Lower limit of weak flame in a heated channel

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Background

For highly efficient combustion, HiCOT, HCCI, etc…

- Controlling initial state of combustion important
- Exergy (Availability) efficiencies of combustion process significantly improved

General characteristics of <u>combustion with heat recirculation</u> studied in the context of microcombustion (Maruta et al. PCI 30, 2005)

• 1-D straight meso-scale channel with temperature gradient

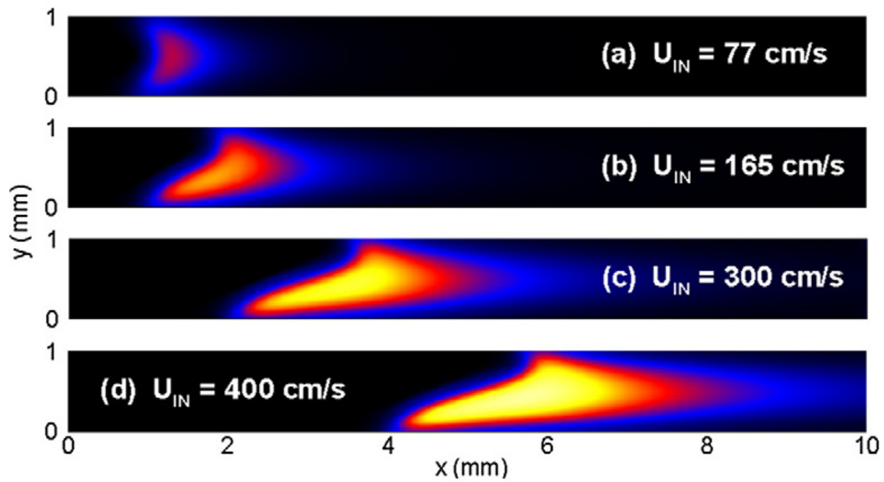
- S-shaped curve (Normal and weak flames identified)
- *Flames with repetitive extinction and ignition* (FREI) identified

Background

• 1-D straight meso-scale channel with temperature gradient covered by:

-Dynamics of flame in narrow tube examined
(Jackson, Buckmaster, Lu, Kyritsis, Massa, PCI31, 2007)

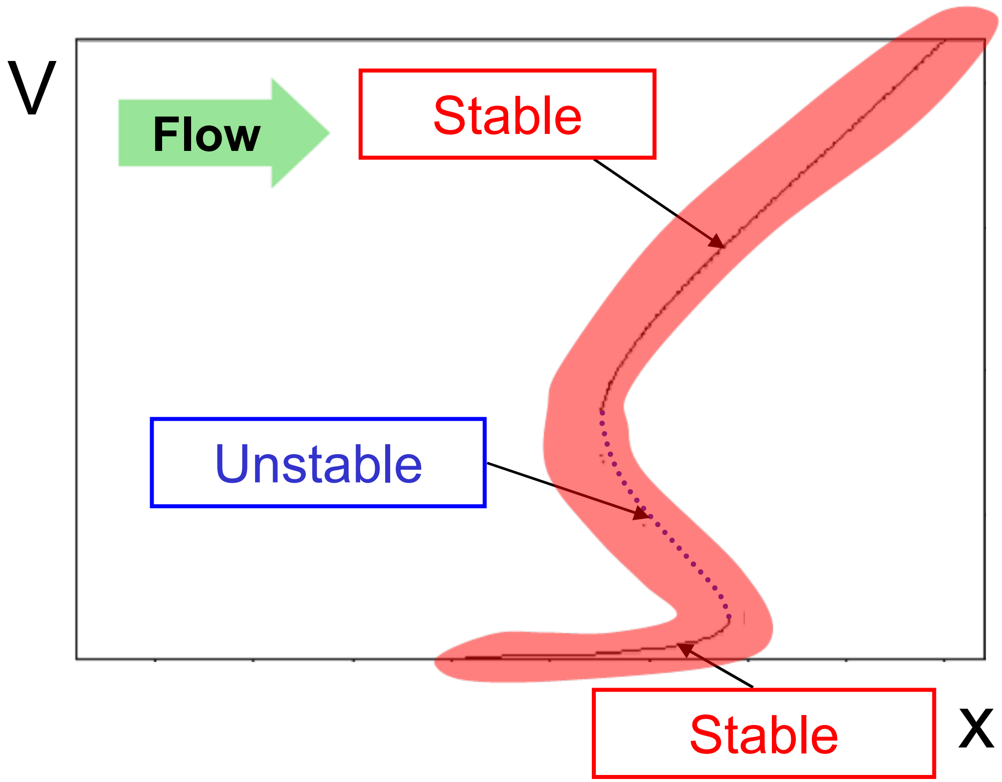
- DNS study, Hydrogen/air flames confirmed details of FREI Flames in high velocity region highlighted
(Pizza, Frouzakis, Mantzaras, Tomboulides, Boulouchos CNF152, 2008)



Objectives

- Further understandings of weak flame characteristics required
  - Weak flame limit ?
  - Relation with ignition and weak flame ?

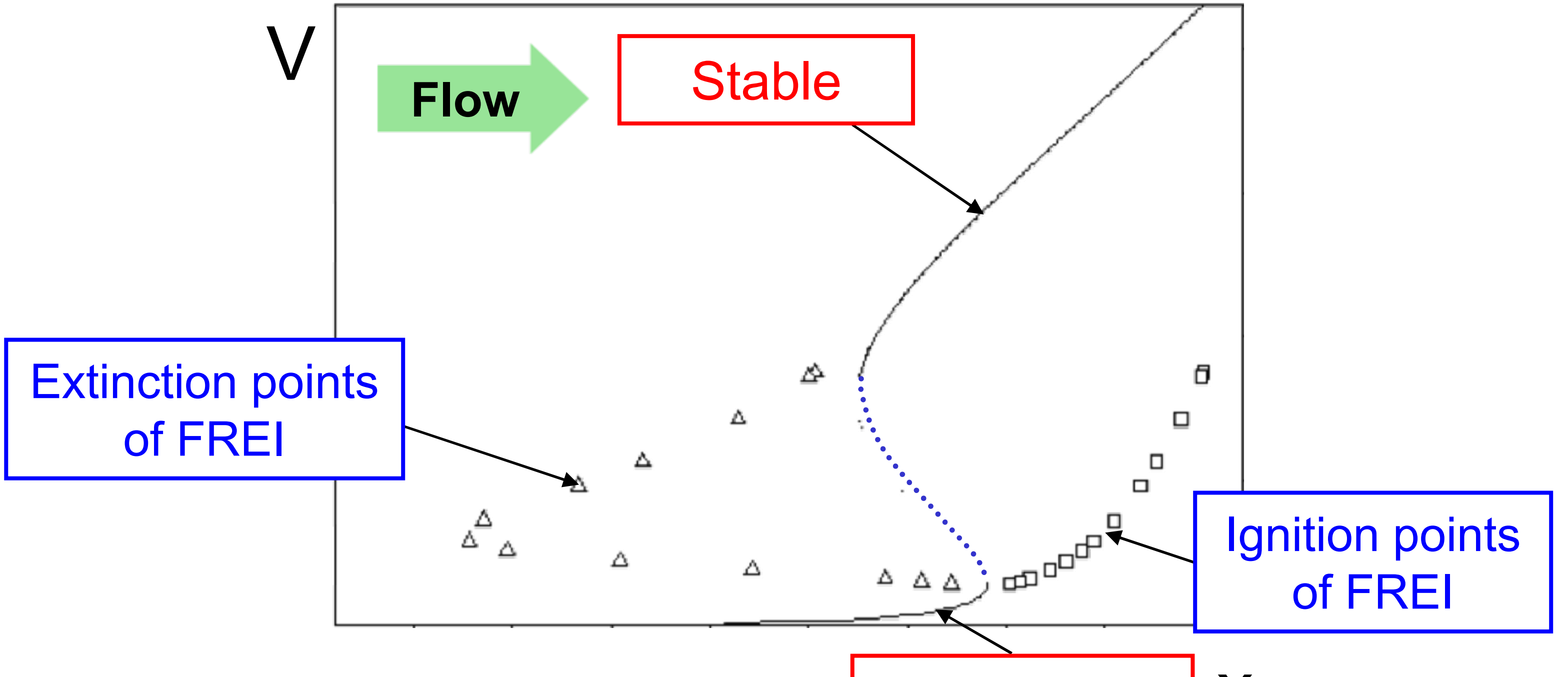
Overall picture of flame responses understood by linear stability analysis



