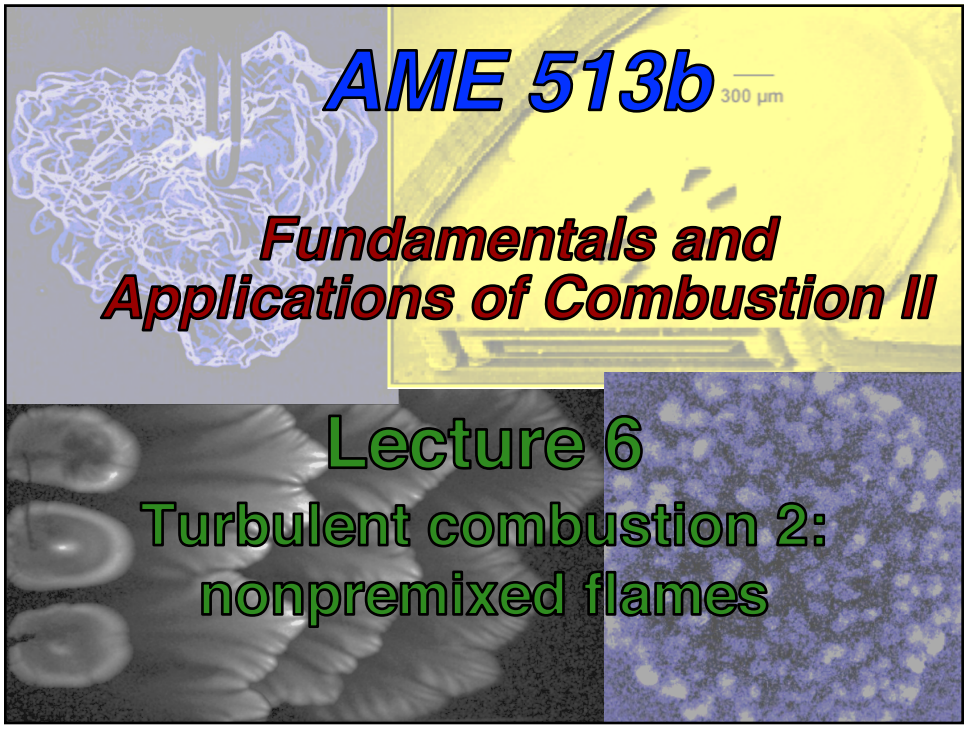

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Non-premixed flames - review

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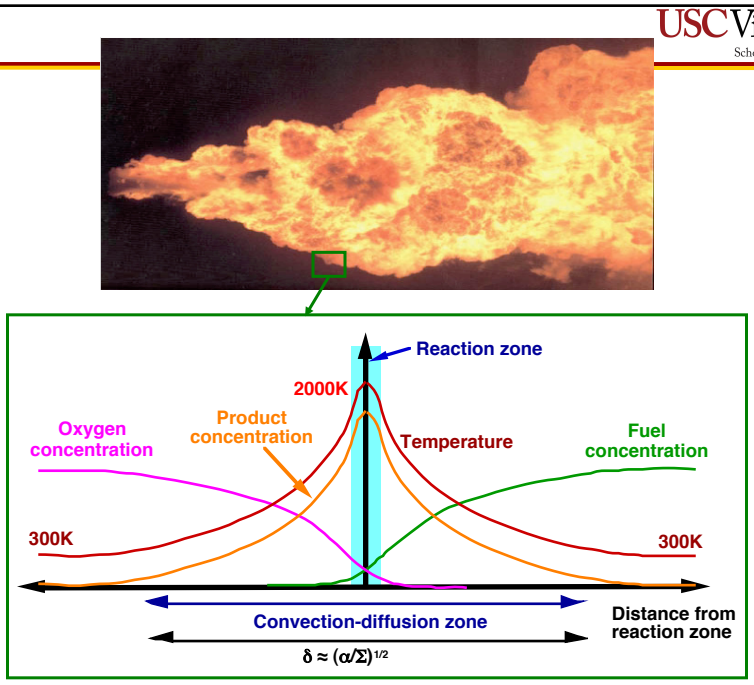
- Nonpremixed: no inherent propagation rate (unlike premixed flames where propagation rate = S_L)
- No inherent thickness δ (unlike premixed flames where thickness ~ α/S_L) - in nonpremixed flames, determined by equating convection time = $\delta/U = \Sigma^{-1}$ to diffusion time $\delta^2/\alpha \Rightarrow \delta \sim (\alpha/\Sigma)^{1/2}$
- Have to mix first then burn
- Burning occurs near stoichiometric contour where reactant fluxes in stoichiometric proportions (otherwise surplus of one reactant)
- Burning must occur near highest T since $\omega \sim \exp(-E/RT)$ is very sensitive to temperature (like premixed flames)
- Simplest approach: "mixed is burned", i.e. $\omega >> \Sigma$
- Stoichiometric mixture fraction Z_{st} = mass fraction of fuel stream in a stoichiometric mixture of fuel and oxidant streams

$$Z_{st} = \frac{1}{1+S}; S \equiv \frac{\nu_{ox} M_{ox} Y_{F,-\infty}}{\nu_F M_F Y_{ox,\infty}}$$

ν = stoichiometric coefficient, M = molecular weight, Y = mass fraction

•2



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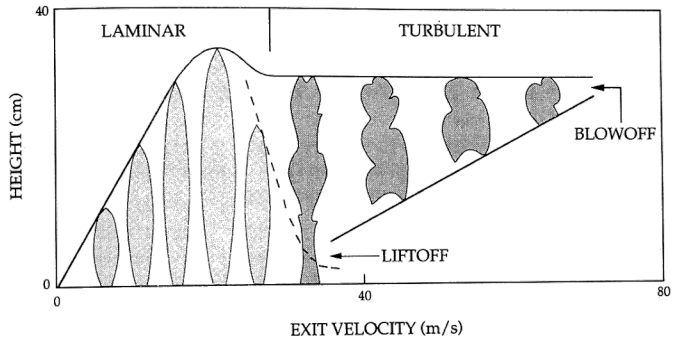
Nonpremixed turbulent jet flames

- Laminar: $L_f \sim U_o d_o^2/D$
- Turbulent (Hottel and Hawthorne, 1949)
  - $D \sim u'L_I$; $u' \sim U_o$; $L_I \sim d_o \Rightarrow L_f \sim d_o$ (independent of Re)
  - High $U_o \Rightarrow$ high $u' \Rightarrow$ Da small – flame "lifts off" near base (why base first?)
  - Still higher U_o - more of flame lifted
  - When lift-off height = flame height, flame "blows off" (completely extinguished)



