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# Effect of Hydrogen Addition on Burning Rate and Surface Density of Turbulent Lean Premixed Methane-Air Flames


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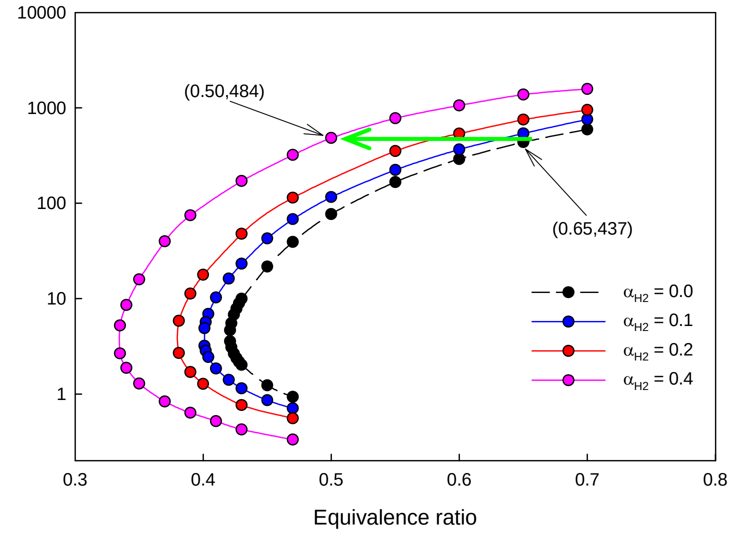
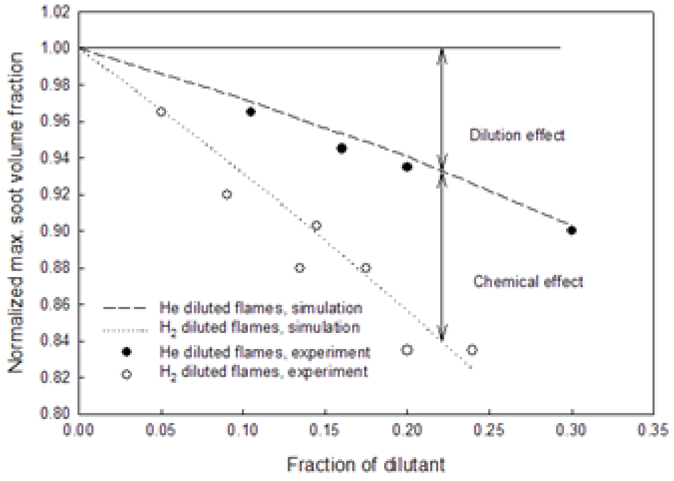
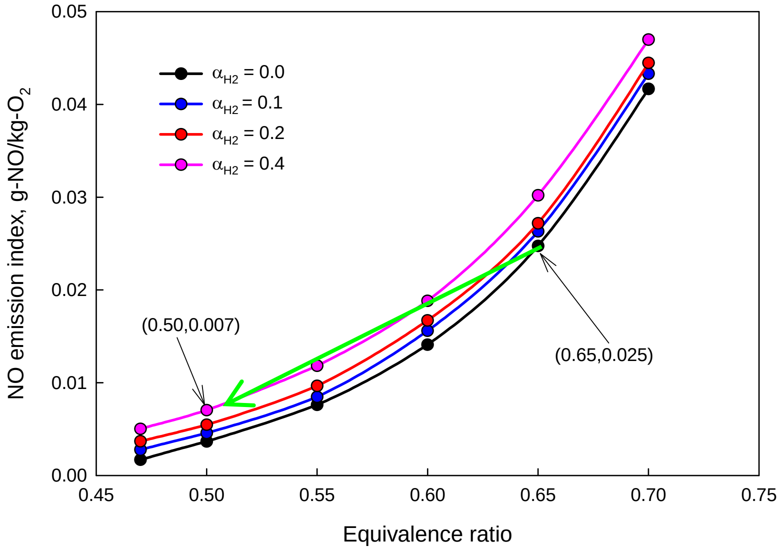
# Background (1)

- $H_2$ is a clean burning component, but relatively expensive
- Mixing a small amount of $H_2$ with other fuels is an effective way to use $H_2$
- $H_2$ enriched combustion significantly improves fuel efficiency and reduces pollutant ($NO_x$, PM) emissions



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# Background (2)

- How does $H_2$ addition affect flame speed?
  - $H_2$ enrichment increases laminar flame speed
  - Contradictory results exist for turbulent flame speed
    - Traditional theory predicts a decrease in the ratio of turbulent to laminar flame speeds with the addition of $H_2$
      - supported by Liu and Lenze (1988) and Mandilas et al. (2007)
      - but inconsistent with the results of Goix and Shepherd (1993), Hawkes et al. (2004) and Cohé et al. (2007)
    - Does $H_2$ addition affect flame surface characteristics?
  - Further study is needed