S-shaped flame responses

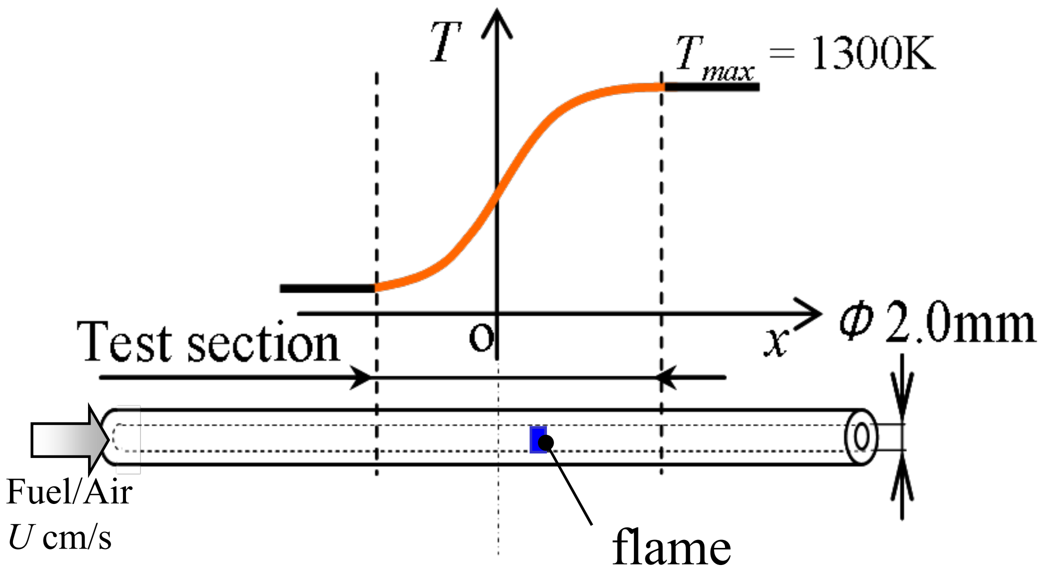
(Maruta et al. CESW40, 2004: PCI 30, 2005)

Overviews of our completed studies



Unstable middle branch confirmed to correspond flames with repetitive ignition and extinction (FREI) (Minaev et al., CTM 2007)

