad})	0.13 s	0.41 s

- Conclusions
  - Buoyancy unimportant for near-stoichiometric flames (t_{inv} & $t_{vis} >> t_{chem}$)
  - Buoyancy strongly influences near-limit flames at 1g (t_{inv} & $t_{vis} < t_{chem}$)
  - Radiation effects unimportant at 1g ($t_{vis} << t_{rad}$; $t_{inv} << t_{rad}$)
  - Radiation effects dominate flames with low S_L ($t_{rad} \approx t_{chem}$), but only observable at µg
  - Radiation > conduction only for d > 3 cm
  - Radiation time scale t_{rad} is small enough (≈ 1 s) that radiation effects on flames can be observed in drop tower experiments
  - Reynolds number ~ $Vd/\nu \sim (gd^3/\nu^2)^{1/2} \Rightarrow$ turbulent flow unavoidable at 1g for large systems (d > 10 cm)

Near-limit flames in vertical tubes

- Limit composition, propagation speed, and shape depend on orientation - *buoyancy effects*

Upward propagation

Downward propagation

Flammability limits – losses - continued…

- Big tube, no gravity – extinction caused by radiative loss ($t_{chem} \approx t_{rad}$)

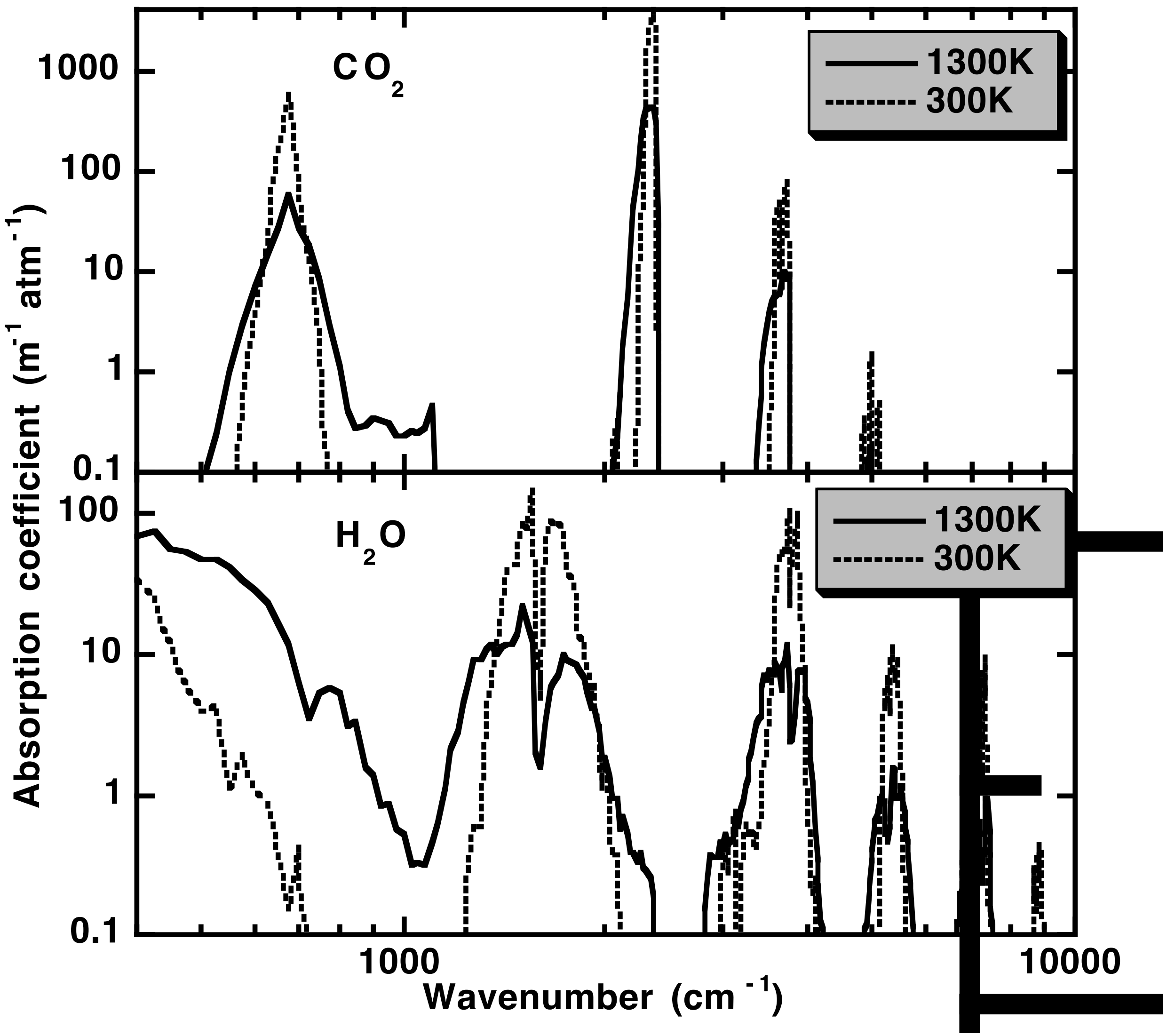
$$S_{L,\lim} = \frac{1}{\rho_\infty C_p}\sqrt{\frac{1.2\beta\Lambda\lambda_f}{T_f}} \quad \text{(no reabsorption)}$$

- prediction consistent with μg experiments

$$\textbf{Impact of heat loss} \sim \frac{\textbf{Heat loss}}{\textbf{Heat release}} \sim \frac{T^2}{e^{-E/RT}} \Uparrow \textbf{ as } T \Downarrow$$

- **Reabsorption** significant when $a_P^{-1} < d$
  - Extends limits & increases S_L – theoretically no limit with graybody absorbers
  - Gases – spectral radiation – 2 mechanisms allow radiation to escape even with reabsorption
    - » Absorption spectra of products different from reactants
    - » Spectra broader at high T than low T

Absorption spectra of H_2O & CO_2



Reabsorption effects on premixed flames

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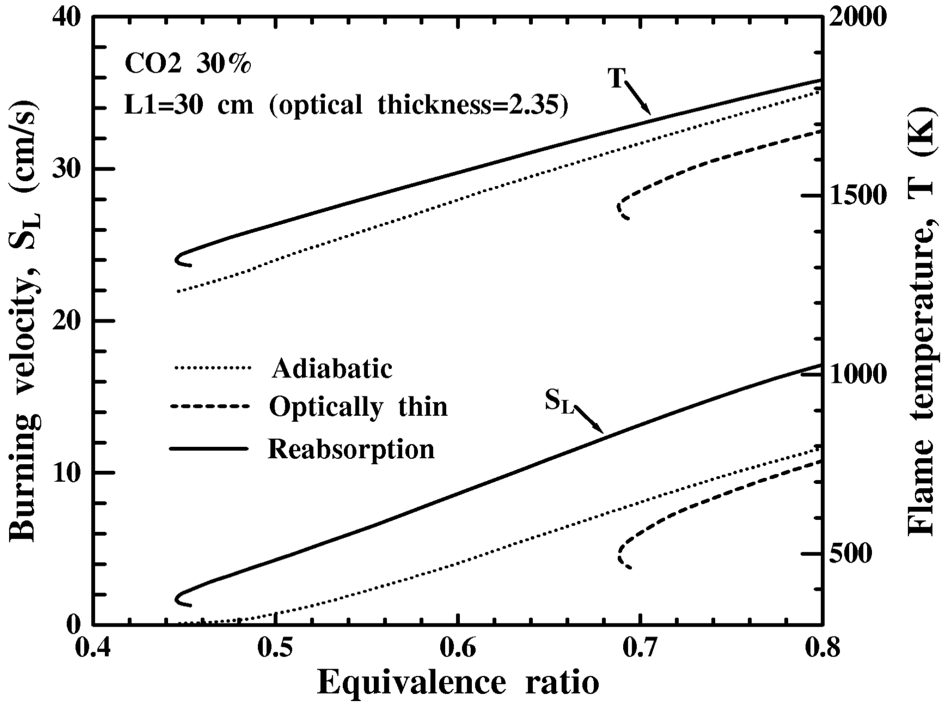
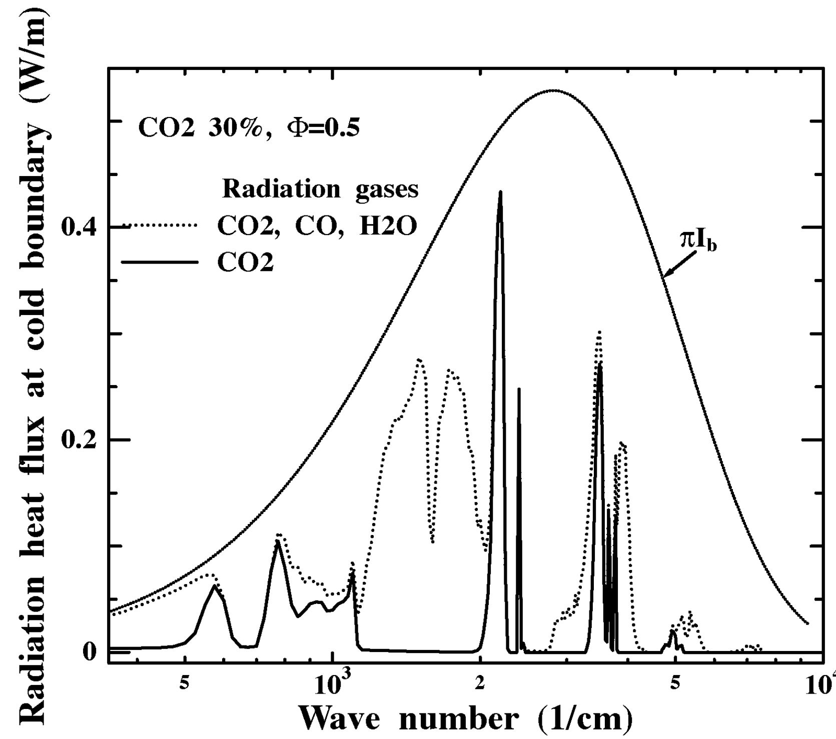