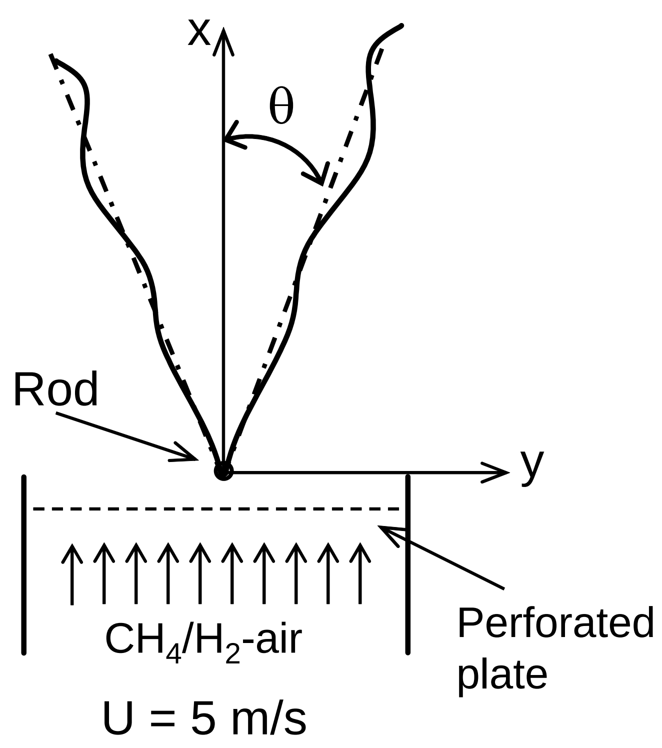
$$S_T / S_L = 1 + A\left( v' / S_L \right)^n$$

# Objective

- Investigate the effect of $H_2$ addition on flame surface density and burning velocity of lean premixed $CH_4$/air flames

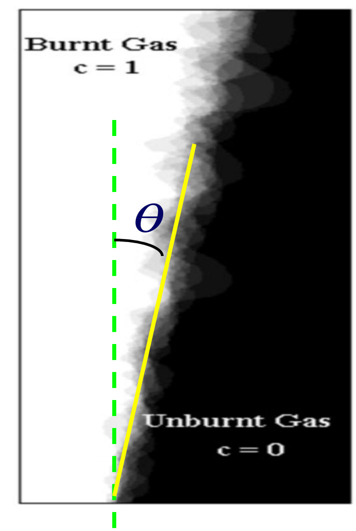
# Flame Configuration

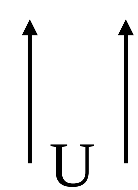
- V-shaped $CH_4$/air premixed flames
- Turbulence
  - Set 1: turbulent intensity = 4%, integral length scale = 4.8 mm, Re = 60
  - Set 2: turbulent intensity = 8%, integral length scale = 7.3 mm, Re = 180
- $\phi$ = 0.55, 0.6
- $V'/S_L = 1 \sim 2$
- $H_2$ fraction: $V_{H2}/(V_{H2}+V_{CH4}) = 0 \sim 0.3$



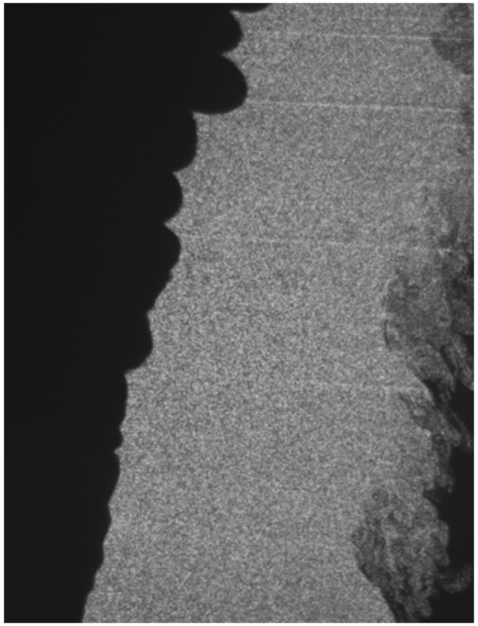
# Experimental Methodology

- Laser tomography technique was employed
  - Unburned mixture was seeded by incense particles and illuminated by laser sheet
  - Tomography of flame front was recorded by a CCD camera
  - 300 imagines were taken for each flame
  - Imagines were analyzed and binarized by a Matlab based software
  - Mean progress variable, changing from 0 (unburnt side) to 1 (burnt side), was obtained by averaging the 300 imagines
- Flame brush thickness: the horizontal distance from 0 to 1
- Burning velocity: $S_T = U * \sin\theta$
- Flame surface density: $F_{SD} = \frac{1}{n}\sum \frac{dL}{ds}$