Wall temperature profile established by an external heat source



Meso-scale channel

Quartz glass tube
d=2.0mm, L=300mm

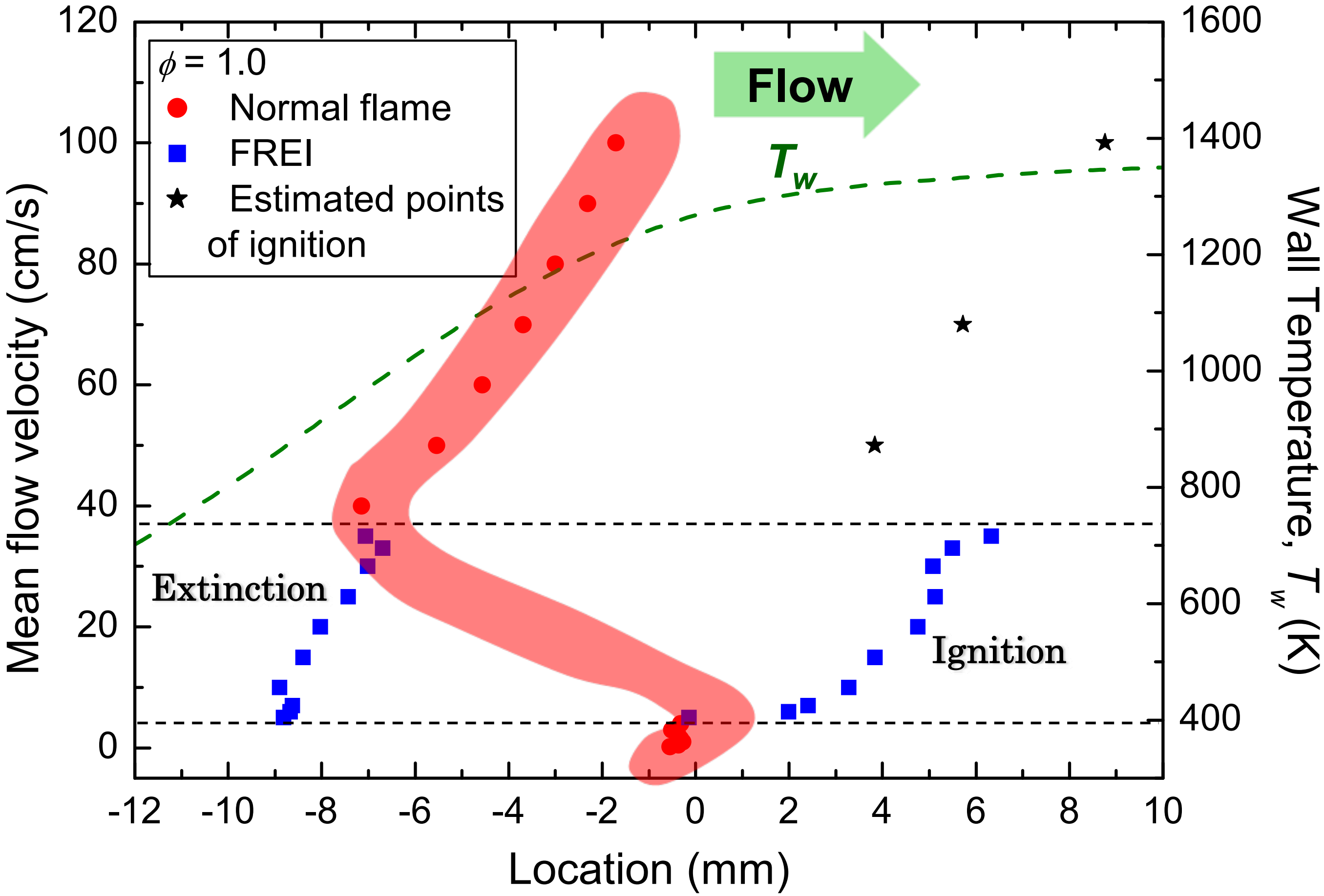
Mixture

Channel : Methane / Air

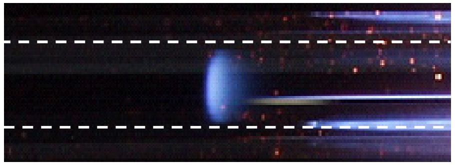
Visualization

Digital still camera
with CH filter

Experimental results ~ Flame responses ~

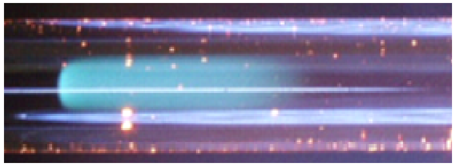


(1) Normal



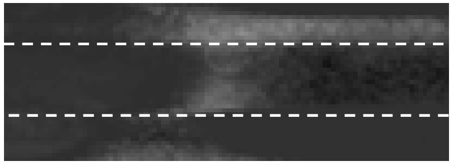
V=50cm/s

(2) FREI



V=20cm/s

(3) Normal



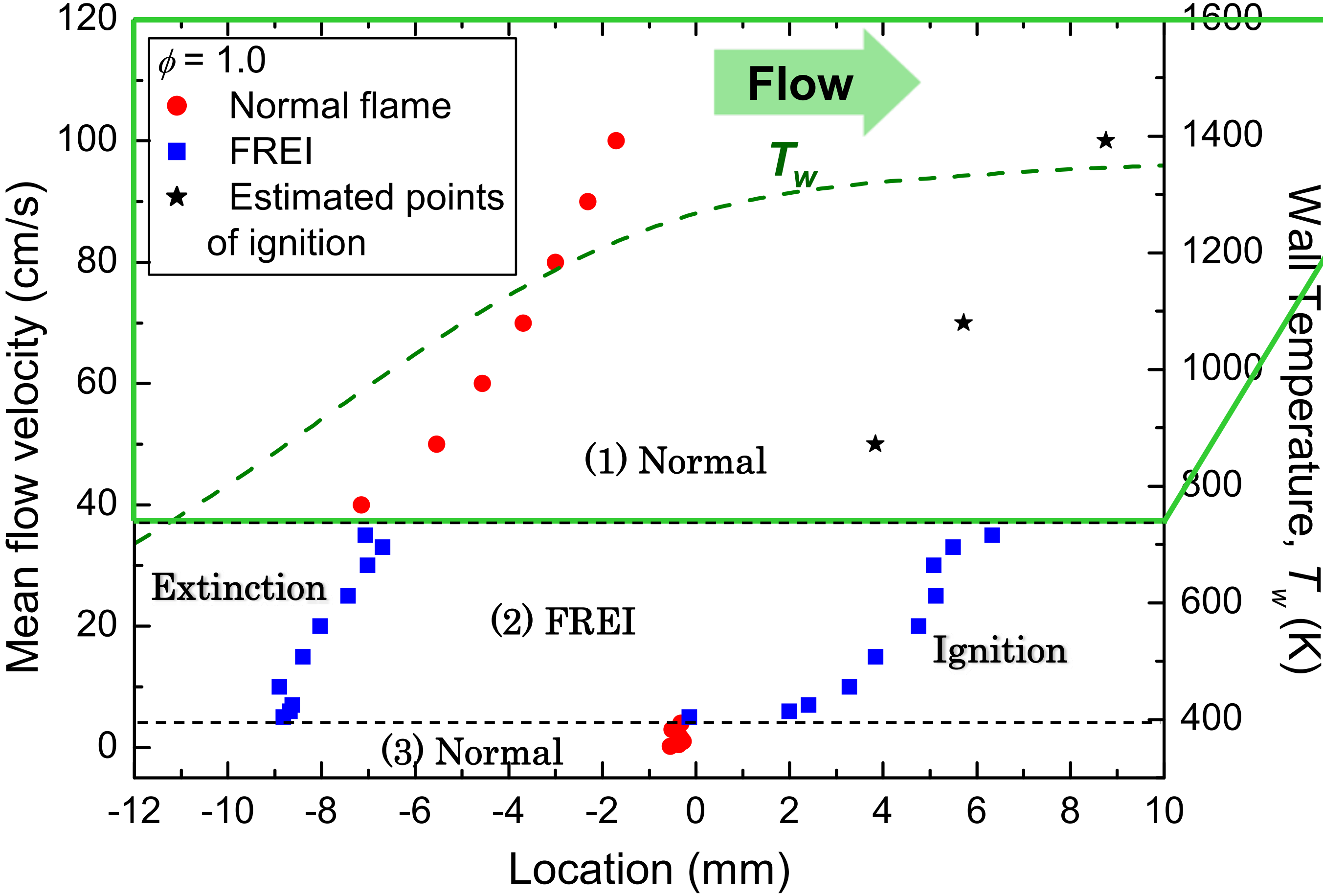
V=0.2cm/s

High and low flow velocity regions → Normal flame