KAUST high-P facility

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Scaling of turbulent jets

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- Hinze (1975)
- Determine scaling of mean velocity ($\bar{u}$), jet width (r_{jet}) and mass flux through jet ($\dot{m}$) with distance from jet exit (x)
- Assume u'(x) ~ $\bar{u}(x)$, $L_I(x) \sim r_{jet}(x)$
- Note that mass flux is not constant due to entrainment!
- Conservation of momentum flux (Q):

$$Q = \dot{m}\bar{u} = (\rho\bar{u}A_{jet})\bar{u} \sim \rho\bar{u}^2 r_{jet}^2 = \text{constant} \Rightarrow \bar{u} \sim (Q/\rho r_{jet}^2)^{1/2}$$

- Kinetic energy flux (K) (not conserved - dissipated!)

$$K = 1/2\dot{m}\bar{u}^2 \sim (\rho\bar{u}A_{jet})\bar{u}^2 \sim \rho\bar{u}^3 r_{jet}^2 \sim Q\bar{u} \Rightarrow dK/dx = Q(d\bar{u}/dx)$$

- KE dissipation

$$\frac{dK}{dx} = \frac{dK}{dm}\frac{dm}{dx} \sim -\frac{u'^3}{L_I}\frac{d(\rho \cdot Volume)}{dx} \sim -\frac{\rho\bar{u}^3}{r_{jet}}\frac{d(\pi r_{jet}^2 x)}{dx} \sim -\frac{\rho\bar{u}^3}{r_{jet}} r_{jet}^2 \sim -\frac{Q\bar{u}}{r_{jet}}$$

Scaling of turbulent jets

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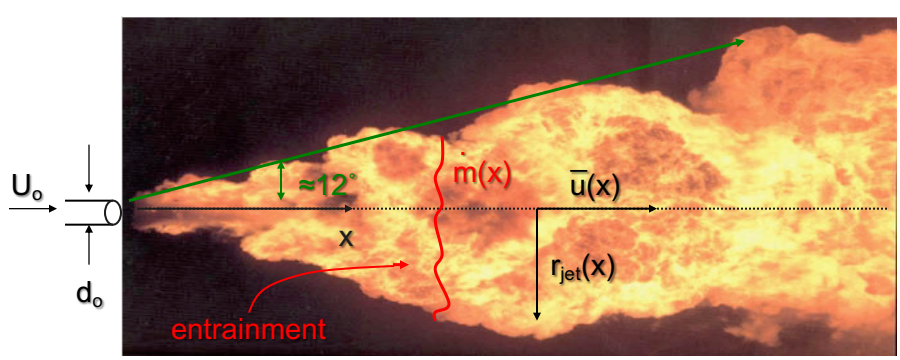

Scaling of turbulent jets

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Combining $\frac{dK}{dx} \sim \frac{Q\bar{u}}{r_{jet}}$ and $\frac{dK}{dx} \sim -Q\frac{d\bar{u}}{dx} \Rightarrow \frac{\bar{u}}{r_{jet}} \sim -\frac{d\bar{u}}{dx} = -\frac{d\bar{u}}{dr_{jet}}\frac{dr_{jet}}{dx}$

From previous page $\bar{u} \sim \sqrt{\frac{Q}{\rho r_{jet}^2}} = \sqrt{\frac{Q}{\rho}}\frac{1}{r_{jet}}$ thus $\frac{d\bar{u}}{dr_{jet}} \sim -\sqrt{\frac{Q}{\rho}}\frac{1}{r_{jet}^2}$

Then $\frac{\bar{u}}{r_{jet}} \sim -\frac{d\bar{u}}{dr_{jet}}\frac{dr_{jet}}{dx} \Rightarrow \sqrt{\frac{Q}{\rho}}\frac{1}{r_{jet}^2} \sim -\left(-\sqrt{\frac{Q}{\rho}}\frac{1}{r_{jet}^2}\right)\frac{dr_{jet}}{dx} \Rightarrow \frac{dr_{jet}}{dx} = \text{Constant}$

$\Rightarrow r_{jet} \sim x$ (experiment: spread $\theta \approx \pm 12^\circ$)

$Q \sim \rho\bar{u}^2 r_{jet}^2 = \text{constant} \Rightarrow \bar{u} \sim (Q/\rho)^{1/2}x^{-1}; \dot{m} = \rho\bar{u}A_{jet} \sim \rho\bar{u}r_{jet}^2 \sim (\rho Q)^{1/2}x$

$\text{Re}_L = \frac{u'L_I}{\nu} \sim \frac{\bar{u}r_{jet}}{\nu} \sim \frac{((Q/\rho)^{1/2}x^{-1})x^1}{\nu} = \text{Constant} \sim \frac{U_o d_o}{\nu}$

Mean strain $\sim \frac{u'}{L_T} \sim \frac{u'}{L_I \text{Re}_L^{-1/2}} \sim \frac{u'}{L_I}\left(\frac{U_o d_o}{\nu}\right)^{1/2} \sim \frac{\bar{u}}{r_{jet}}\left(\frac{U_o d_o}{\nu}\right)^{1/2} \sim \frac{U_o d_o / x}{x}\left(\frac{U_o d_o}{\nu}\right)^{1/2} \sim \text{Re}_{d_o}^{3/2}\frac{\nu}{x^2}$

Liftoff of turbulent jets

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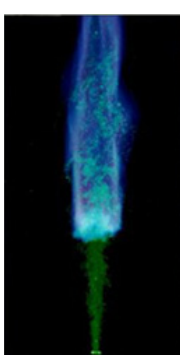
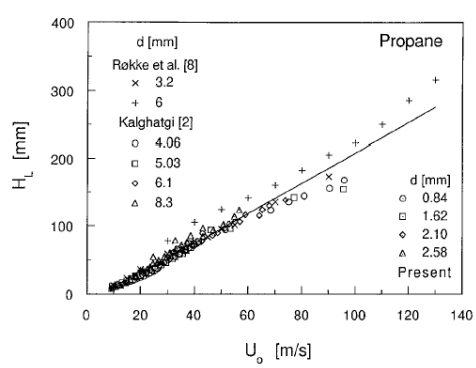
- Scaling suggests mean strain ~ $\text{Re}_{do}^{3/2}\nu/x^2$
- For fixed fuel & ambient atmosphere (e.g. air), strain rate at flamelet extinction (Σ_{ext}) ≈ constant
- Liftoff height (x_{LO}) ~ $(\nu/\Sigma_{ext})^{1/2}\,\text{Re}_{do}^{3/4} \sim u_o^{3/4}d_o^{3/4}$
- Experiments - closer to $x_{LO} \sim u_o^1 d_o^0$ - but how to make dimensionless? Need time scale, i.e. $x_{LO} \sim u_o^1 d_o/\omega$, where $\omega \approx S_L^2/\alpha \approx S_L^2/\nu$, leading to $x_{LO}S_L/\nu \sim u_o/S_L$