# Typical Imagines

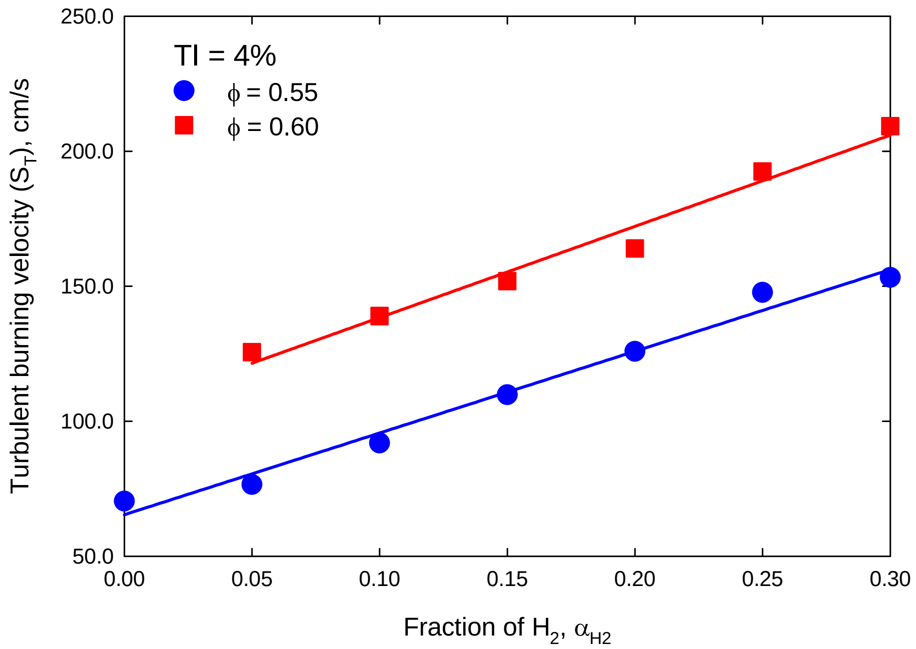


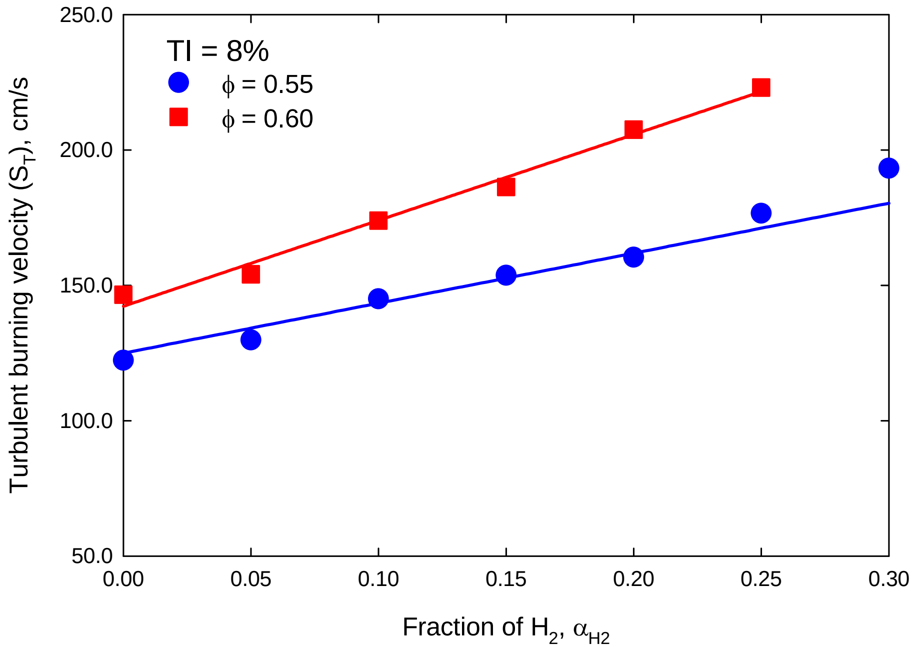
$\alpha_{H2}$: 0%

$\alpha_{H2}$: 0.3

- $H_2$ addition increases the wrinkle extent of flame surface at a constant equivalence ratio and turbulence level