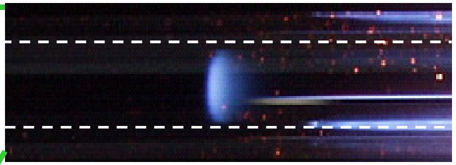
Middle velocity region → FREI

→ **S-shaped flame responses**

Experiments ~ Higher velocity region ~

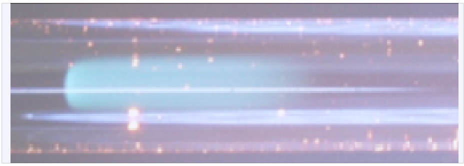


(1) Normal



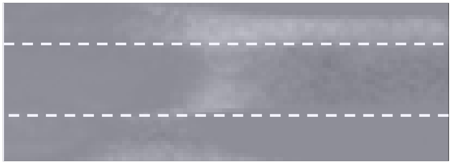
V=50cm/s

(2) FREI



V=20cm/s

(3) Normal

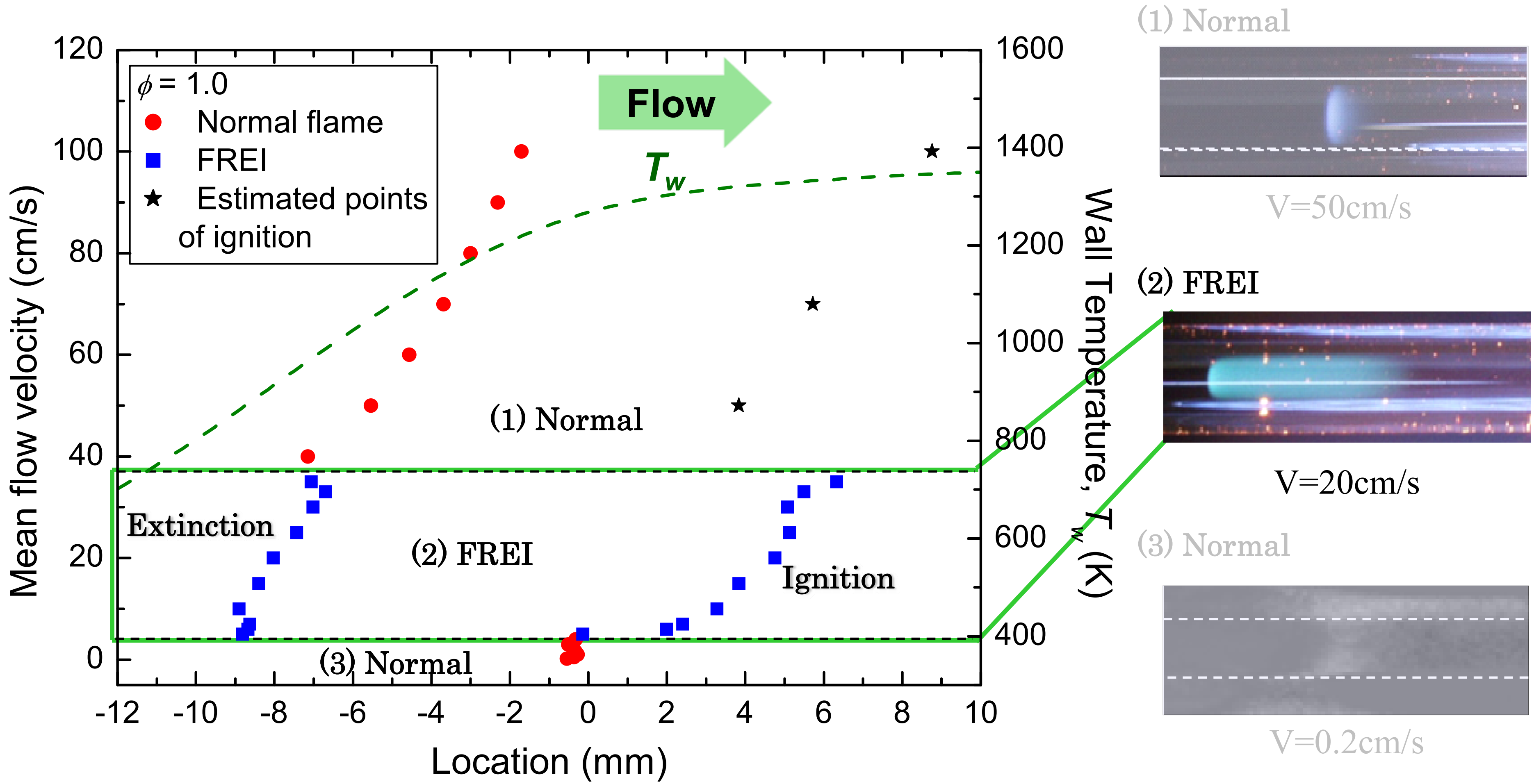


V=0.2cm/s

Self-ignition at downstream side ➡ stabilized at upstream location

Flame position shifts toward upstream with the decrease of flow velocity

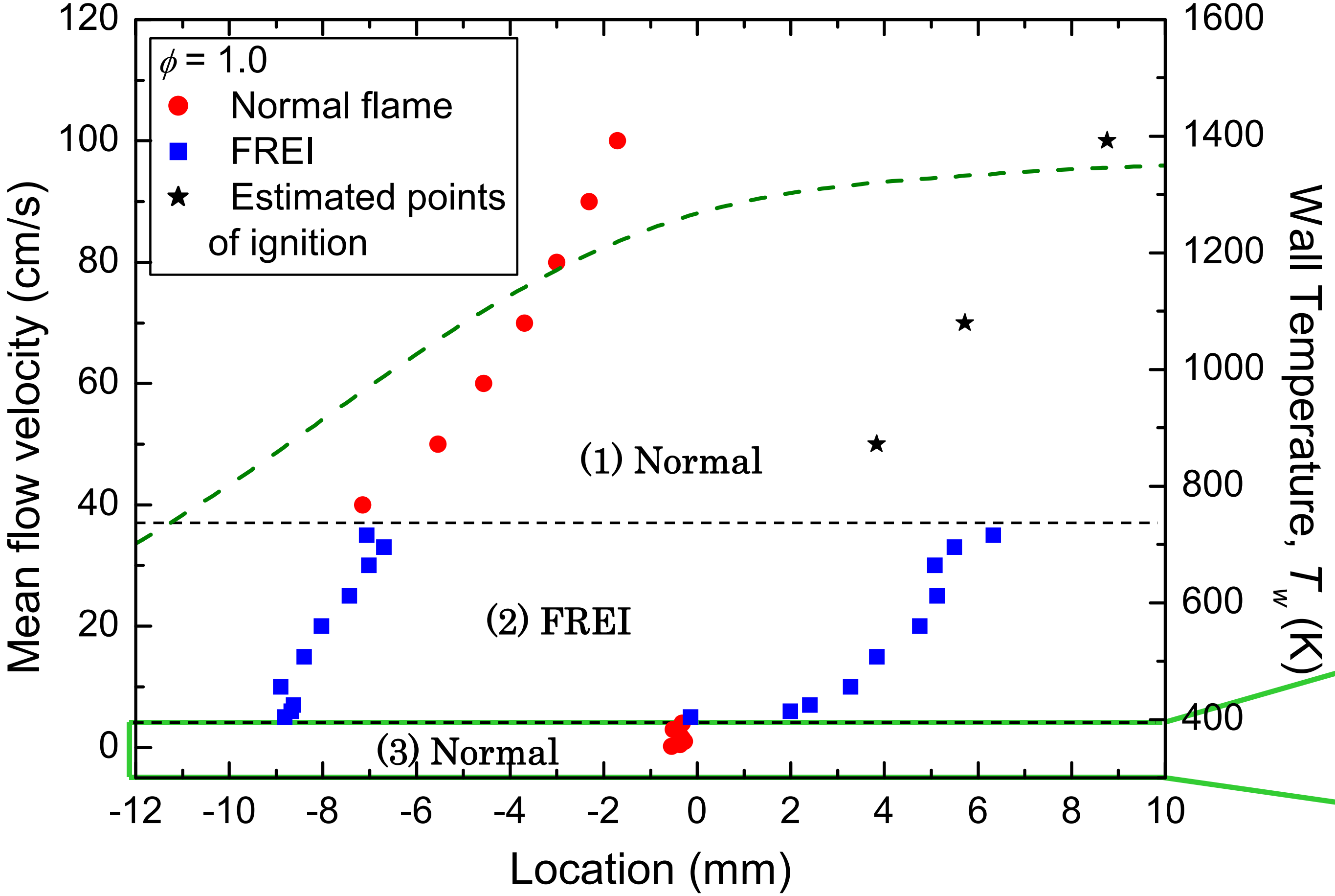
Experiments ~ Moderate velocity region ~