Methane-air mixtures with 30% of N_2 replaced with CO_2, 1 atm

Condensed-phase combustion - flame spread

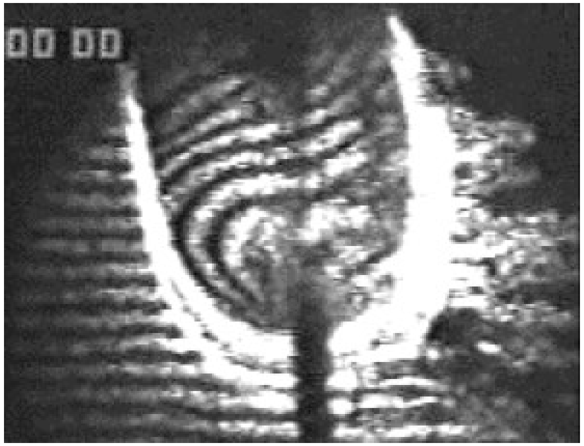
- Flame spread rate (S_f) with opposing flow U, infinite-rate kinetics (mixing limited)

$$S_f = \frac{\pi}{4}\frac{\lambda_g}{\rho_s C_{p,s}\tau_s}\frac{T_f - T_v}{T_v - T_\infty}$$ (thin fuel) - independent of P and U

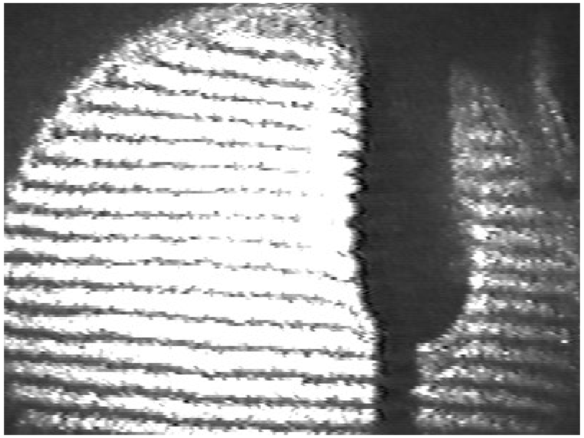
$$S_f = U\frac{\lambda \rho C_P}{\lambda_s \rho_s C_{p,s}}\left(\frac{T_f - T_v}{T_v - T_\infty}\right)^2$$ (thick fuel) - $S_f \sim P^1U^1$

- Diffusive transport time scale (t_{diff}) ≈ $\delta/U \approx \alpha/U^2$
- Heat loss parameter $H \sim t_{diff}/t_{rad} = \alpha/U^2 t_{rad} \sim P^{-1}U^{-2}$
  - Optically-thin: S_f lower at µg: $U = S_f << U(1g) \Rightarrow$ higher H
  - Dual-limit behavior
    - » Large U: residence-time limited: $t_{diff} \leq t_{chem}$
    - » Small U: heat loss: $t_{diff} \geq t_{rad}$
    - » Most robust U ≈ 10 cm/s - less than 1g buoyant flow!
- Radiation not all lost if ambient atmosphere absorbs
  - O_2-N_2, O_2-He, O_2-Ar: $S_f(1g) > S_f(\mu g)$ due to radiative loss
  - O_2-CO_2, O_2-SF_6: $S_f(1g) < S_f(\mu g)$ due to reabsorption
  - International Space Station uses CO_2 fire extinguishers!

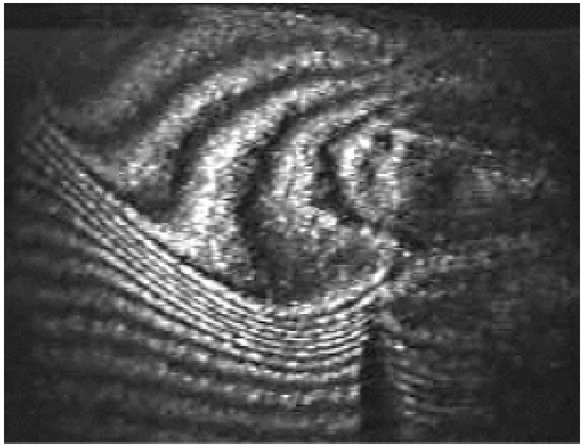
Flame spread - 1g vs. μg, optically-thin vs. thick