G. Mungal (Stanford)



Cha and Chung, 1996

Liftoff of turbulent jets

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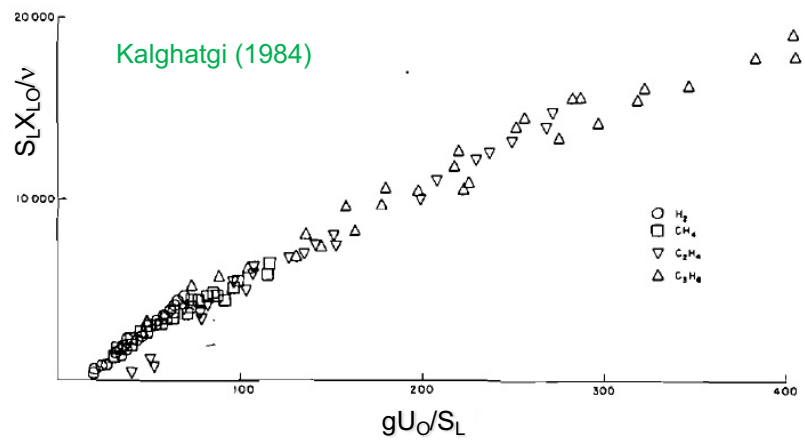
- Similar trend ($x_{LO} \sim u_o^1 d_o/\omega$) seen in other fuels, scaled by highest S_L of fuel/air mixture and fuel density ratio function g

$$g(\overline{\rho}) = 0.04 + 0.46\overline{\rho} + 0.5\overline{\rho}^2; \overline{\rho} = \rho_{fuel}/\rho_{air}$$



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Lifted turbulent flame theories (Lyons, 2007)

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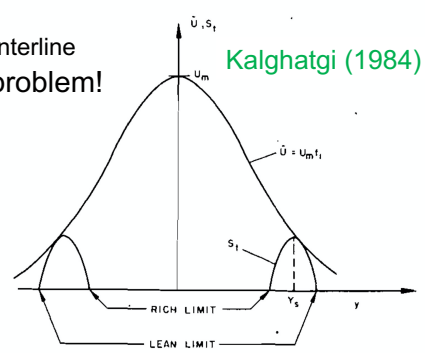
- Premixed flame theory: $S_L \approx \overline{u}$ at $x = x_{LO}$ (≈ edge-flame theory)
- Critical scalar dissipation (Peters & Williams, 1983): $\omega \approx$ mean turbulent strain at $x = x_{LO}$
- Turbulent flame theory: $S_T \approx \overline{u}$ at $x = x_{LO}$ (Kalghatgi, 1984)
  - Which S_T? Flamelet or distributed? Which model?
  - Need to satisfy 2 conditions
    - » $S_T \approx \overline{u}$
    - » Stoichiometric mixture (maximum S_T)
    - » Stabilization point may not be at jet centerline
- What are predictions? Homework problem!



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EDGE FLAMES - motivation

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- Reference: Buckmaster, J., "Edge flames," *Prog. Energy Combust. Sci.* 28, 435-475 (2002)
- Laminar flamelet model used to describe local interaction of premixed & nonpremixed flames with turbulent flow
- Various regions of turbulent flow will be above/below critical extinction strain (Σ_{ext})
- Issues
  - Can flame "holes" or "edges" persist?
  - Will extinguishment in high-Σ region spread to other regions?
  - Will burning region re-ignite extinguished region?
  - Will Σ at edge locate (Σ_{edge}) be at higher or lower strain than extinction strain for uniform flame (Σ_{ext})?
  - How is edge propagation rate affected by Σ?
  - Lewis number effects?

Edge flames

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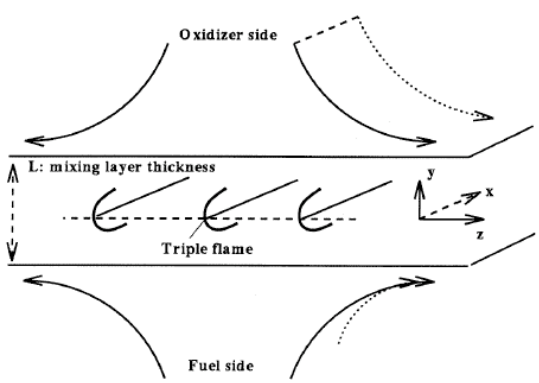
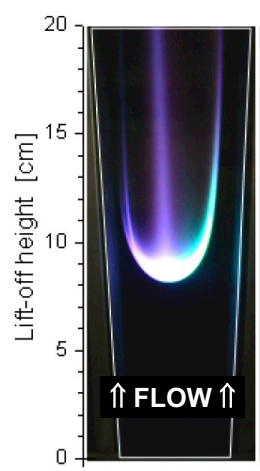
- Flame propagates from a burning region to a non-burning region, or retreats into the burning region
- Could be premixed or non-premixed



Non-premixed edge-flame in a counterflow



Kim et al., 2006

Edge flames - nonpremixed - theory

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- Daou and Linan, 1998
- Configuration as in previous slide
- No thermal expansion
- Non-dimensional stretch rate $\varepsilon = (\Sigma\alpha/S_L^2)^{1/2}$ or Damköhler number $\sim S_L^2/\Sigma\alpha \sim \varepsilon^{-2}$

  S_L = steady unstretched S_L of stoichiometric mixture of fuel & air streams
- Effects of stretch
  - Low ε: flame advances, "triple flame" structure - lean premixed, rich premixed & trailing non-premixed flame branches
  - Intermediate ε: flame advances, but premixed branches weaker
  - High ε: flame retreats, only nonpremixed branch survives
  - Note that stretch rate corresponding to zero edge speed is always less than the extinction stretch rate for the uniform (edgeless, infinite) flame sheet - edge flames always weaker than uniform flames - retreat in the presence of less strain than required to extinguish uniform flame
- Le effects: as expected - lower Le yields higher edge speeds, broader extinction limits