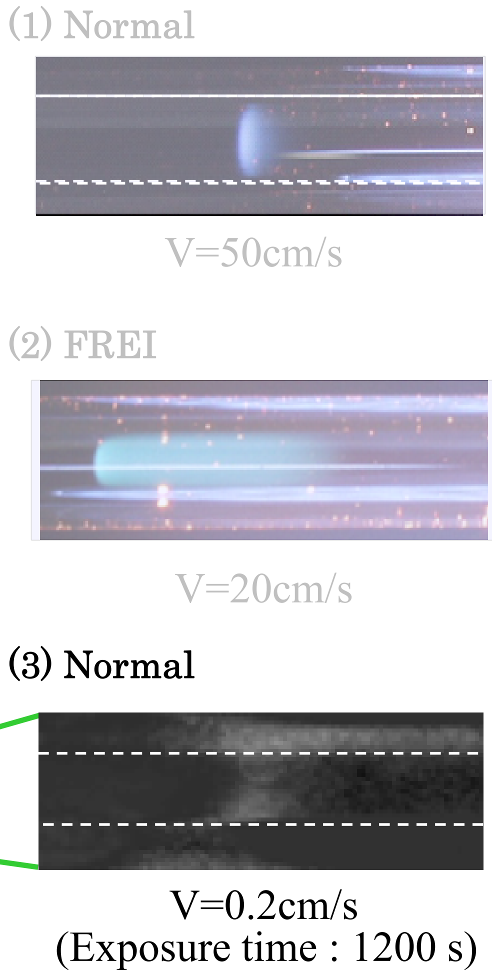


Ignition in downstream → Flame kernel moves toward the upstream

← Flame extinction due to low temperature of the wall ←

Experiments ~ Lower velocity region ~

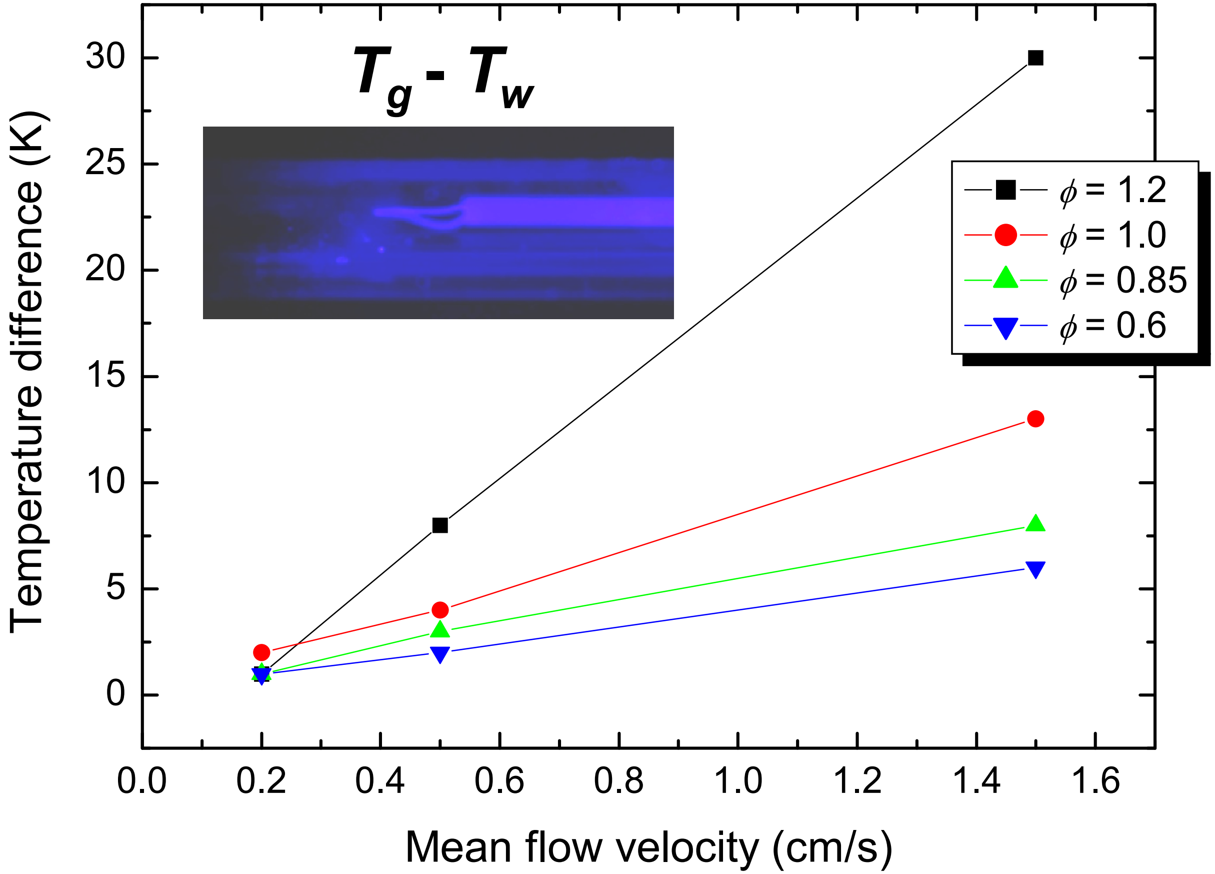




V_m < 0.2 cm/s ➡ No luminous flame ➡ Lowest burning velocity?

Flame is stabilized near the ignition position with very small heat release

Experiments ~ Gas and wall temperature differences ~



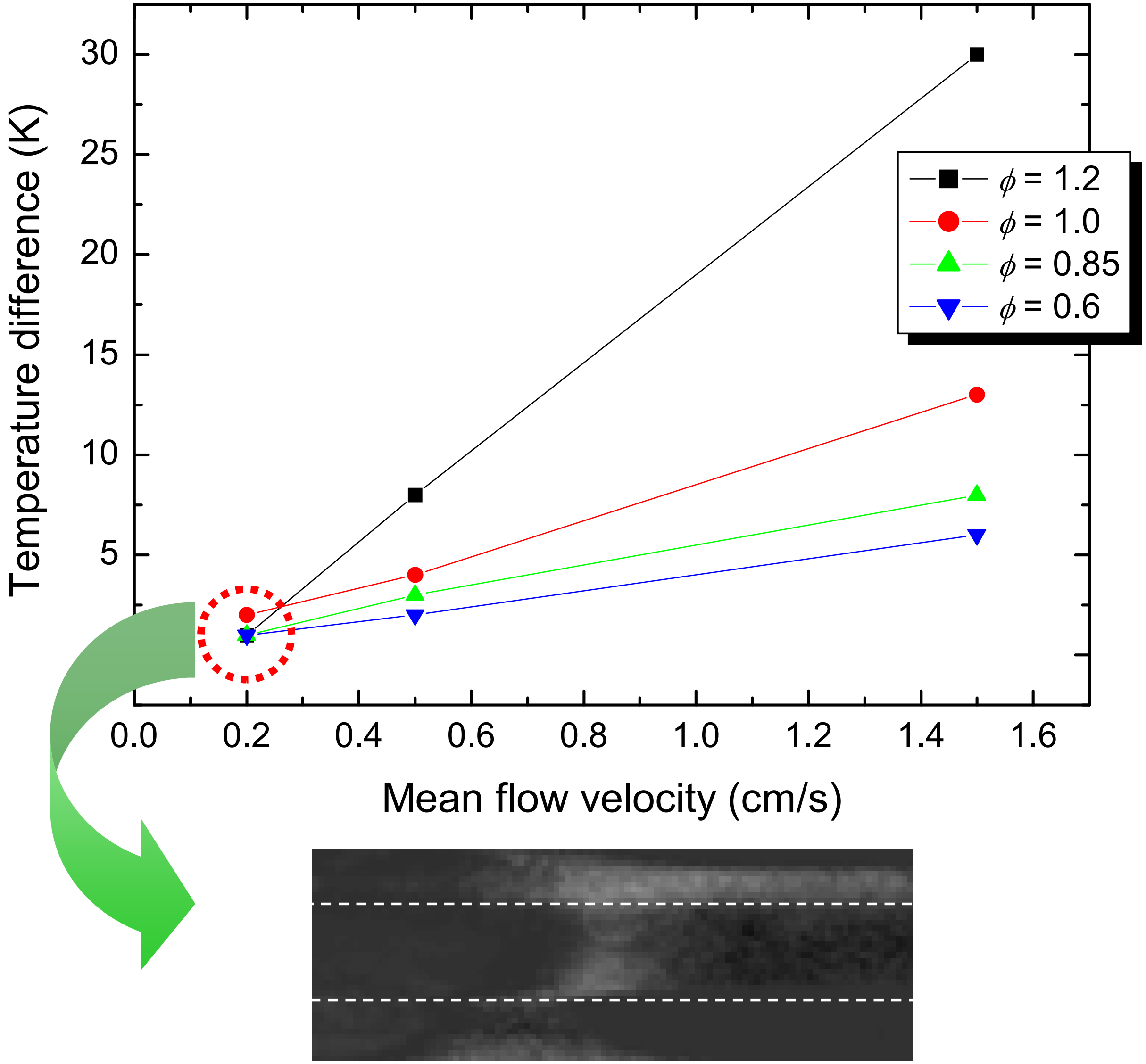
V = 0.2 cm/sec, T_w = 1225 K ⇒ T_g - T_w < 2 K

⇒ **Small temperature increase** + Flame position of weak flame close to an ignition point

Lowest flame temperature corresponds to ignition temperature

Universal ignition temperature can be identified

Experiments ~ Gas and wall temperature differences ~



Mechanism of lower limit of weak flame?