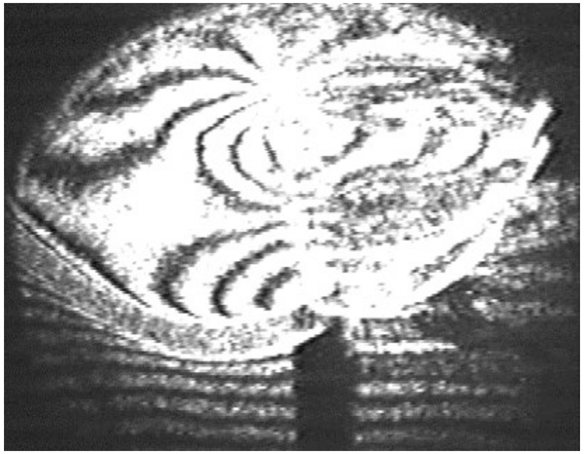
$30\% \ O_2$ in N_2, 1g



$42\% \ O_2$ in SF_6, 1g

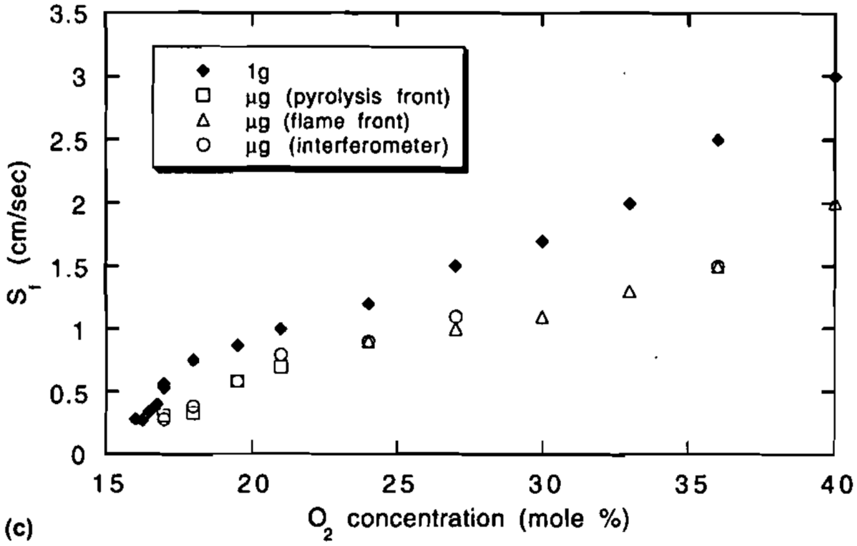


$30\% \ O_2$ in N_2, μg

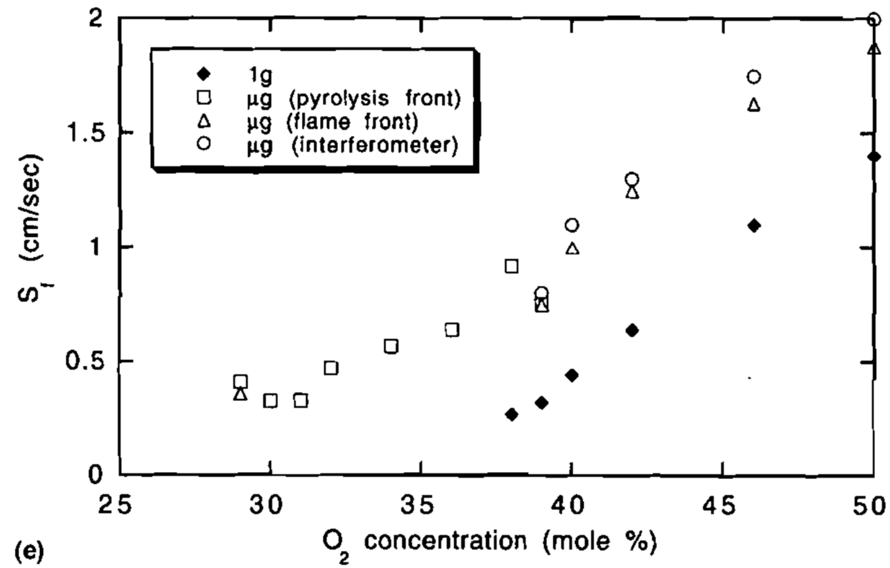


$42\% \ O_2$ in SF_6, μg

Flame spread in transparent & absorbing atmospheres



N_2 inert



SF_6 inert

Summary

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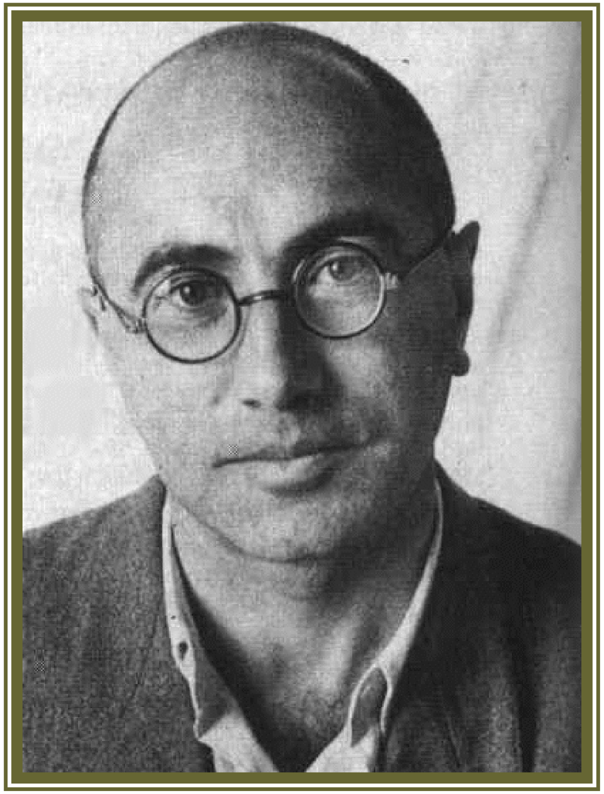
- What we have learned from μg combustion research?
  - Time scales
    - » *when buoyancy, radiation, etc. is important*
  - Radiative loss – gas-phase & soot
    - » *causes many of the observed effects on burning rates & extinction conditions*
  - Dual limits (high-speed blow-off & low-speed radiative)
    - » *seen for practically all types of flames studied to date*
  - Spherical flames (flame balls, droplets, ≈ candle flames)
    - » *long time scales, large domains of influence, radiative loss*
  - Oscillations near extinction
    - » *Common, not yet fully understood*
  - Thermophoresis in sooting flames
    - » *Affects net heat release, soot oxidation, radiative loss*
- Challenges
  - Reabsorption of emitted radiation – scale and spectrum-dependent
  - Chemistry of near-limit mixtures
  - Soot formation, accumulation, oxidation, radiation

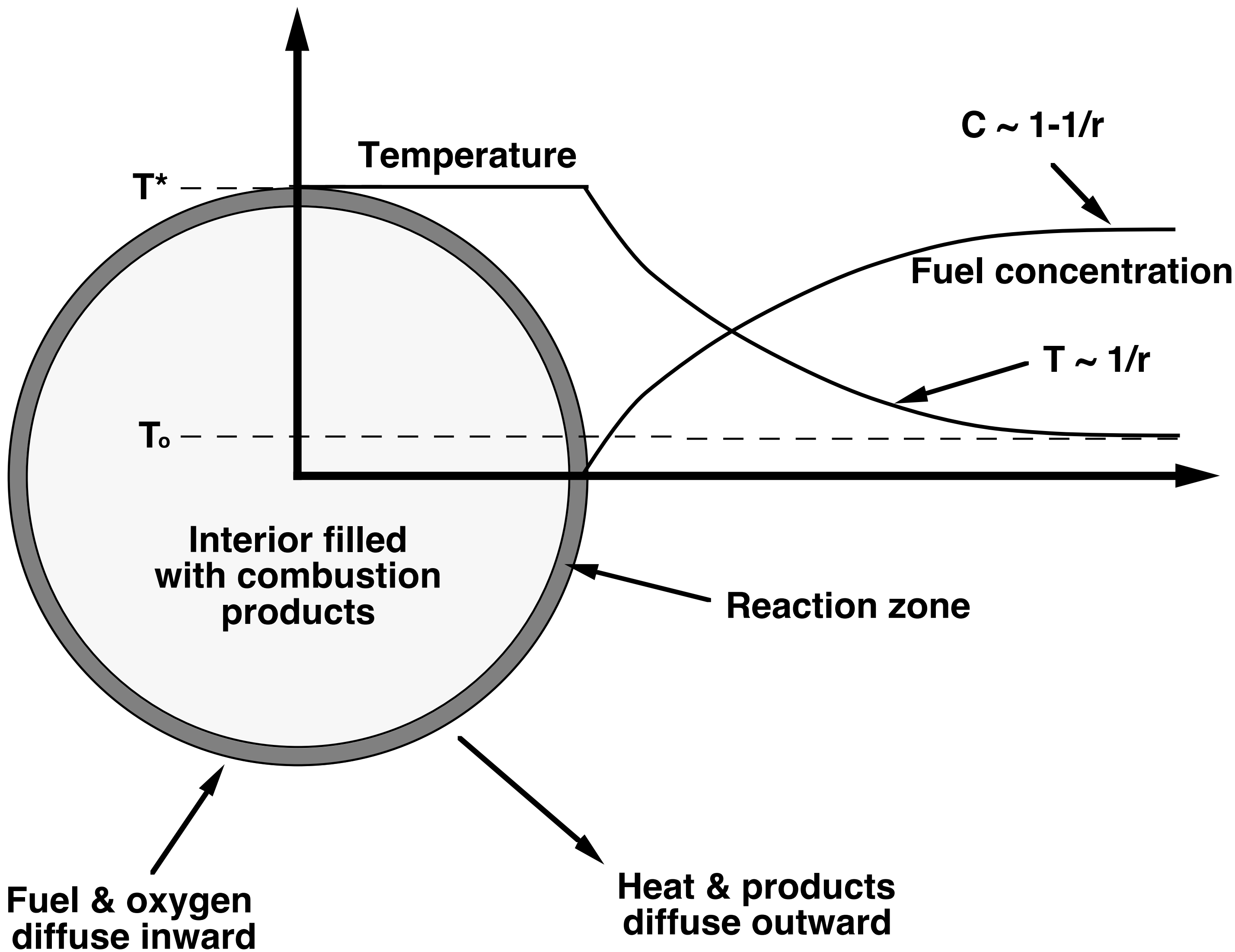
BACKUP SLIDES

"FLAME BALLS"

- Zeldovich, 1944: stationary spherical flames possible since $\nabla^2 T$ & $\nabla^2 C = 0$ have solutions for *unbounded* domain in spherical geometry
- Mass conservation requires $U \equiv 0$ everywhere (<u>no stretch</u>) – only <u>diffusive</u> transport
- $T \sim 1/r$ - unlike propagating flame where $T \sim e^{-r}$ - dominated by 1/r tail (with r^3 volume effects!)
- Buckmaster, 1985; Joulin, 1985: adiabatic flame balls are *unstable*