Edge flames - nonpremixed - theory

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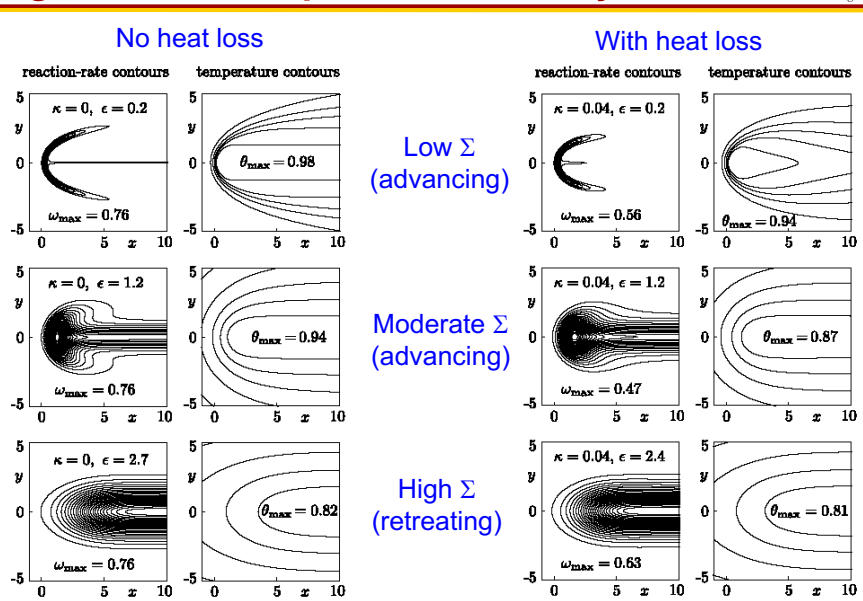

Daou et al., 2002

Edge flames - nonpremixed - theory

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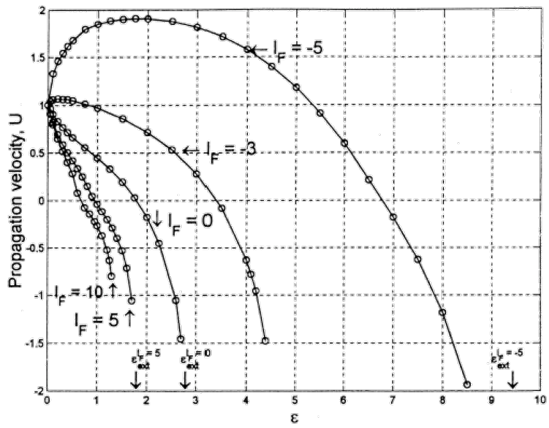
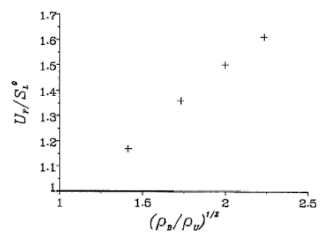
- Daou and Linan, 1998 ($l_F = \beta(Le_{Fuel} - 1)$)
- Thermal expansion effect (Ruetsch et al., 1995): $U/S_L \sim (\rho_\infty/\rho_f)^{1/2}$ with proportionality constant shown





Edge flames - nonpremixed - with heat loss

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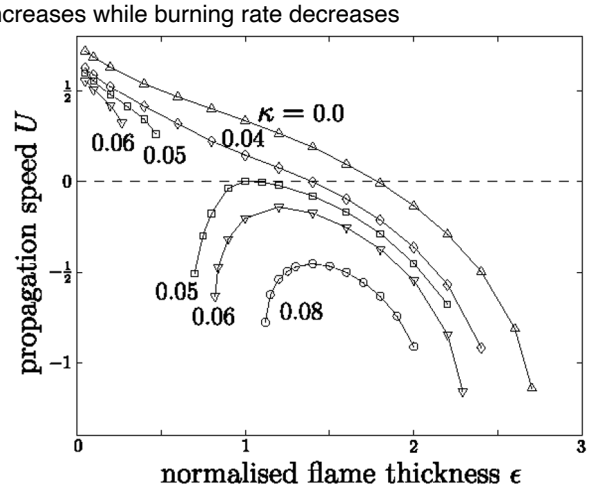
- Daou et al., 2002
- κ = dimensionless heat loss $\approx 7.5\beta/Pe^2$; $Pe \equiv S_L d/\alpha$ (see Cha & Ronney, 2006)
- With heat loss: trailing non-premixed branch disappears at low ε - nonpremixed flame extinguishes because mixing layer thickness $\sim (\alpha/\Sigma)^{1/2}$ (thus volume, thus heat loss) increases while burning rate decreases



Experiments - nonpremixed edge-flames

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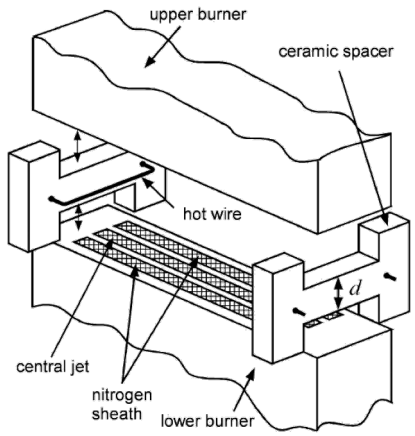
- Cha & Ronney (2006)
- Use parallel slots, not misaligned slots
- Use jet of N_2 to "erase" flame, then remove jet to watch advancing edge, or establish flame, then zap with N_2 jet to obtain retreating flame



Edge flames - nonpremixed - experiment

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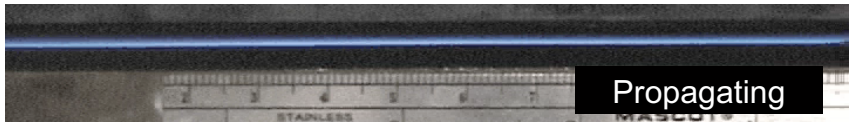