Computations

Calculation code

1-D steady state flame code (Kee et al., 1989)

Energy equation

$$\dot{M}\frac{dT}{dx}-\frac{1}{c_p}\frac{d}{dx}\left(\lambda A\frac{dT}{dx}\right)+\frac{A}{c_p}\sum_{k=1}^{K}\rho Y_k V_k c_{pk}\frac{dT}{dx}+\frac{A}{c_p}\sum_{k=1}^{K}\dot{\omega}_k h_k W_k \boxed{-\frac{A}{c_p}\frac{4\lambda Nu}{d^2}(T_w-T)}=0$$

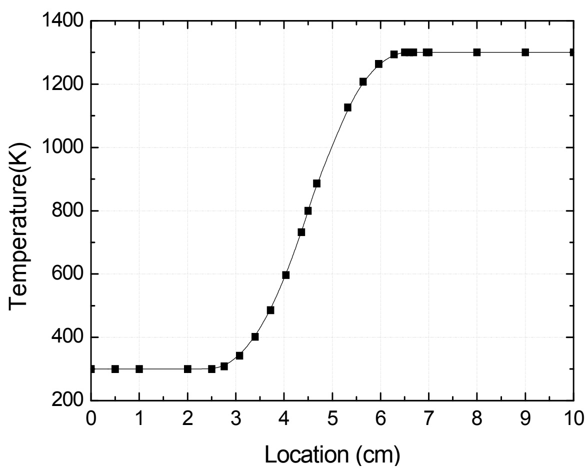
Convective heat transfer

Chemistry

GRI-mech 3.0

Assumption

- **Fixed wall temperature**
- ***Nu* = 4 (Constant)**



Wall temperature profile

Computations ~ Flame responses ~

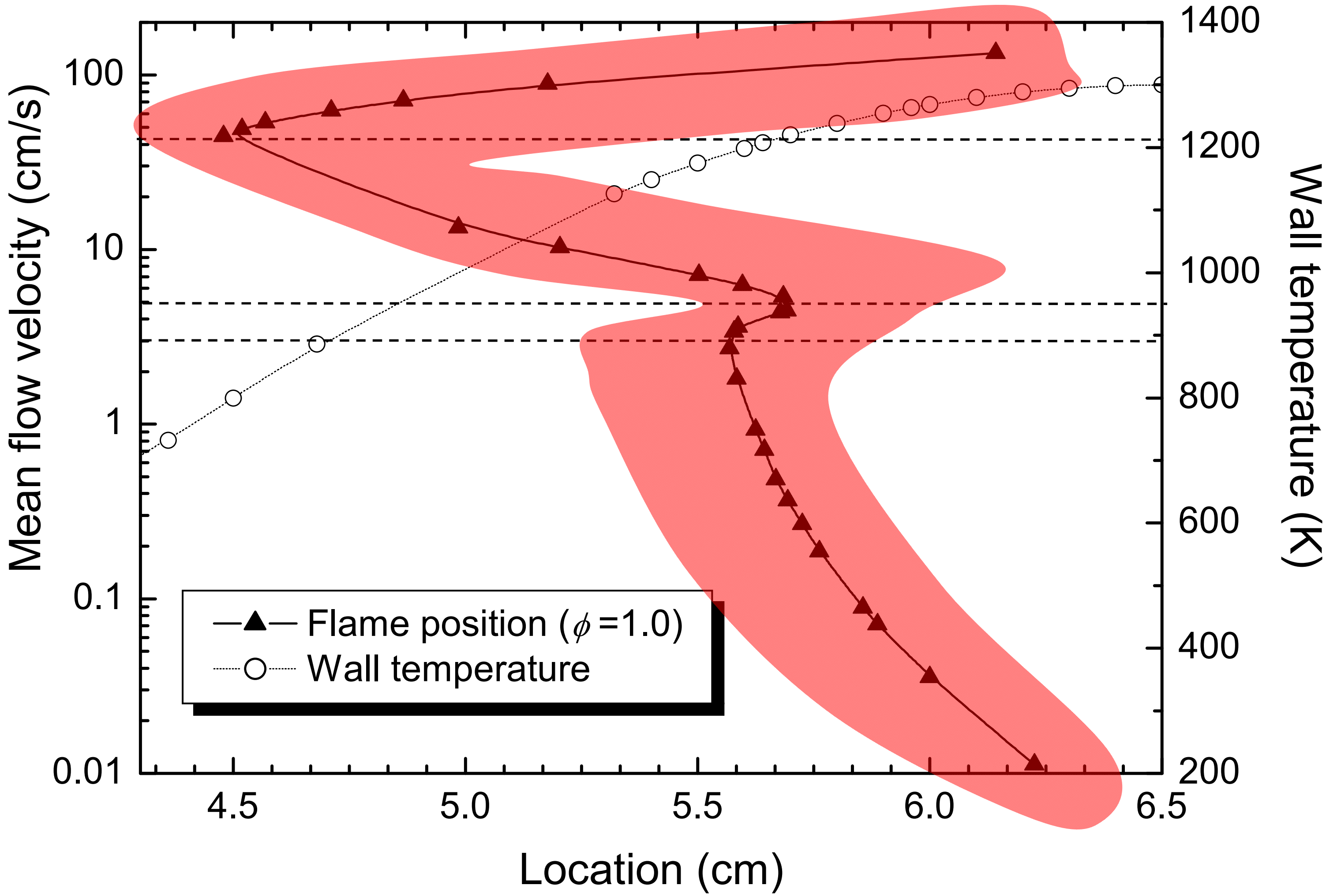
(1) Normal

(2) FREI

(3) Normal

(No flame)