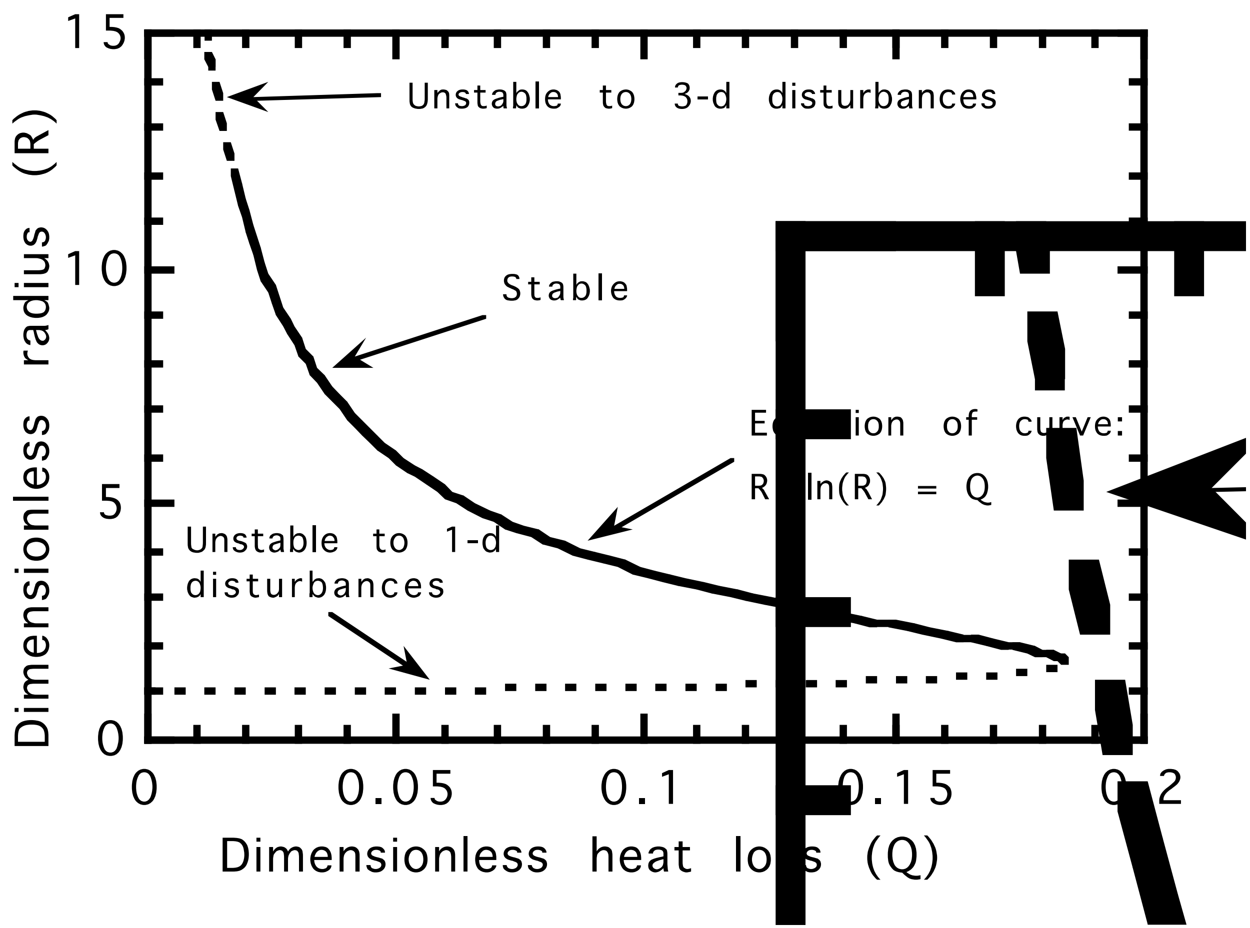
Flame ball schematic



Flame balls - continued

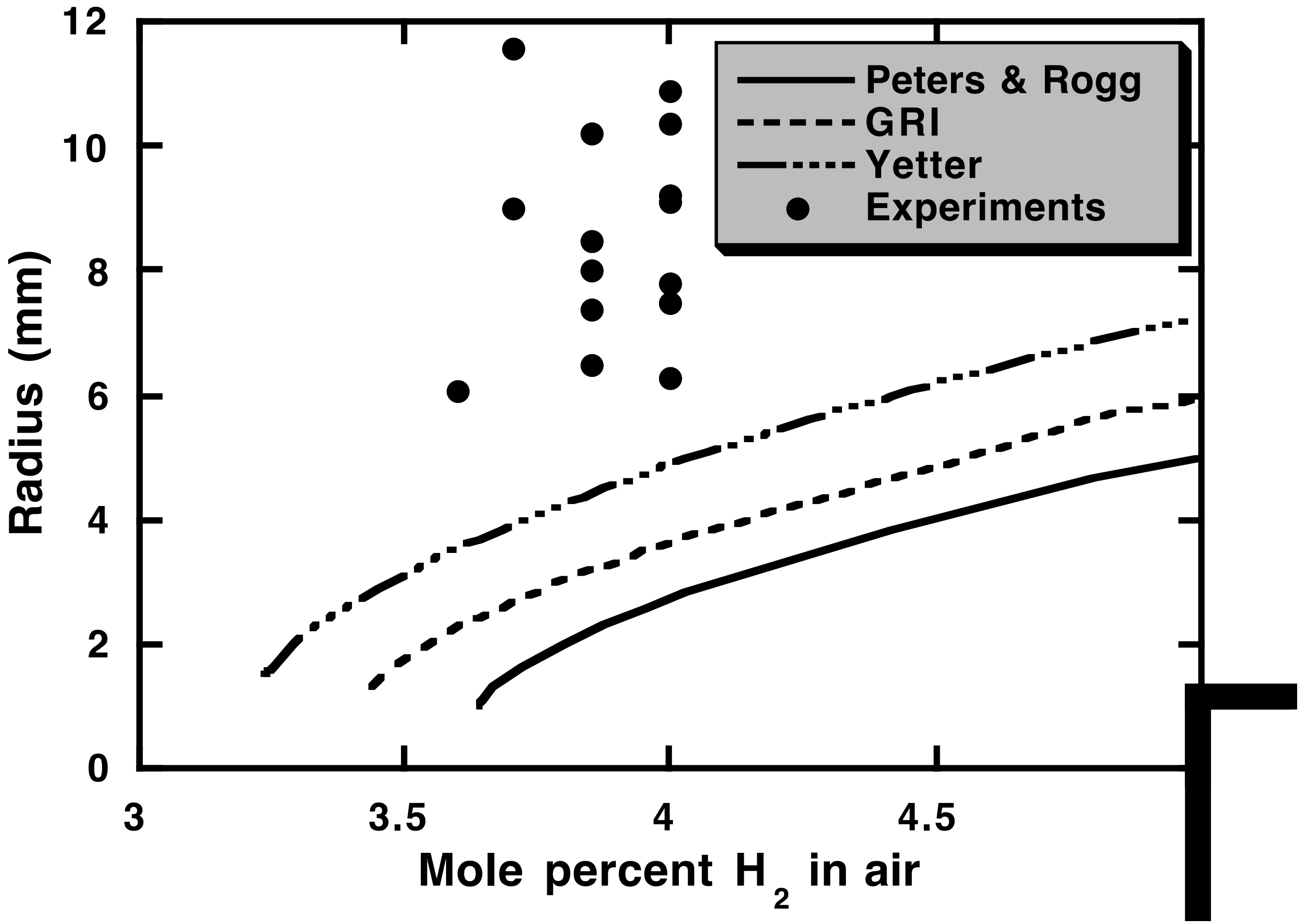
- Ronney (1990): seemingly stable, stationary flame balls accidentally discovered in drop-tower experiment
- Confirmed in parabolic aircraft flights (Ronney *et al.*, 1993)
- Only seen at µg, low Le, near extinction limits
- Space experiments (STS-83 & 94, 1997)
  - Stable for > 500 seconds (!)
  - Weakest flames ever burned (1 – 2 Watts/ball)
  - Very long evolution time scales ~ $(\beta r^*)^2/\alpha \approx 100$ s
- Buckmaster, Joulin & collaborators: window of *stable* conditions with radiative loss & low Le
- Detailed numerical modeling (Yale, USC)
  - Dual limits
  - Unsatisfactory agreement with experiment
  - Results sensitive to $H + O_2 + H_2O \rightarrow HO_2 + H_2O$
  - Reabsorption effects in H_2-O_2-CO_2 & H_2-O_2-SF_6 mixtures
  - ???