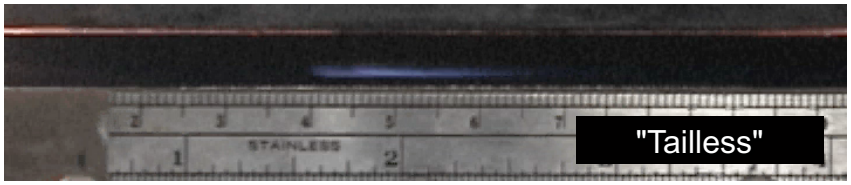

Edge flames - nonpremixed - experiment

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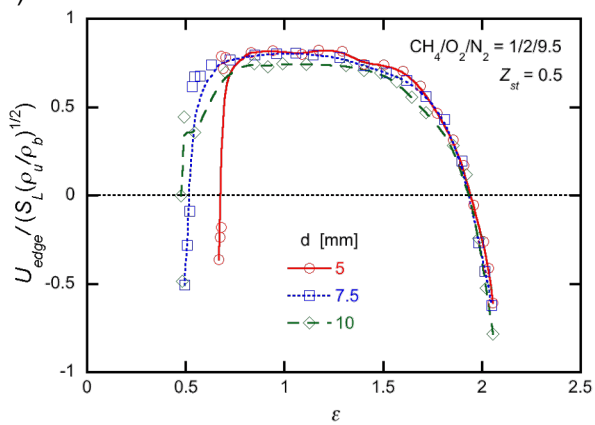
- Behavior very similar to model predictions with heat loss - negative at low or high ε, positive at intermediate ε with $U_{edge}/S_L \approx 0.7(\rho_\infty/\rho_f)^{1/2}$ (prediction: ≈ 1.8)
- Propagation rates ≈ same for different gaps when scaled by strain rate Σ except at low Σ (thus low V_{jet}) where smaller gap ⇒ more heat loss (higher κ)



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Edge flames - nonpremixed - experiment

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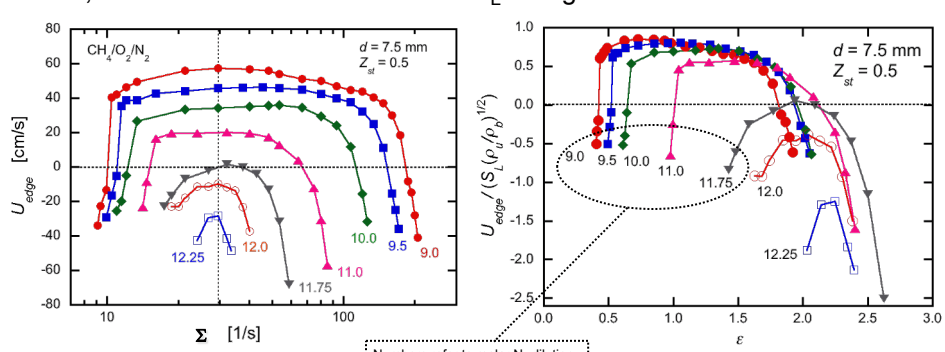
- Dimensional U_{edge} vs. stretch (Σ) can be mapped into scaled U_{edge} vs. scaled stretch rate (ε) for varying mixtures
- Little effect of mixture strength when results scaled by ε, except at low Σ, where weaker mixture ⇒ lower S_L ⇒ higher κ



Dimensional

Numbers refer to molar N_2 dilution when fuel and oxidant streams are mixed in stoichiometric proportions (CH_4:O_2:N_2 = 1:2:N)

Dimensionless

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Edge flames - nonpremixed - experiment

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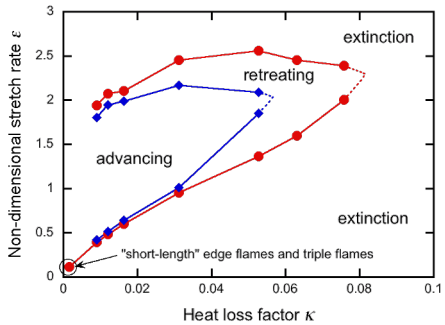
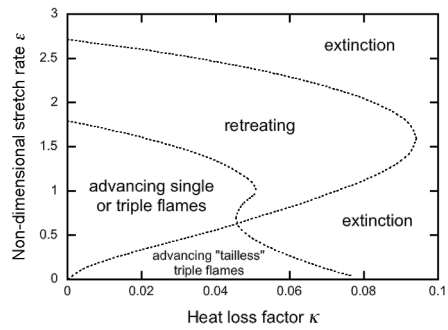
- High stretch (ε) or heat loss (κ) causes extinction - experiments surprising consistent with experiments, even quantitatively
- Very difficult to see "tailless" flames in experiments
  - Model assumes volumetric heat loss (e.g. radiation) - mixing layer thickness can increase indefinitely, get weak non-premixed branch that can extinguish when premixed branches do not
  - Experiment - heat loss mainly due to conduction to jet exits, mixing layer thickness limited by jet spacing



Experiment (Cha & Ronney, 2006)



Prediction (Daou et al., 2002)

Edge flames - nonpremixed - experiment

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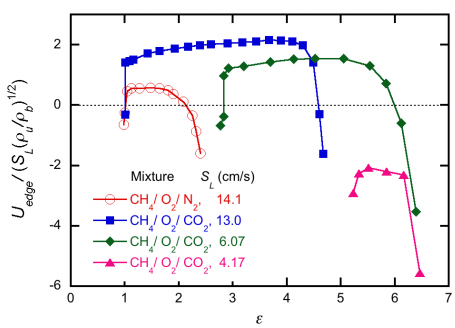
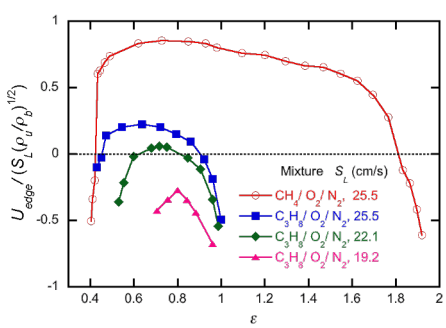
- Lewis number effects VERY pronounced - at low Le, MUCH higher U_{edge} than mixture with same S_L (thus κ) with Le ≈ 1
- Opposite trend for Le > 1



Low Le (CH_4-O_2-CO_2)
(Le_{fuel} = 0.74; Le_{O2} = 0.86)



High Le (C_3H_8-O_2-N_2)
(Le_{fuel} = 1.86; Le_{O2} = 1.05)

Edge flames - nonpremixed - experiment

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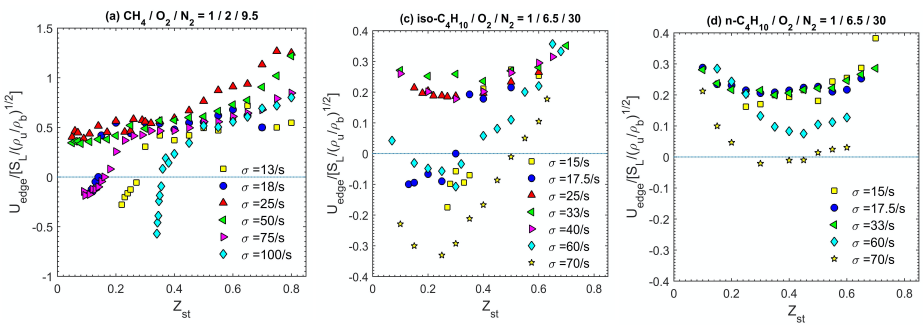
- U_{edge} not at all symmetric with respect to Z_{st} = 0.5!
- Due to shift in reaction zone (radical production) from O_2 to fuel side as Z_{st} increases; radicals don't need to "swim upstream" & cross stagnation plane to reach and decompose O_2
- Lewis number effects for large fuel molecules – non-monotonic trend
- More easily decomposed fuels (n-butane vs. iso-butane) have smaller fragments, lower effective Le, higher U_{edge}



Note strain rate $\Sigma = \sigma$ here!