# Burning Velocity




- $H_2$ addition leads to increase in burning velocity

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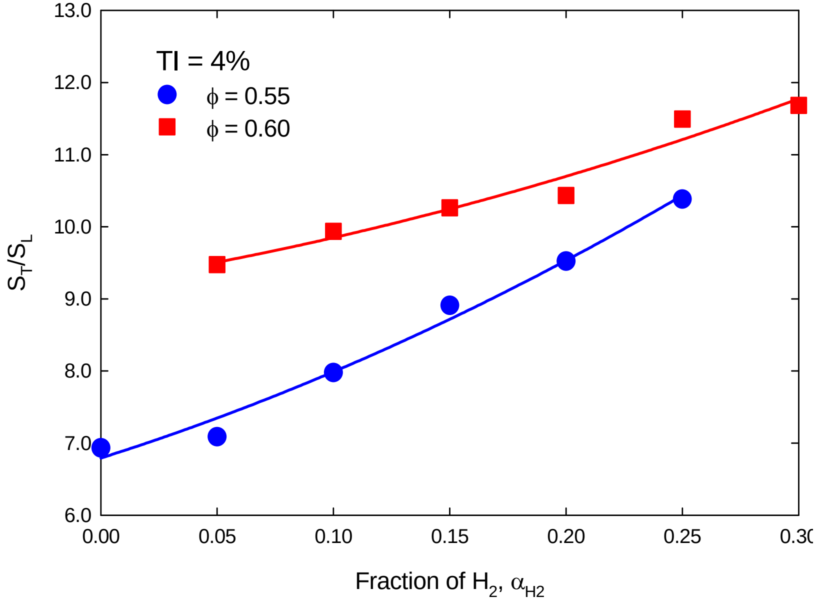
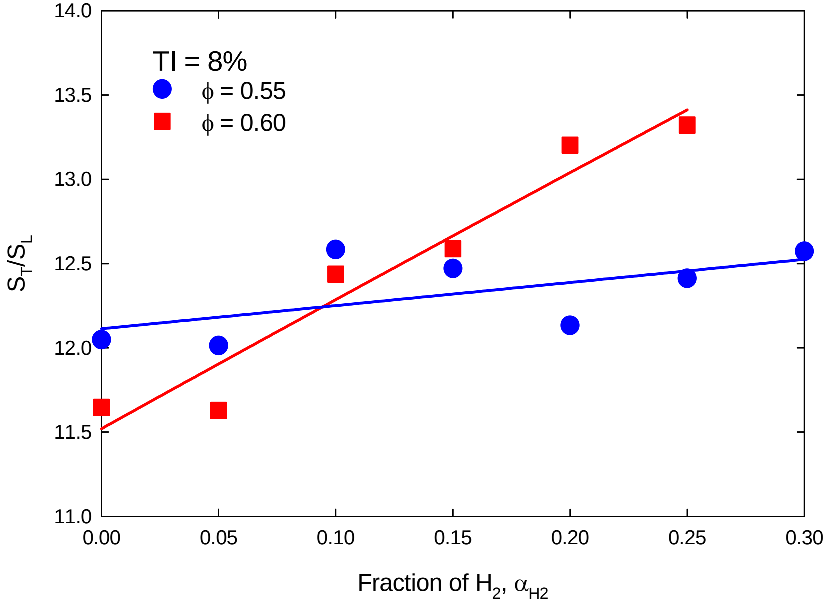
# Ratio of Turbulent to Laminar Burning Velocities




- $H_2$ addition results in increase in the ratio too, implying that turbulent burning velocity increases faster than laminar burning velocity when $H_2$ is added
- Inconsistent with traditional theory? $\rightarrow$ $$S_T/S_L = 1 + A\left(v'/S_L\right)^n$$
- ***Why?***