Theory of non-adiabatic flame balls



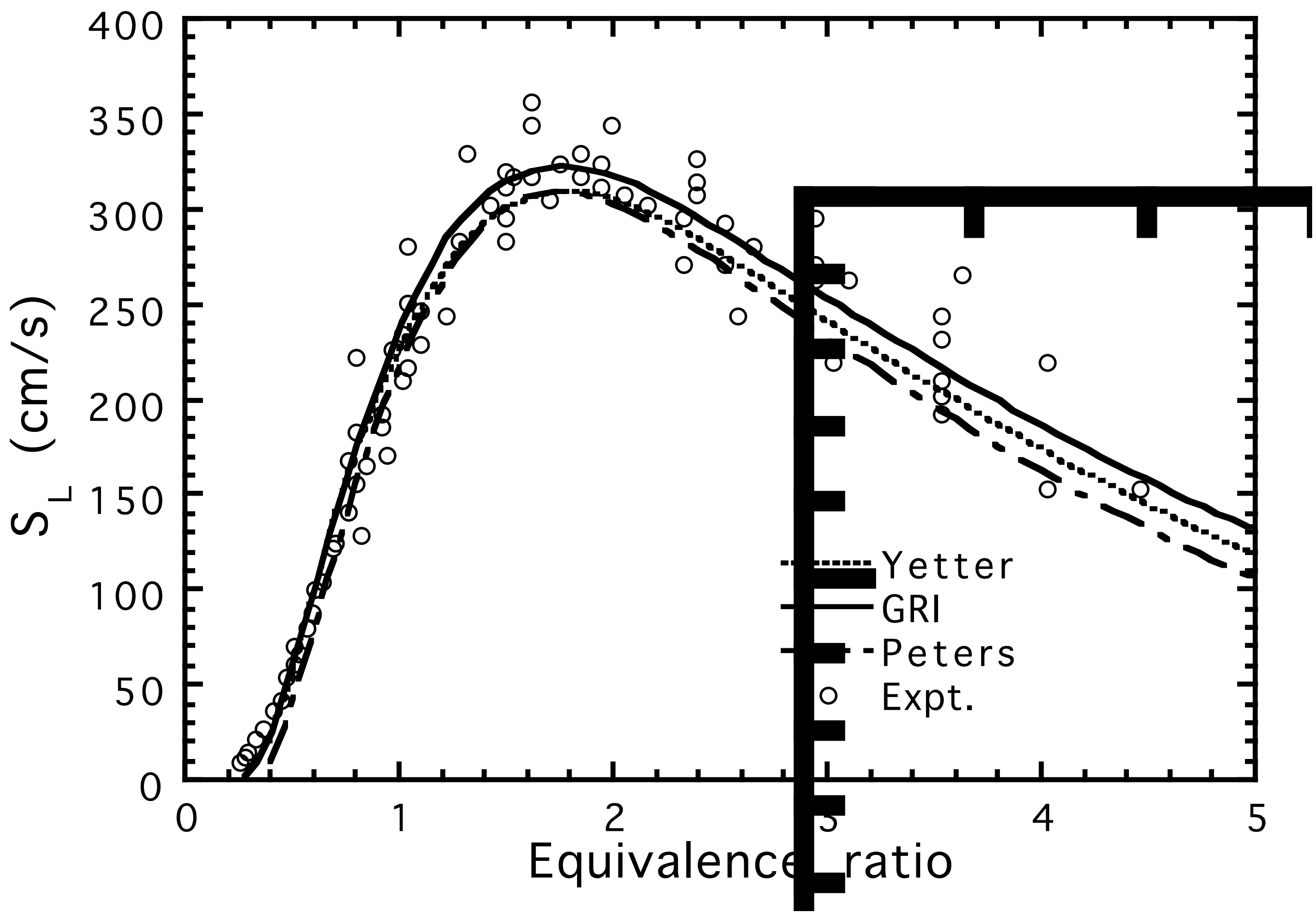
Buckmaster, Joulin, Ronney (1990)

Comparison of predicted & measured radii



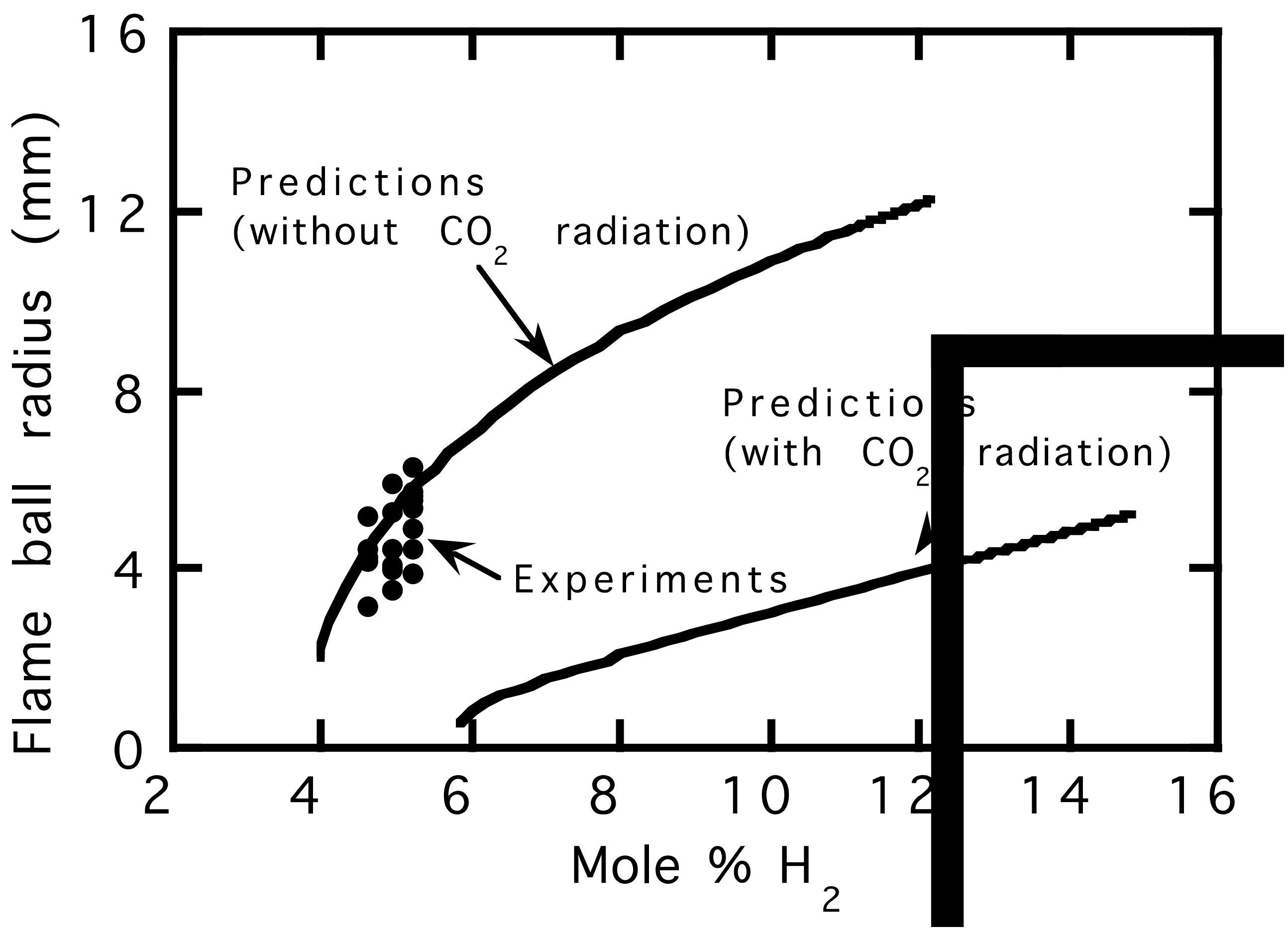
H_2-air mixtures, 1 atm

Comparison of predicted & measured S_L



H_2-air mixtures, 1 atm

Evidence of reabsorption effects in flame balls



H_2-O_2-CO_2 mixtures (H_2:O_2 = 1:2)

EXAMPLES - NONPREMIXED GAS FLAMES

- Counterflow flames
  - Nonpremixed flames – less freedom of movement – flame must lie where stoichiometric flux ratio maintained
  - Radiating gas volume ~ flame thickness ~ $(\alpha/\Sigma)^{1/2}$
- Computations & μg experiments – simple C-shaped dual-limit response
- Conductive loss to burners at low Σ? $(\Sigma_{min})^{-1} \approx t_{cond}$