Song et al., 2006

Edge flames – nonpremixed – low Le

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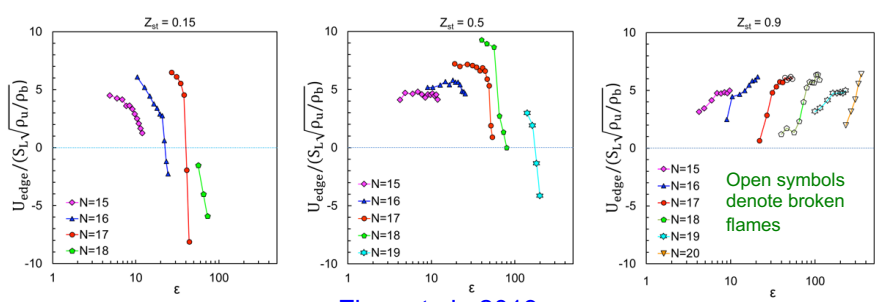
- Low Le_f, high Z_{st}: diffusive-thermal (cellular) instability (Chen et al., 1992; Kim et al., 1996)
- What happens in H_2-O_2-N_2 edge-flames? High Z_{st} should have higher U_{edge} due to Le effects; is there also a chemical effect?



Zhou et al., 2019

Edge flames – nonpremixed – low Le

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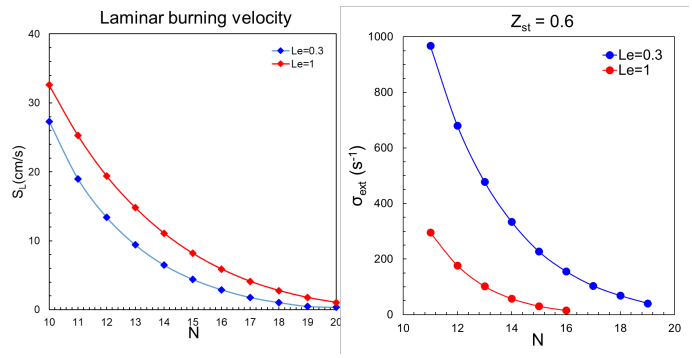
- Strong Le effects on strained flames cause unreasonably large U_{edge} & σ_{ext}
- S_L hardly changes with Le, but σ_{ext} sure does
- How to incorporate Le effects? Use $\varepsilon = \sigma/\sigma_{ext}$, "$S_{L,eff}$" = $(\alpha\omega)^{1/2}$ = $(\alpha\sigma_{ext})^{1/2}$

$$\tilde{U} \equiv U_{edge} \big/ S_{L,eff} = U_{edge} \big/ \sqrt{\alpha\sigma_{ext}}$$



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Edge flames – nonpremixed – low Le

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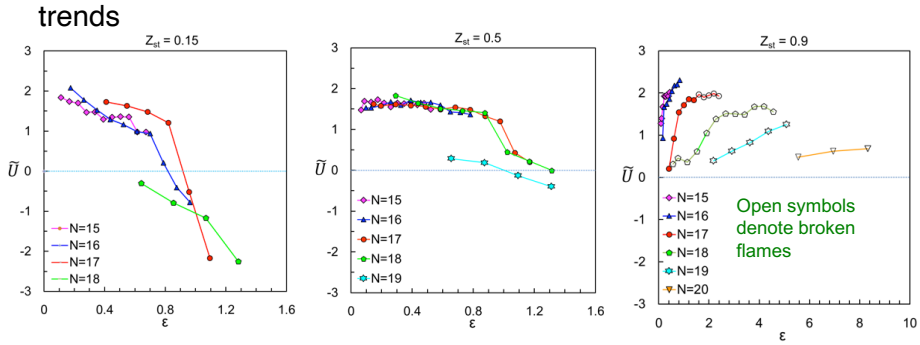
- Low and intermediate Z_{st} show monotonically decreasing $\tilde{U}$ with increasing ε, but high Z_{st} shows opposite trend due to lower effective Le
- Proposed scaling with σ_{ext} works – all Z_{st} (thus all Le) show similar trends



Zhou et al., 2019

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Edge flames – nonpremixed – low Le

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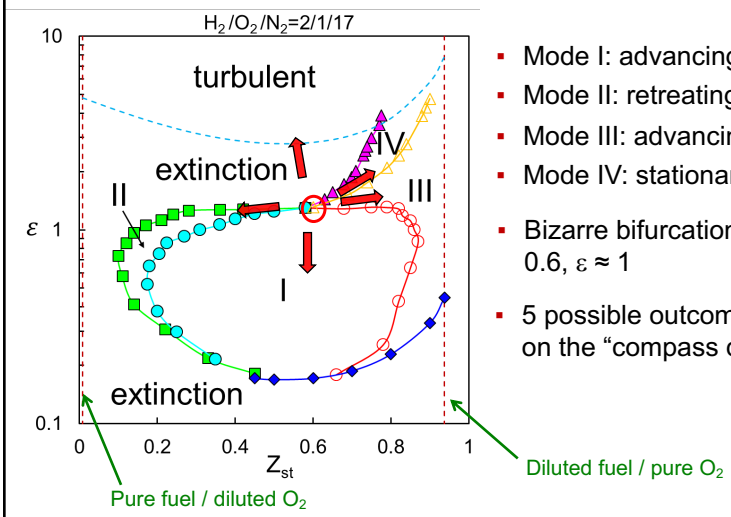

- Mode I: advancing continuous flame
- Mode II: retreating continuous flame
- Mode III: advancing broken flame
- Mode IV: stationary broken flame
- Bizarre bifurcation point at $Z_{st} \approx 0.6$, $\varepsilon \approx 1$
- 5 possible outcomes depending on the "compass direction"!