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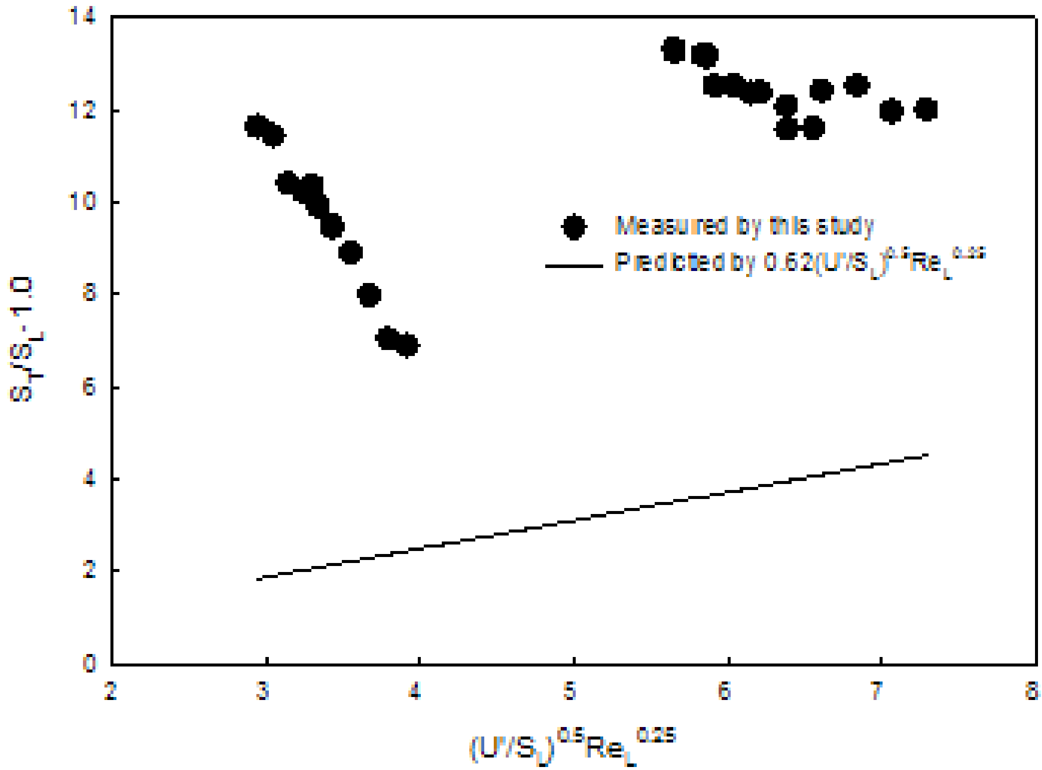
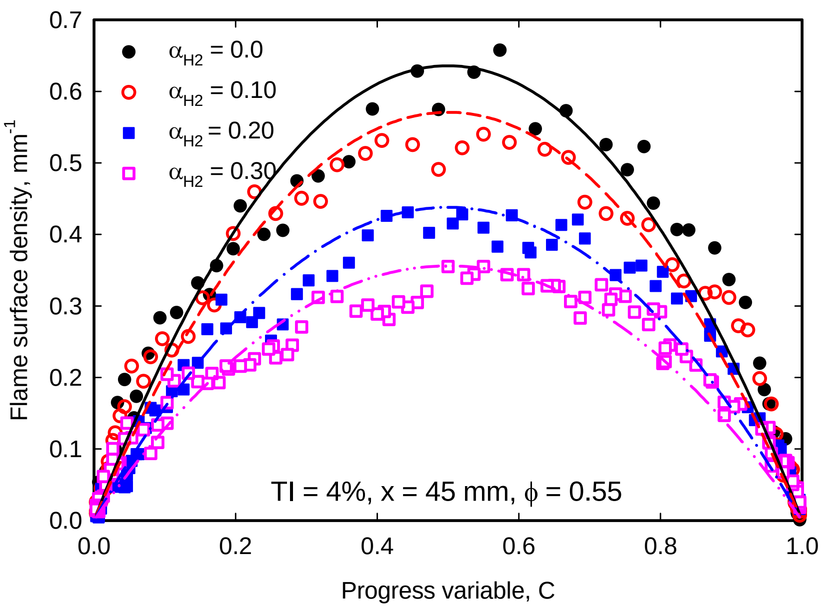
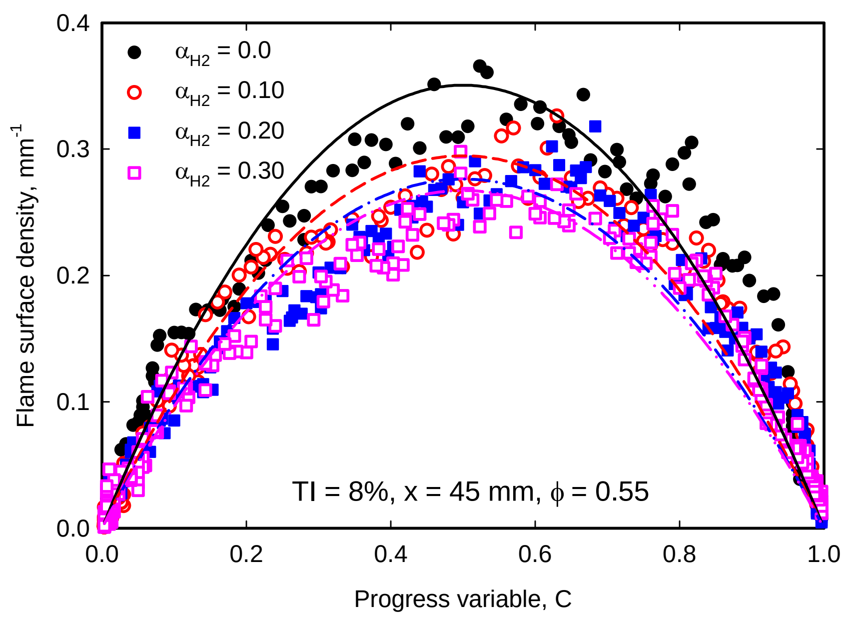