Nonpremixed-gas flames - gas-jet flames

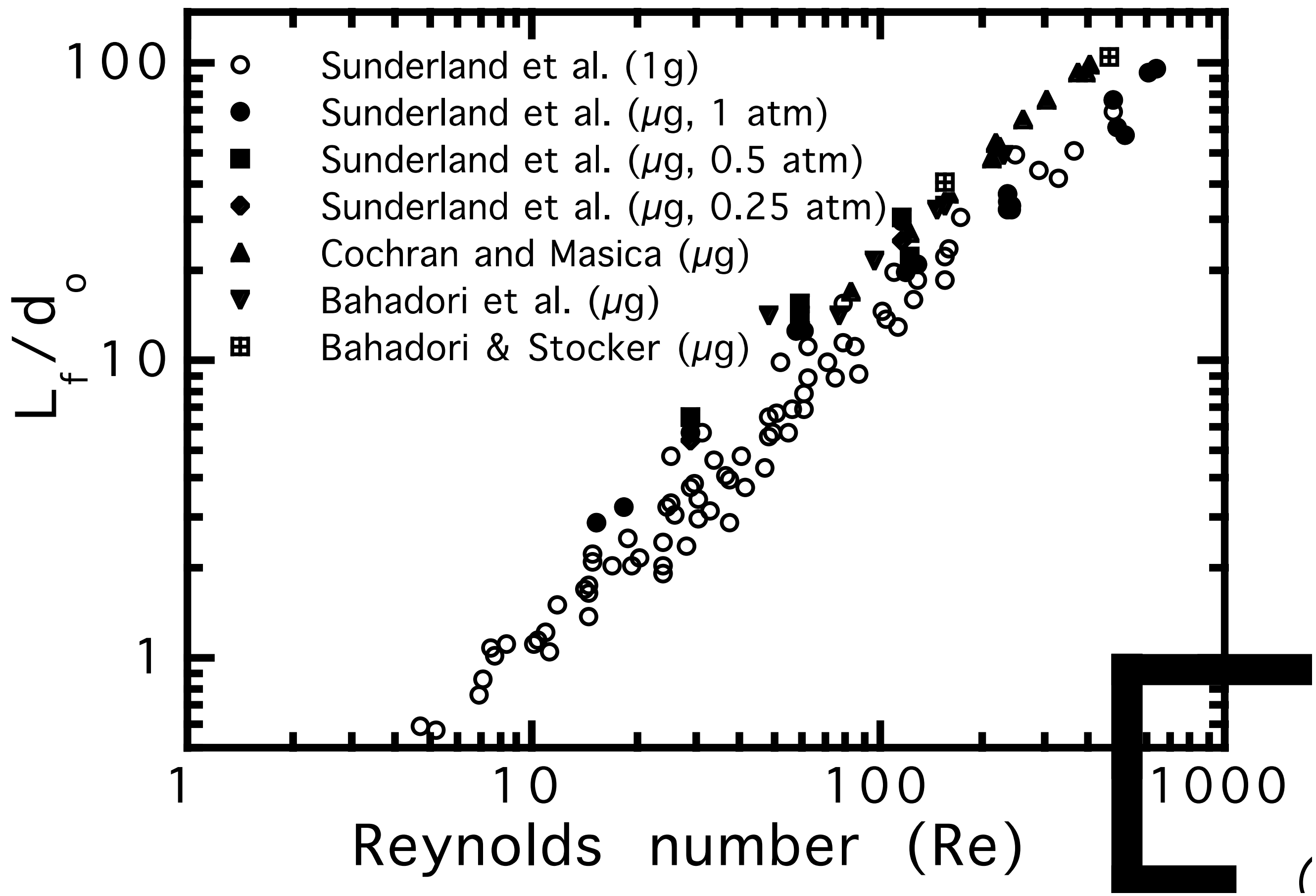
- Flame height (L_f) and residence time (t_{jet}) determined by equating diffusion time (d^2/D) to convection time (L_f/U)
- Mass conservation: $U(0)d(0)^2 \sim U(L_f)d(L_f)^2$ (round jet); $U(0)d(0) \sim U(L_f)d(L_f)$ (slot jet)
- Buoyant flow: $U(L_f) \sim (gL_f)^{1/2}$; nonbuoyant: $U(L_f) = U(0)$

Geometry	Flow	L_f	t_{jet}
Round-jet	Momentum	$U_o d_o^2/D$	d_o^2/D
Round-jet	Buoyant	$U_o d_o^2/D$	$(U_o d_o^2/gD)^{1/2}$
Slot-jet	Momentum	$U_o d_o^2/D$	d_o^2/D
Slot-jet	Buoyant	$(U_o^4 d_o^4/D^2 g)^{1/3}$	$(U_o^2 d_o^2/g^2 D)^{1/3}$

Gas-jet flames - results

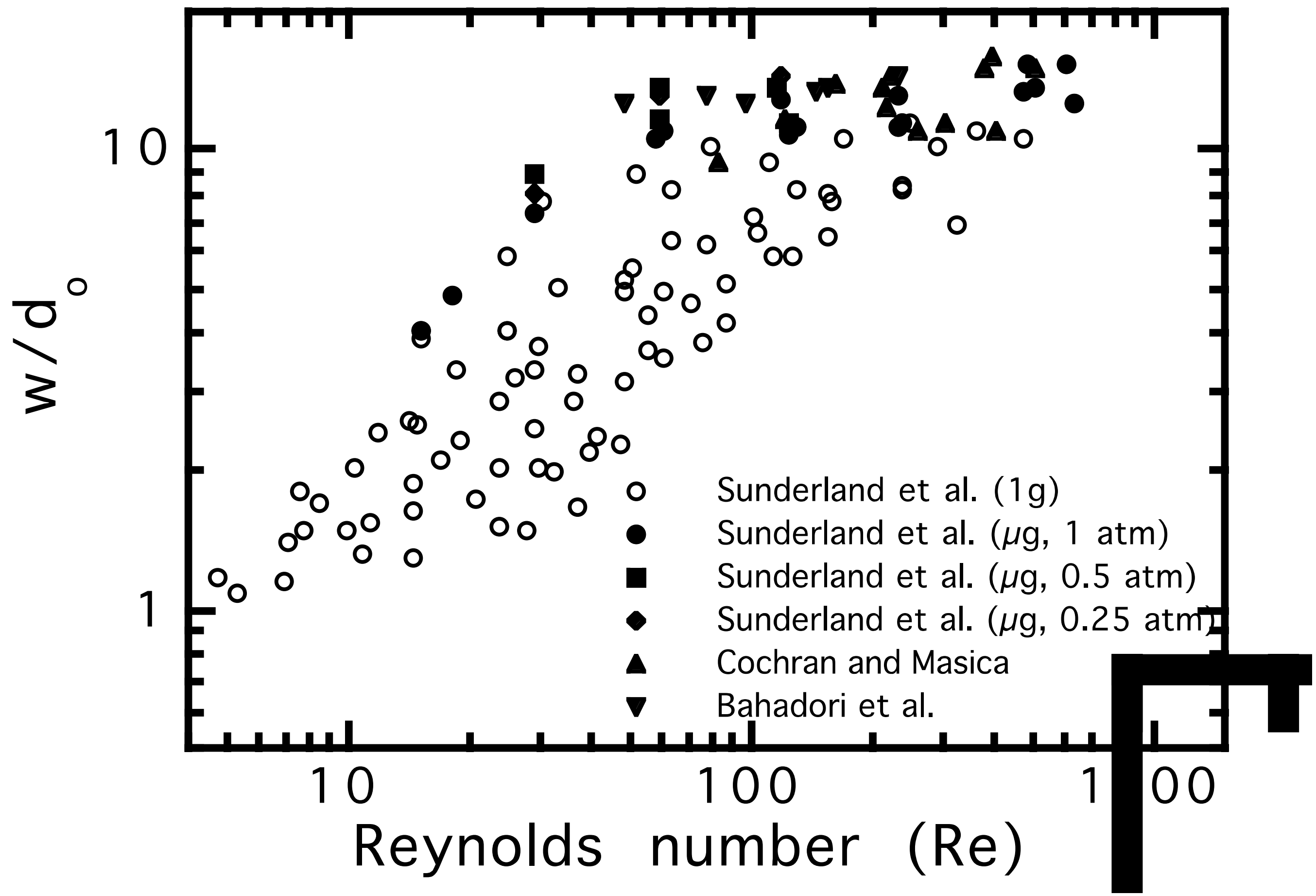
- $L_f \approx$ same at 1g or μg for round jet (what about slot jet?)
- t_{jet} larger at μg than 1g for round jet
  - ⇒ Larger μg flame width ~ $(Dt_{jet})^{1/2}$ - greater difference at low Re due to axial diffusion & buoyancy effects
  - ⇒ Greater radiative loss fraction at μg (≈ 50% vs. 8%)
- Turbulent flames: $D \sim u'L_I$; $u' \sim U_o$; $L_I \sim d_o$
  - ⇒ $L_f \sim d_o$ (independent of Re)
  - Differences between 1g & μg seen even at high Re - buoyancy effects depend on entire plume
- Soot formation
  - Typically greater at μg due to larger t_{jet} - outweighs lower T
  - Smoke points seen at μg - WHY???
    - » $t_{jet} \sim U_o^{1/2}$ for buoyant flames BUT...
    - » t_{jet} independent of U_o for nonbuoyant flames !
    - » Axial diffusion effects negligible at Re > 50
  - Thermophoresis effects - concentrates soot in annulus