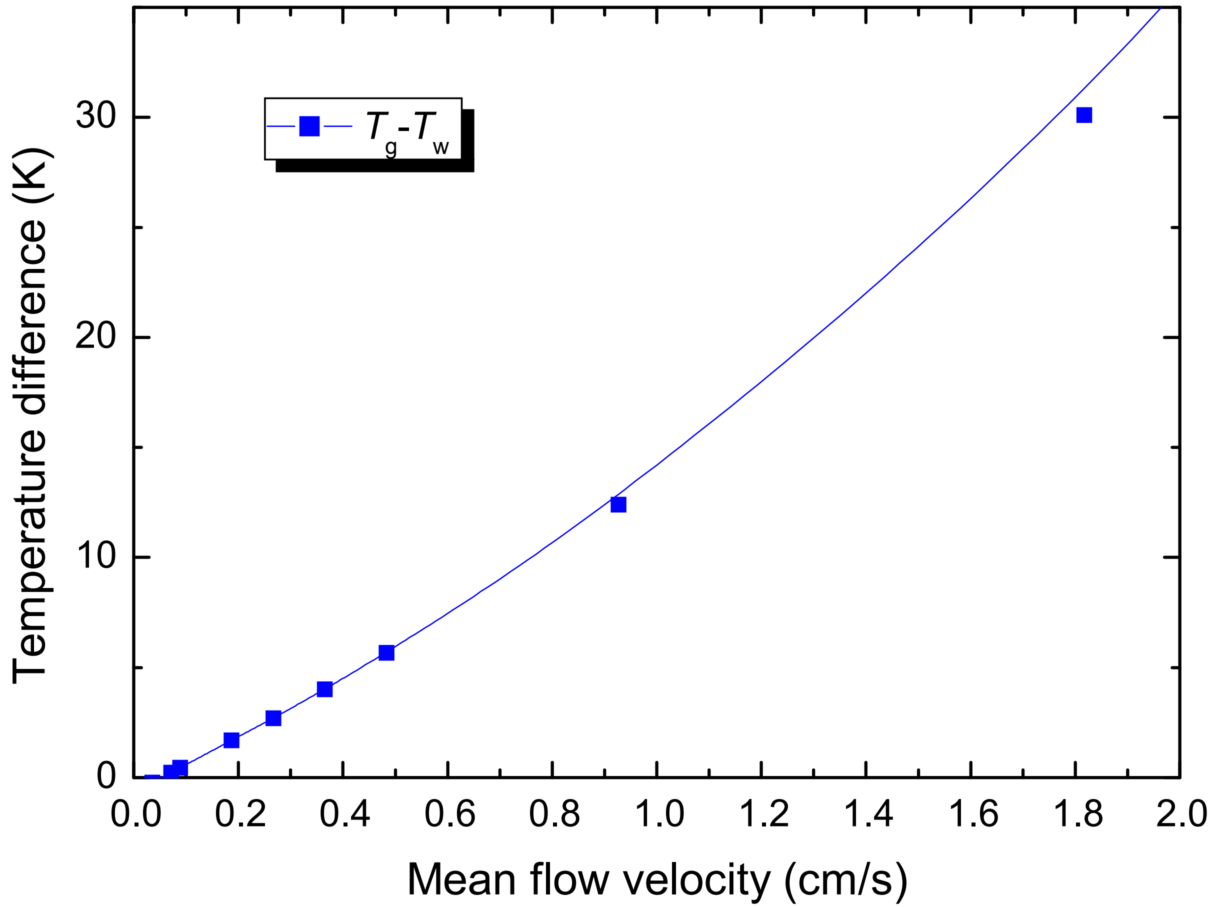
Experimental flame responses



Two stable and two unstable solutions agreed with experimental regimes

Flame responses exhibit ε-shape ➡ **Limit in lower stable branch**

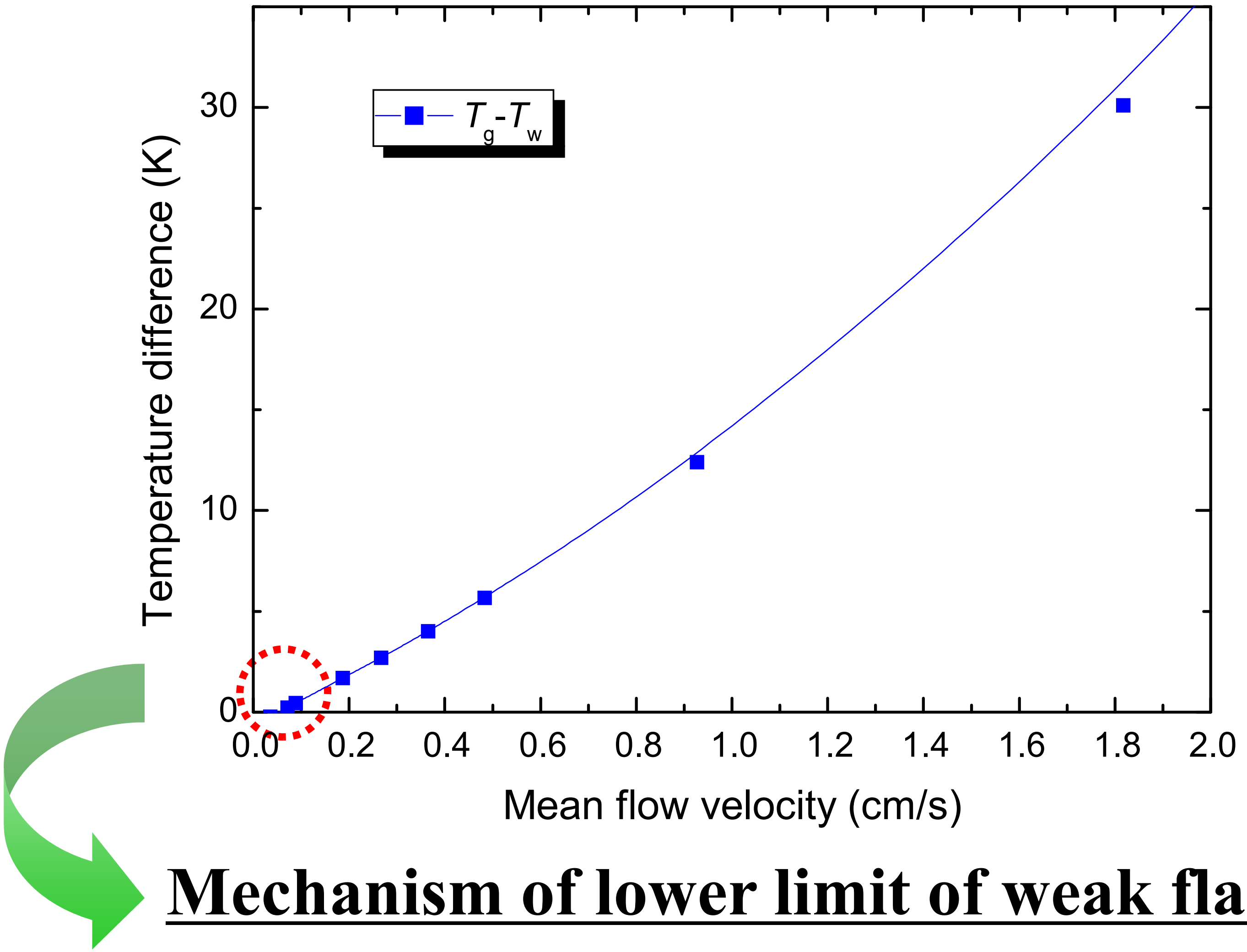
Computations ~ Gas and wall temperature difference ~



Difference becomes smaller with the decrease of flow velocity

$T_g - T_w < 2$ K ⇨ $V = 0.1$ cm/s, $T_w = 1230$ K

There exists the lowest burning velocity



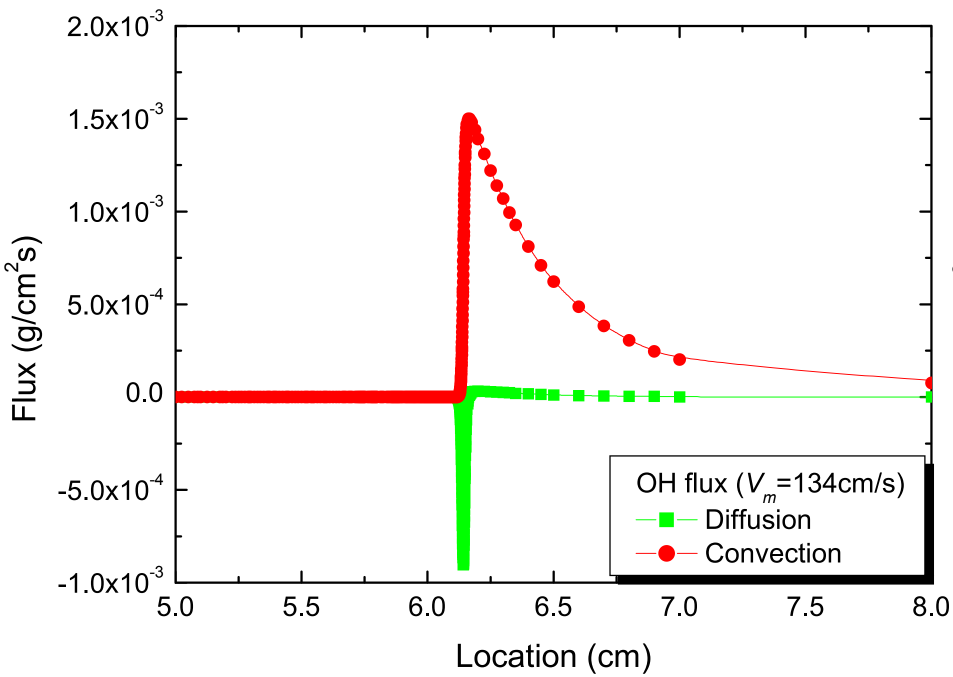
Mechanism of lower limit of weak flame?