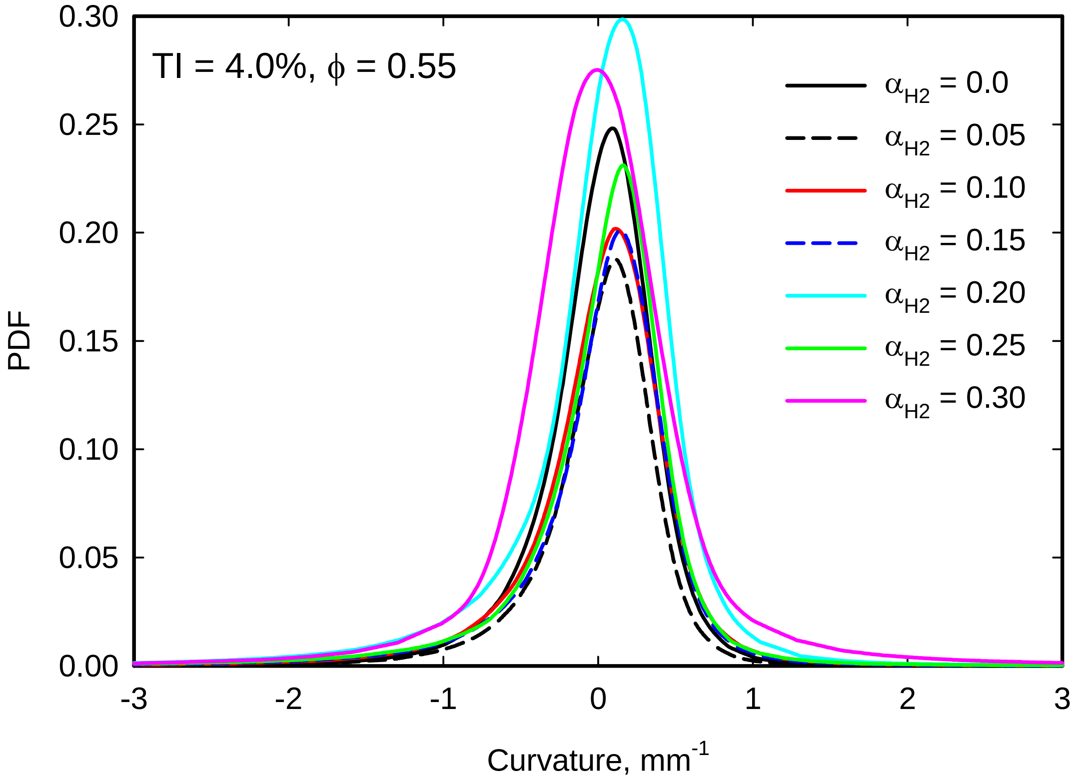
# Flame Surface Density



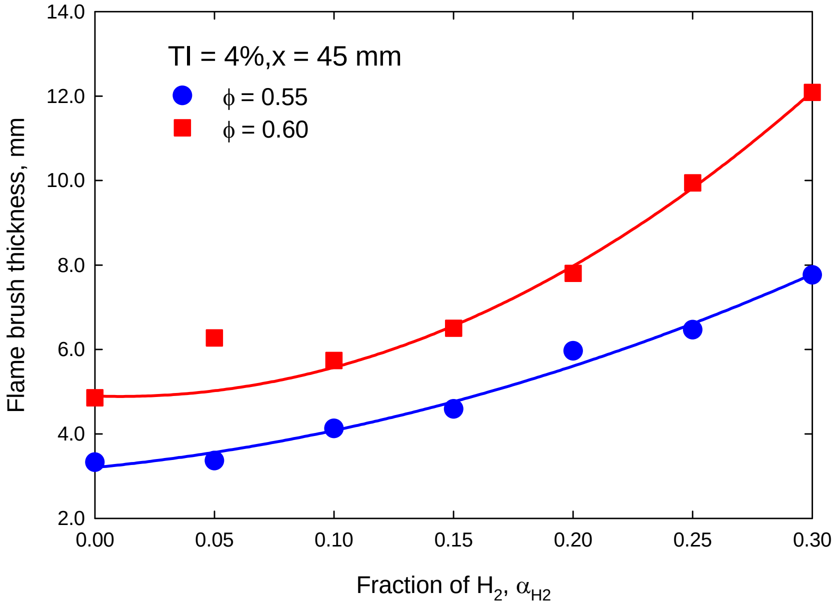

- Flame surface density slightly decreases with the addition of $H_2$

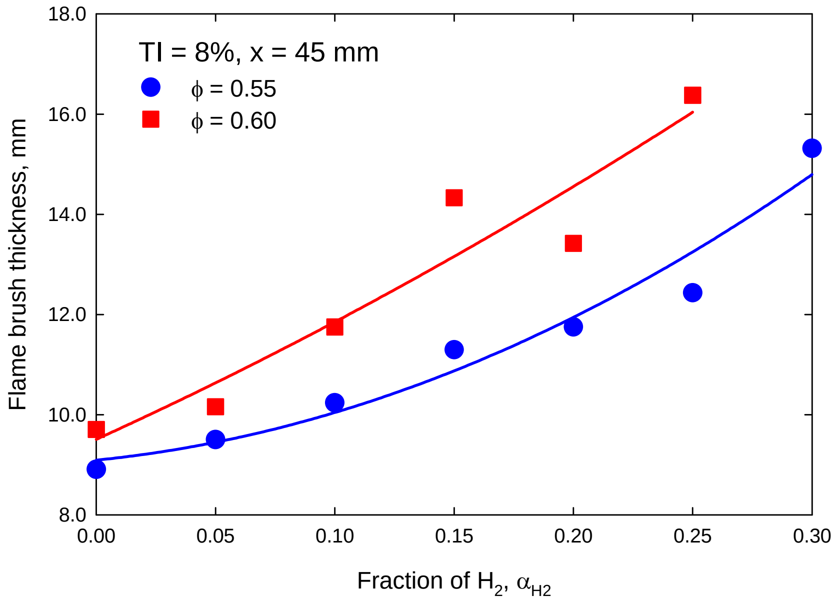
# Curvature




- No clear trend can be observed for the variation of curvature with the addition of $H_2$