Flame lengths at 1g and μg



Sunderland *et al.* (1998) - CH_4/air

Flame widths at 1g and μg



Sunderland *et al.* (1998) - CH_4/air

Turbulent flame lengths at 1g and μg

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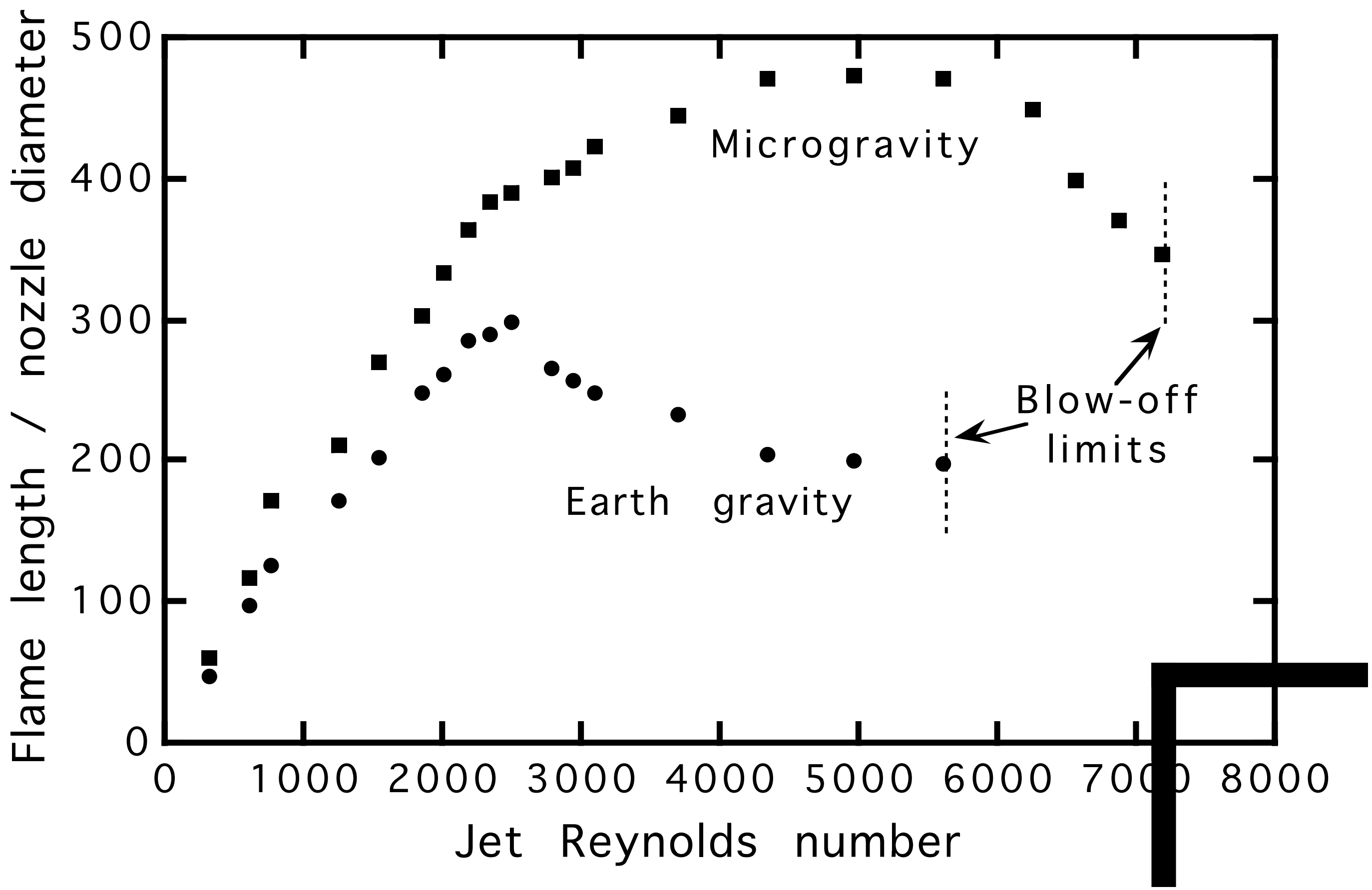

Bahadori *et al.* (1997) - C_3H_8/air

Sooting gas-jet flames at 1g and μg

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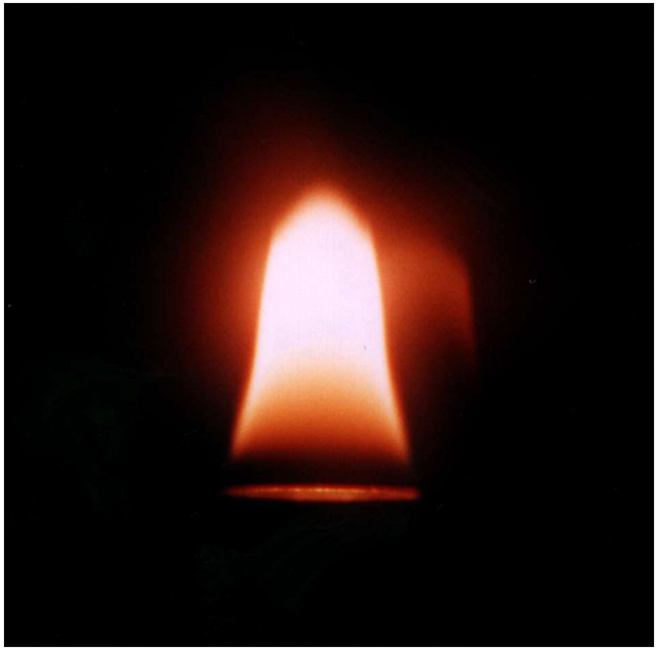
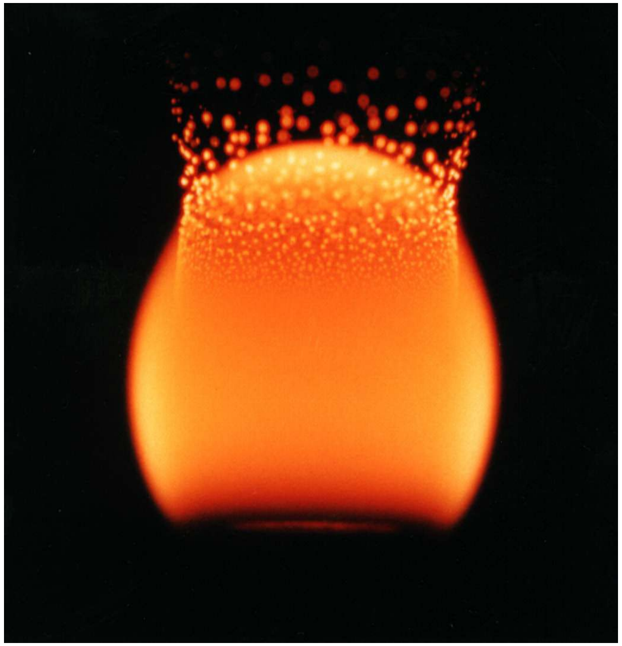


1g



μg

n-butane in air, 10mm diameter jet, Re = 42

Fujita *et al.*, 1997

EXAMPLES - Condensed-phase - droplets

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- Spherically-symmetric model (Godsave, Spalding 1953)
  - Steady burning possible - similar to flame balls
    (large radii: transport diffusion-dominated)
  - Mass burning rate = $(\pi/4)\rho_d d_d K$; $K = (8\lambda/\rho_d C_P) \ln(1+B)$
  - Flame diameter $d_f = d_d \ln(1+B) / \ln(1+f)$
  - Regressing droplet: $d_{do}^2 - d_d(t)^2 = Kt$ if quasi-steady
- 1st μg experiment - Kumagai (1957) - K(μg) < K(1g)
- Dual-limit behavior
  - Residence-time limited (small d_d): $t_{drop} = d_f^2/\alpha \leq t_{chem}$
  - Heat loss (large d_d): $t_{drop} \geq t_{rad}$
  - Radiative limit at large d_d confirmed by μg experiments