Zhou et al., 2019

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Edge flames – nonpremixed – low Le

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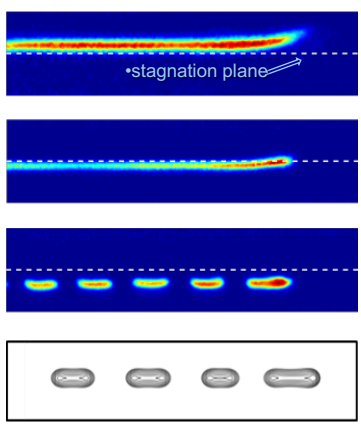

Z_{st} = 0.4 σ = 80/s H_2 / O_2 / N_2 = 2 / 1 / 18

Z_{st} = 0.6 σ = 80/s H_2 / O_2 / N_2 = 2 / 1 / 18

Z_{st} = 0.9 σ = 80/s H_2 / O_2 / N_2 = 2 / 1 / 18

Computed reaction rate contours for an advancing broken flame with *Le*=0.33 (Thatcher & Dold, CTM 1999)

Zhou et al., 2019

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Edge flames – nonpremixed – low Le

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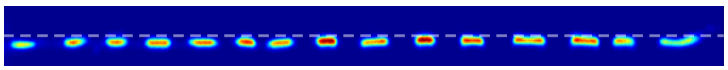
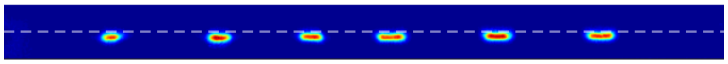
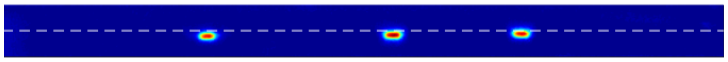
- With increasing dilution or strain, broken flamelets become more sparse and edge-flame changes from propagating (Mode III) to stationary (Mode IV)



Z_{st} = 0.80 σ = 100/s H_2 / O_2 / N_2 = 2 / 1 / 18



Z_{st} = 0.80 σ = 100/s H_2 / O_2 / N_2 = 2 / 1 / 18.5



Z_{st} = 0.80 σ = 100/s H_2 / O_2 / N_2 = 2 / 1 / 19

Zhou et al., 2019

Edge flames – nonpremixed – low Le

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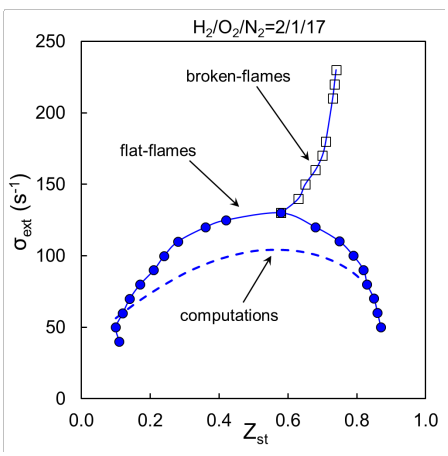

- Computed 1D extinction limits for continuous flames are similar to experiments
- Bifurcation at $Z_{st} \approx 0.6$ allows highly-strained flames at higher Z_{st} & σ to exist as broken flames only
- Limit conditions for continuous flames is same as transition to broken flames
- Flames break only if they have no other choice for survival!

Zhou et al., 2019

Edge flames - premixed - theory

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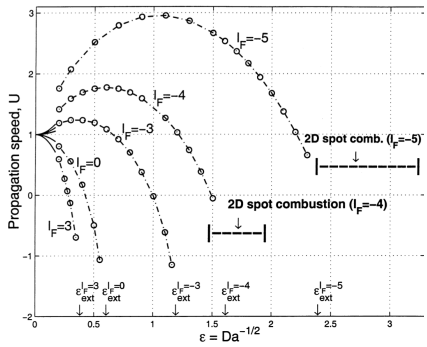
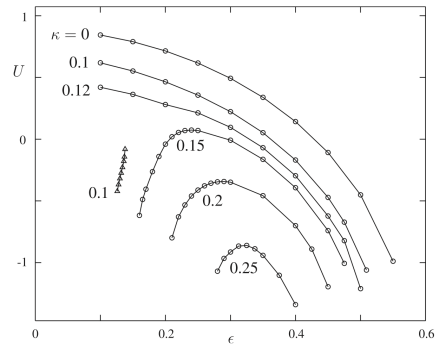
- Similar response of U_{edge} to stretch as nonpremixed flames
- Again larger U_{edge} for low Le
- Again 2nd extinction limit at low strain rates when heat losses present





Daou & Linan, CNF 1999

Daou et al., CTM 2003

Edge flames – twin premixed - images

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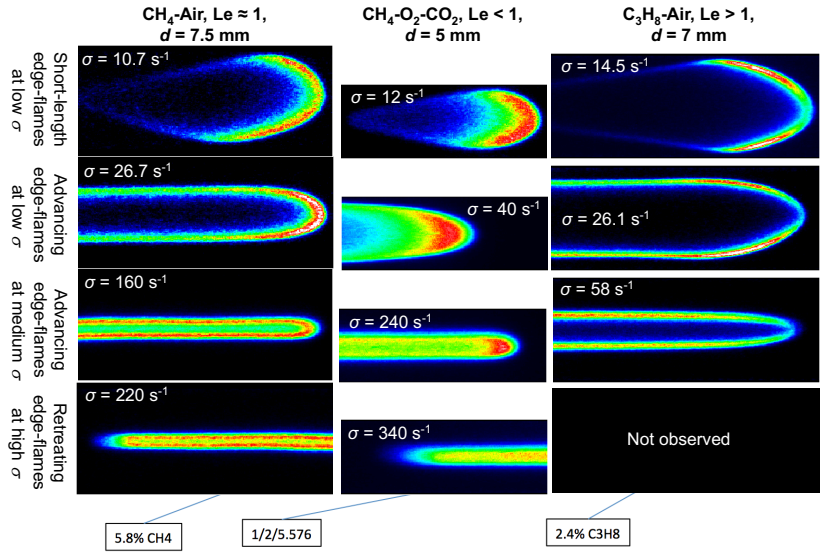
- Lewis number effects very evident – curvature effects on leading edge