# Flame Brush Thickness




- $H_2$ addition leads to increase in flame brush thickness

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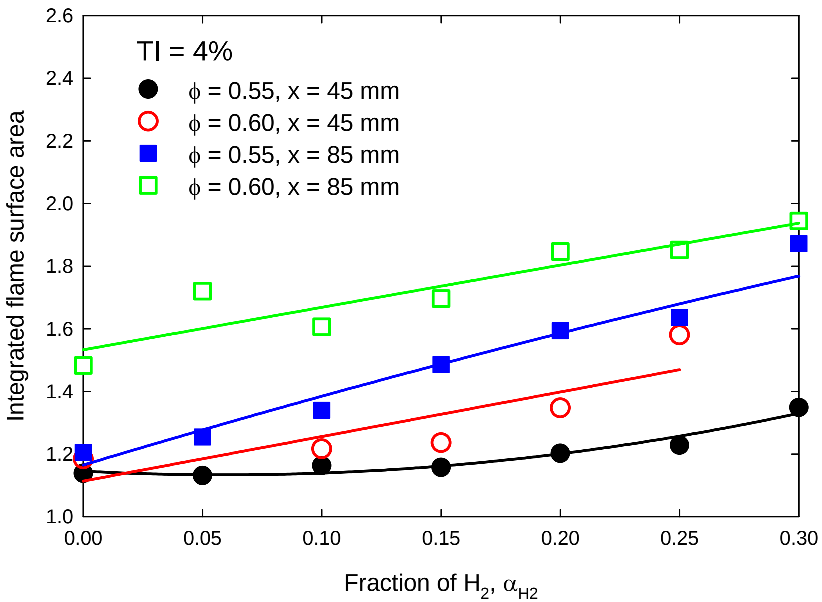
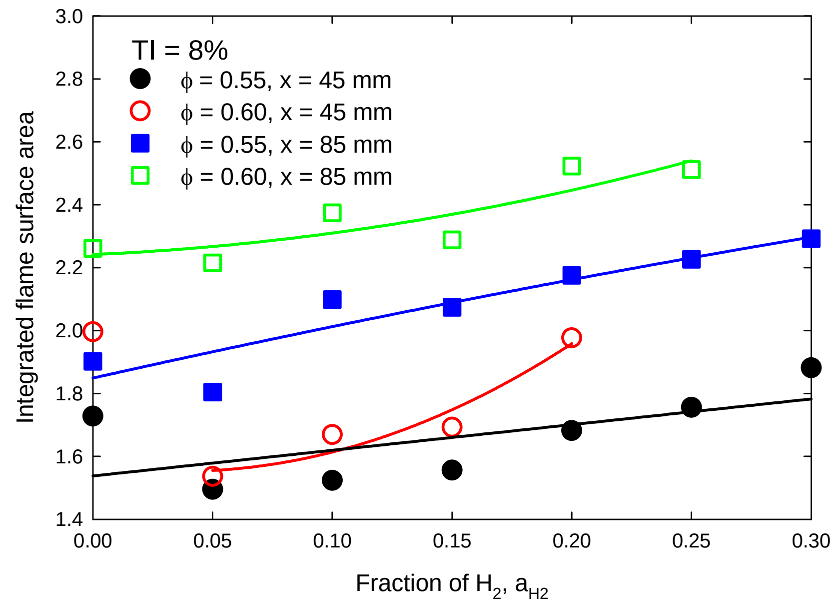
# Integrated Flame Surface Area