Droplet combustion - continued

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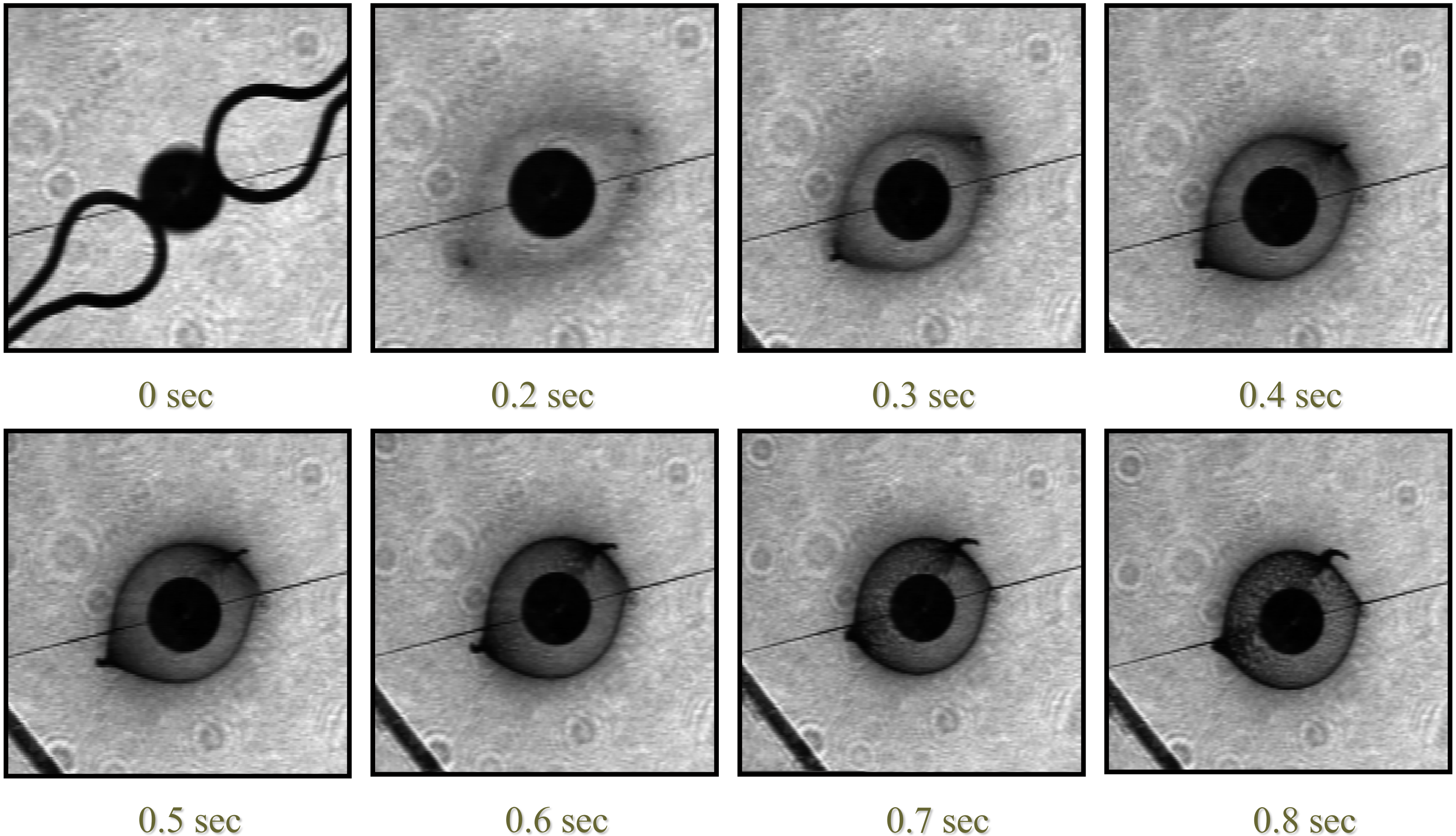
- Large droplets not quasi-steady
  - Extinction occurs at sufficiently large d_d, but d_d decreases during burn - quasi-steady extinction not observable
  - K & d_f/d_d not constant - depend on d_{do} & time
  - Large time scale for diffusion of radiative products to far-field & O_2 from far-field
  - Soot accumulation dependent on d_{do}
  - Absorption of H_2O from products by fuel

Soot formation in μg droplet combustion



n-heptane in air (Lee *et al.*, 1998)

Recommendations for future work

- Radiative reabsorption effects
  - Apparently seen in particle-seeded premixed-gas flames, flame balls, thin-fuel flame spread
  - Easier to study at μg - no interference from turbulence
  - Relevant to IC engines, large furnaces, EGR, flue-gas recirculation
  - May occur in other μg flames, *e.g.*
    - » Droplet combustion - Stefan flow at surface limits conductive flux - ln(1+B) term; radiation not affected

$$\Omega = \ln\left(1 + \frac{B}{1 - R/\Omega}\right);\ R \equiv \frac{q_r d_d C_P}{2\lambda L_V};\ \Omega \equiv \frac{K\rho_d C_P}{8\lambda}$$

    - » Flame spread over thick fuels - could lead to steady spread even at μg in O_2-CO_2, O_2-SF_6

$$S_f = \left[\frac{\Lambda\,\alpha_g^2}{\sqrt{\alpha_g \rho_s C_{P,s} \lambda_s}\left(T_v - T_\infty\right) - \lambda_g\left(T_f - T_v\right)}\right]^{1/2}$$

  - Need faster computational models of radiative transport!

Recommendations for future work - continued

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- High-pressure combustion
  - Buoyancy effects (t_{chem}/t_{vis}) increase with P for weak mixtures
  - Reabsorption effects increase with P
  - Turbulence more problematic
  - Few µg studies - mostly droplets
- 3-d effects
  - Flame spread - effects of fuel bed width
  - Flame balls - breakup of balls
- Gas-jet flames at µg
  - Soot formation - what causes smoke points at µg???
  - Slot jet vs. round-jet
  - Radiative extinction at large d(0)?

Recommendations for future work - continued

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- Spherical diffusion flames - porous sphere experiment
  - Liquid or gaseous fuel
  - Could provide quasi-steady spherical nonpremixed flame
  - Increase fuel mass flow slowly until extinction
  - Difficult experimentally - long times, large chamber
  - Initial results with gaseous fuel - steady-state not reached - should use diluted fuel & enriched O_2 - increases f, reduces $d_f \Rightarrow$ smaller t_{drop}
- "Catalytic flame ball"
  - 1d, steady catalytic system
  - Radius known, T_* and Y_* unknown
  - Extract overall surface reaction rates

$$\Theta(Y_s, T_s) = \rho_s D_s r_s Y_\infty \left(1 - Y_s / Y_\infty\right) / M; \quad \frac{Y_s}{Y_\infty} = 1 - Le\left(\frac{T_s - T_\infty}{T_{ad} - T_\infty}\right)\left(1 + \frac{\sigma \varepsilon_s r_s \left(T_s^4 - T_\infty^4\right)}{\lambda_s \left(T_s - T_\infty\right)}\right)$$

Recommendations for future work - concluded

- Chemical models
  - Many μg combustion phenomena of interest occur near extinction limits
  - Sensitive to chemical mechanism - branching vs. recombination
  - $H + O_2 + M \rightarrow HO_2 + M$ identified for further study

  Could Chaperon efficiency relative to N_2 be temperature dependent?

Premixed-gas flames - stretched flames

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- Nonuniform flow, unsteady/curved flames: "flame stretch"

$$\Sigma \equiv \frac{1}{A}\frac{dA}{dt} \quad \text{(A = flame area)}$$

- Strong stretch ($\Sigma^{-1} \approx t_{chem}$) extinguishes flames
- Moderate stretch strengthens flames for Le < 1

$$\mathrm{Le} \equiv \frac{\text{Thermal diffusivity of the bulk mixture } (\alpha)}{\text{Mass diffusivity of scarce reactant into the bulk mixture (D)}}$$

- Spherical expanding flames, Le < 1: stretch allows flames to exist in mixtures below radiative limit until r_f too large & curvature benefit too weak

$$\Sigma \equiv \frac{1}{A}\frac{dA}{dt} = \frac{1}{4\pi r_f^2}\frac{d}{dt}\left(4\pi r_f^2\right) = \frac{2}{r_f}\frac{dr_f}{dt}$$

Dual limit: radiation at large r_f, curvature-induced stretch at small r_f (ignition limit)

Stretched flames - continued

- Counterflow configuration (Tohoku group)
  - $\Sigma = dU/dy$ – flame located where $U = S_L$
- Increased stretch pushes flame closer to stagnation plane
  - Decreased volume of radiant products
- Similar Le effects as curved flames
- Results
  - Dual limits
  - Flammability extension even for Le > 1
  - Multiple solutions (which ones are stable?)
- Dual limits & Le effects seen in µg experiments, but evidence for multivalued behavior inconclusive