Clayton *et al.*, 2019

Edge flames – twin premixed - U_{edge}

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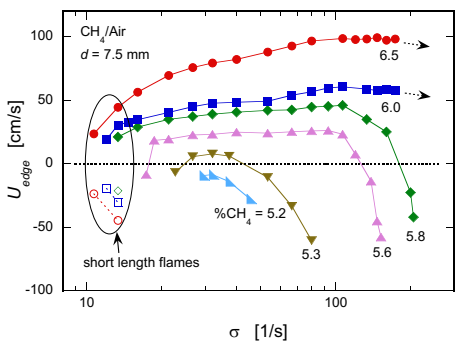
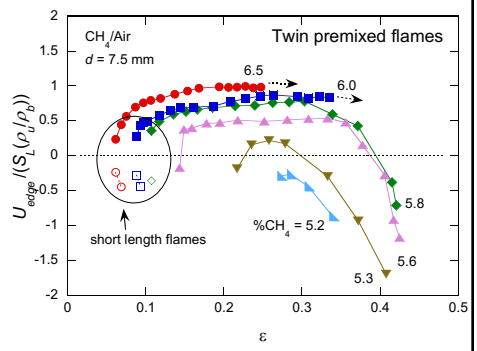
- Propagation rates scale with $(\rho_u/\rho_b)^1$ not $(\rho_u/\rho_b)^{1/2}$
- Again 2 extinction limits, high & low strain rates



Raw data



Scaled data

Clayton *et al.*, 2019

Edge flames – twin premixed - U_{edge}

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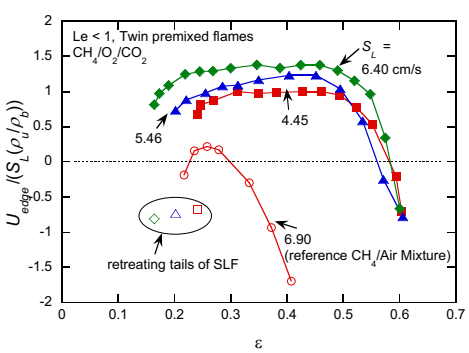
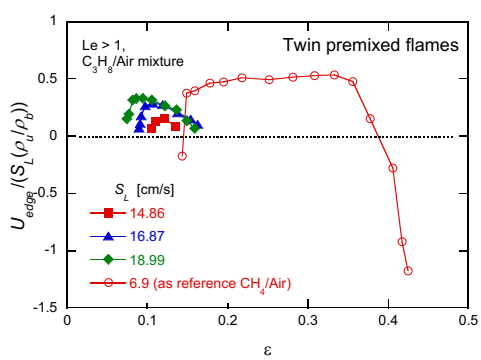
- Lewis number effects similar to nonpremixed edge flames



Low fuel Le



High fuel Le

Clayton *et al.*, 2019

Edge flames – twin premixed - regimes

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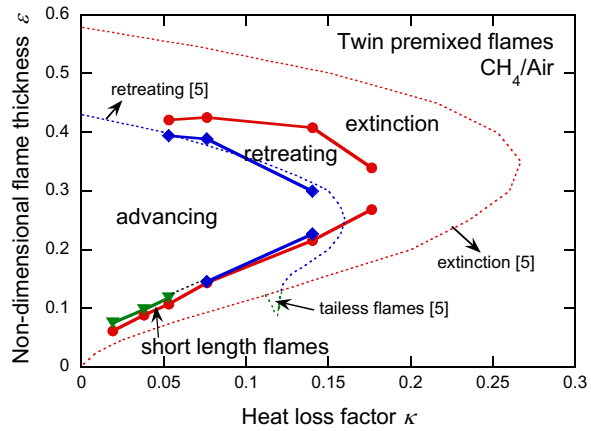
- Regimes of behavior similar to nonpremixed edge flames



Experiments
Clayton *et al.*, 2019

Model predictions
Daou et al., CTM 2003

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Edge flames – single premixed - images

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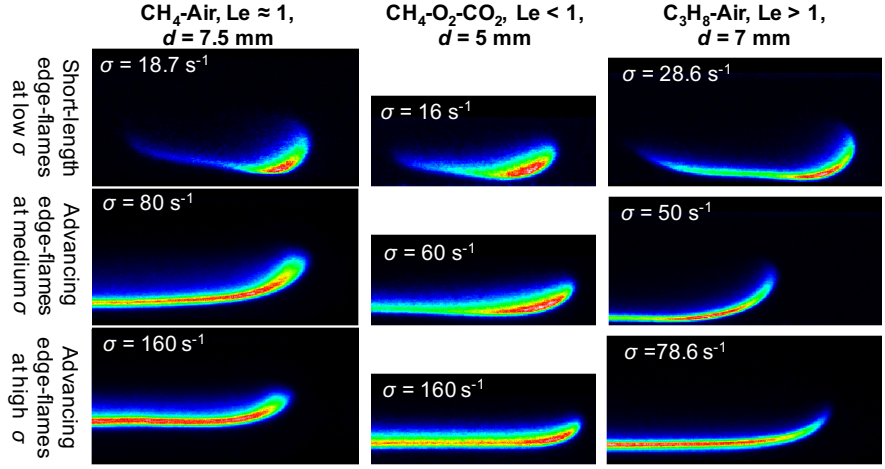

Clayton *et al.*, 2019

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Edge flames – single premixed - U_{edge}

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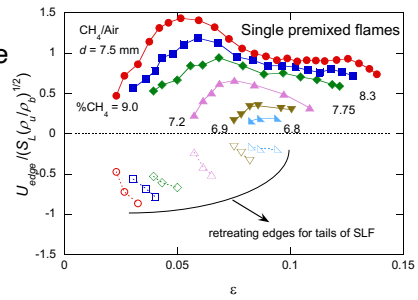
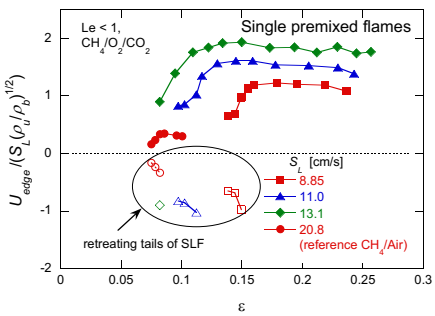
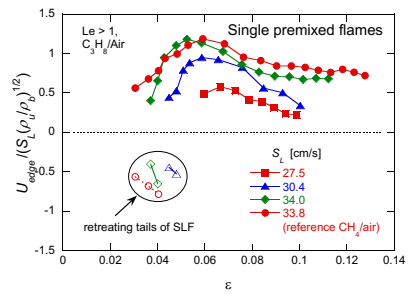
- Propagation rates scale with $(\rho_u/\rho_b)^{1/2}$
- Structure similar to nonpremixed flame – large temperature gradients on <u>both</u> sides of reaction zone, unlike twin premixed flame
- Less Lewis number effect than nonpremixed or twin premixed, especially for Le > 1







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