- $H_2$ addition causes increase in integrated flame surface area, which may increase burning velocity ($S_T \propto F * S_L$)

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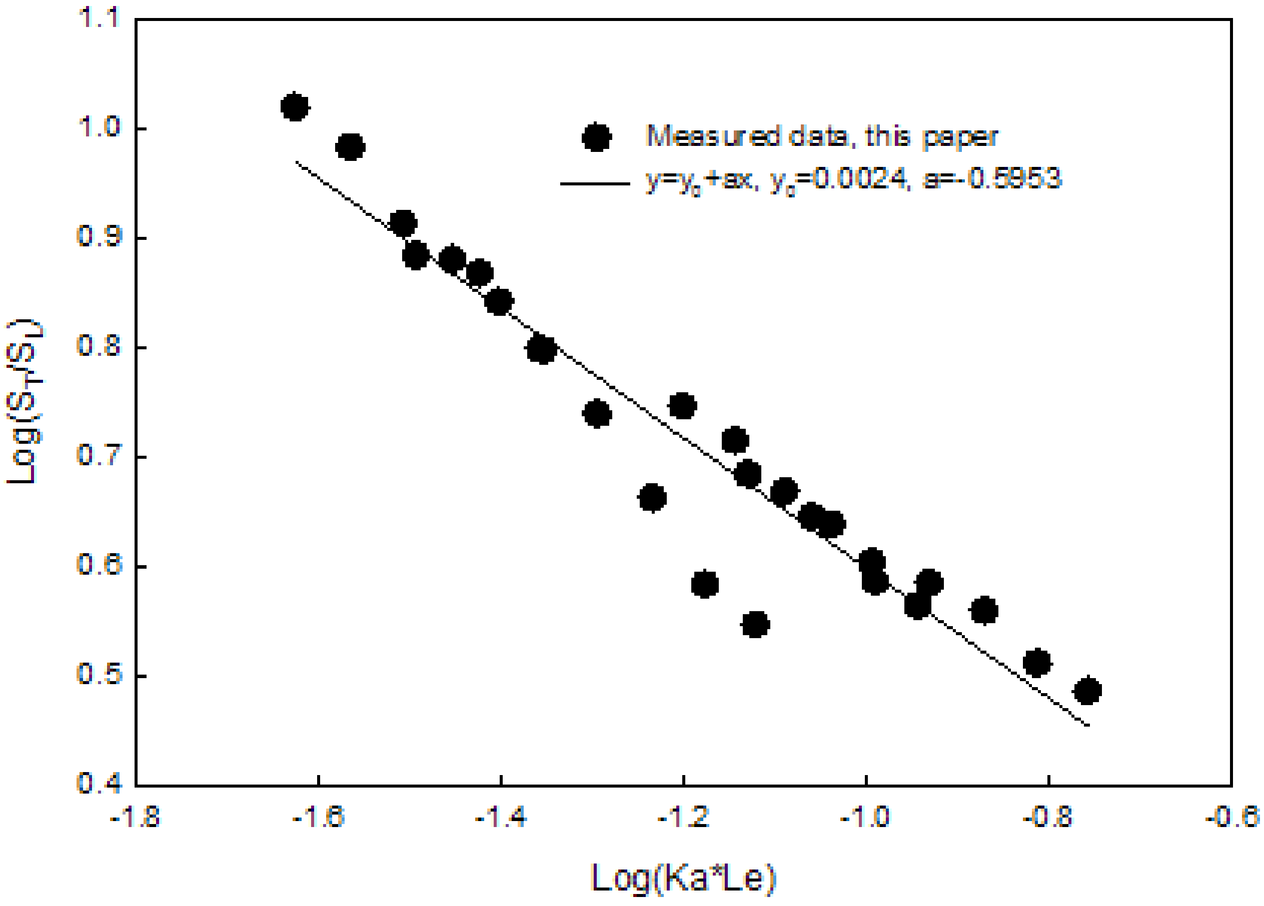

# Conclusions

- Addition of $H_2$ leads to increase in turbulent burning velocity for $CH_4$/air premixed flames
- The increase of turbulent burning velocity is faster than that of laminar burning velocity, which contradicts traditional theory
- $H_2$ addition causes increase in turbulent burning velocity due to not only the physical and chemical property effect (laminar burning velocity), but also the variation in flame structure
  - $H_2$ addition increases flame brush thickness

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