Our assumption: **limit induced by mass dissipation**

Mass transport of light radical (OH)

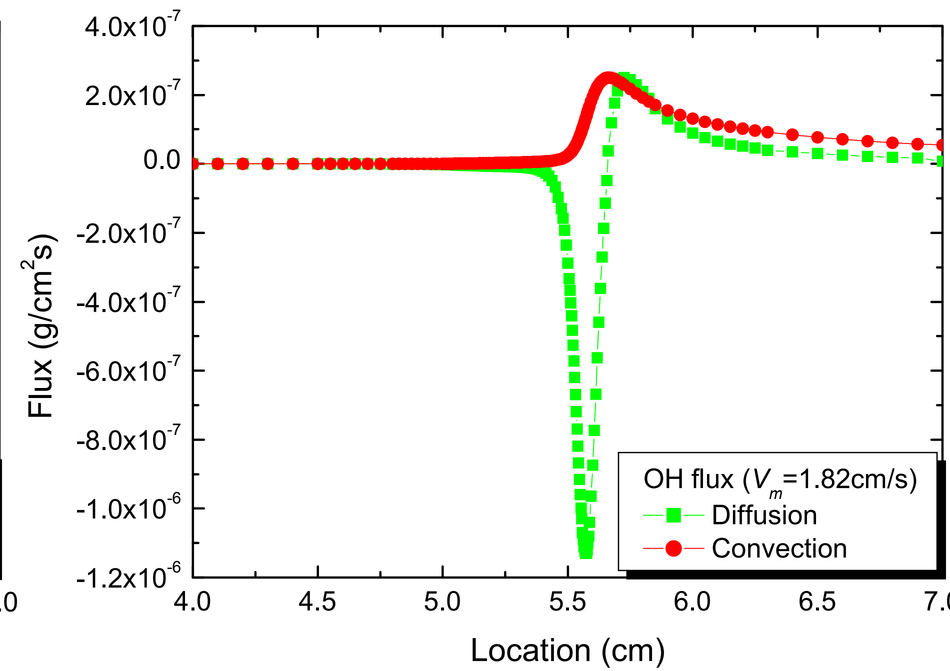
Convective mass flux ➡ $\rho Y_{OH} V_m$ V_m : Mean flow velocity

Diffusive mass flux ➡ $\rho Y_{OH} V_{OH}$ V_{OH} : Diffusion velocity



V_m =134 cm/s

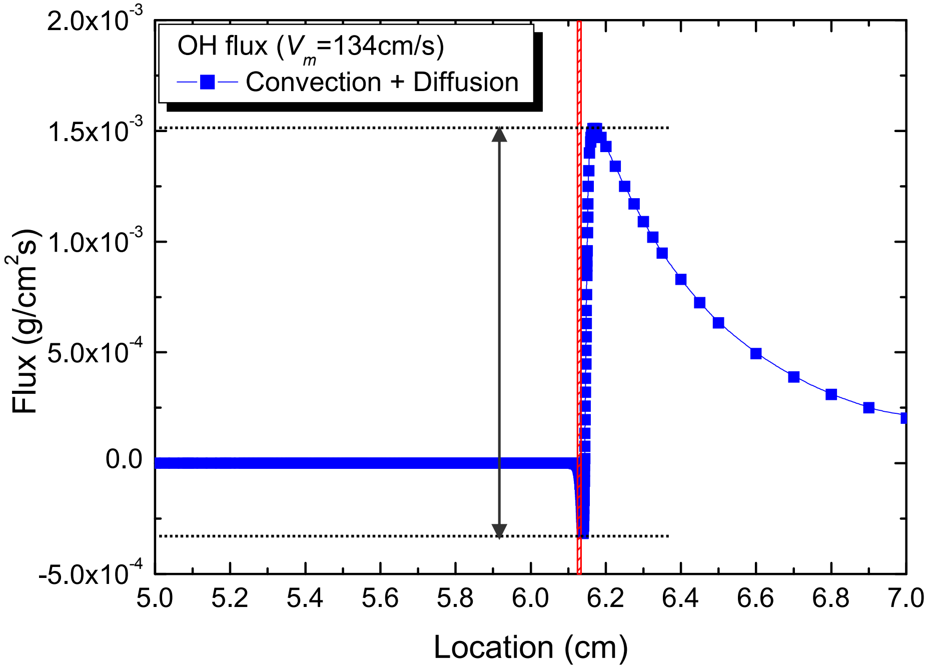
Convection > Diffusion



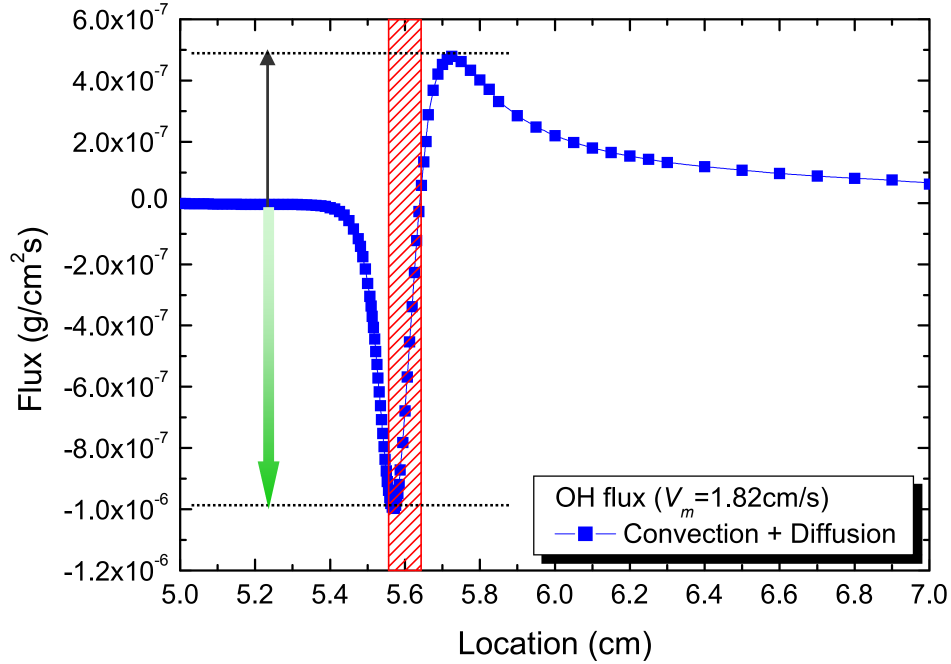
V_m =1.82 cm/s

Convection < Diffusion

Total mass fluxes



V_m =134 cm/s



V_m =1.82 cm/s

Mass dissipation in low velocity region significantly larger than that in higher velocity region: radicals diffuse out

Lower limit of weak flame induced by diffusion effects

Conclusions

- Existence of lower limit of weak flame confirmed experimentally even if heat loss compensated by an external heating.
- Lowest flame temperature corresponded to ignition temperature.
- Computed flame responses exhibited ε-shape, which implies existence of lower limit of weak flame in a lower stable branch.
- Based on computations, mechanism of lower limit of weak flame is supposed to be mass dissipation loss due to mass diffusion in low velocity region.