Characteristics of ultrahigh temperature flame

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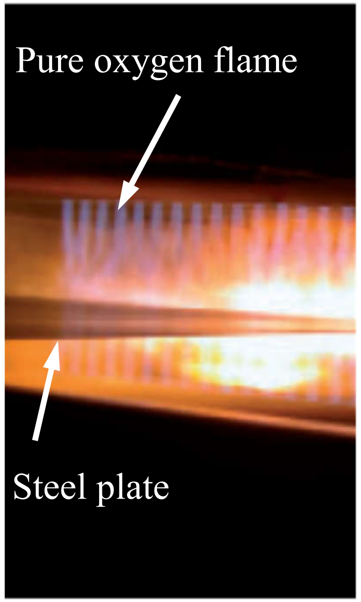
Content

1 Background

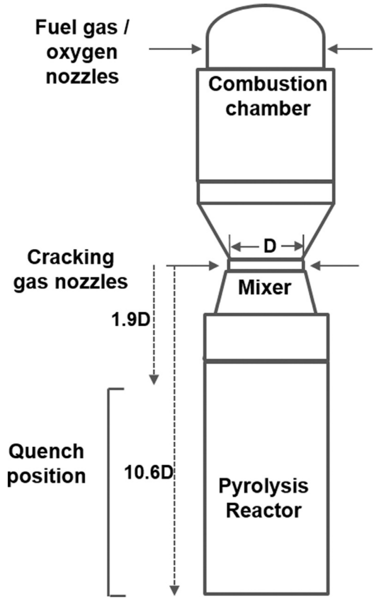
Definition for ultrahigh temperature flame: ***T_f* ≥ 3000 K**

Typical flame: pure oxygen combustion, metal particle burning (Al, Mg)…

Rocket engine[1]



Manufacturing[2]



Pyrolysis reactor for acetylene[3]

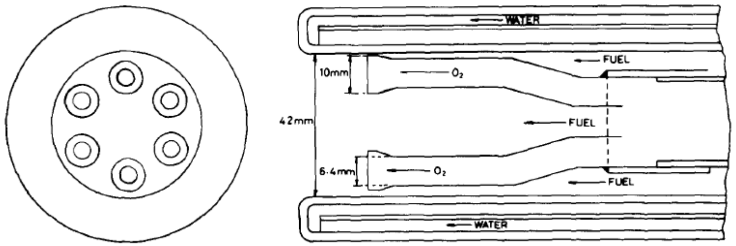
Benefits in industrial field

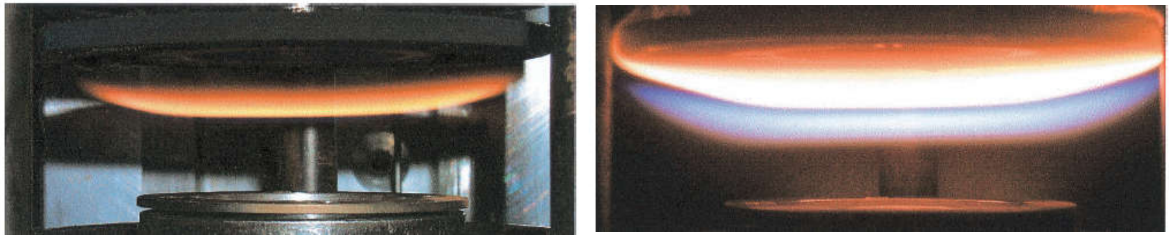
(e.g., Linde Corp. [2])

- Capacity increase **50%**
- Fuel saving up to **50%**
- CO_2 reduction up to **50%**
- NO_x emission reduction
- Reduce scaling losses

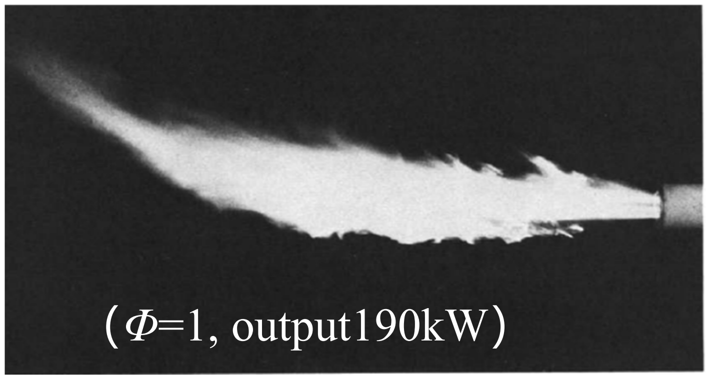
Ref. 1. Image from Baidu, 2. J.Von Schéele, Ironmaking & Steelmaking, 36 (2009) 487-490. 3. Chen et al. PCI 37 (2019)

1 Background-experimental studies

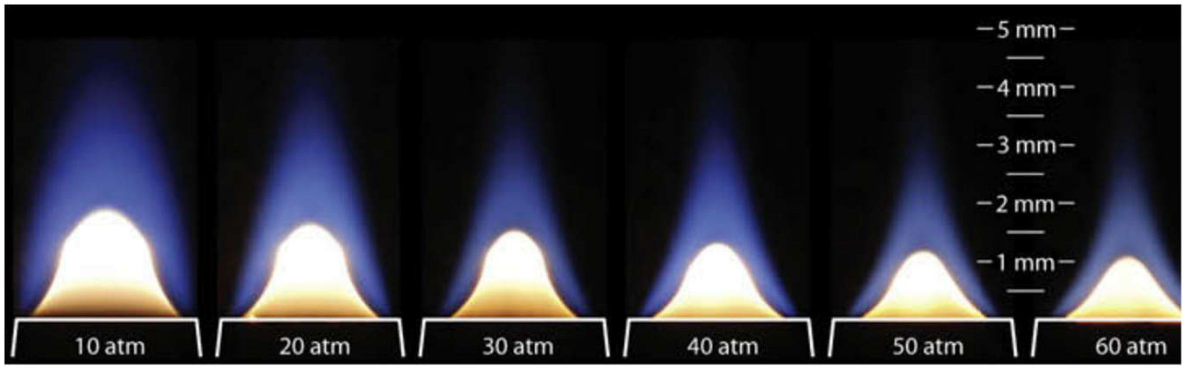




CH_4/air (left) vs. CH_4/O_2 (right) diffusion flames



CH_4/O_2 jet diffusion flame
(mixing, emission and noise)



Pure oxygen flame under various pressures (10-100atm)
(flame structure and soot formation)

Mainly limited to non-premixed combustion in case of flame flash back in **premixed mode**

Ref. Harris et al., CNF 26 (1976) 311-321, Beltrame, et al., CNF124 (2001) 295-310.
Joo et al., CNF 157 (2010) 1194–1201

2 Theoretical analysis-Chemkin

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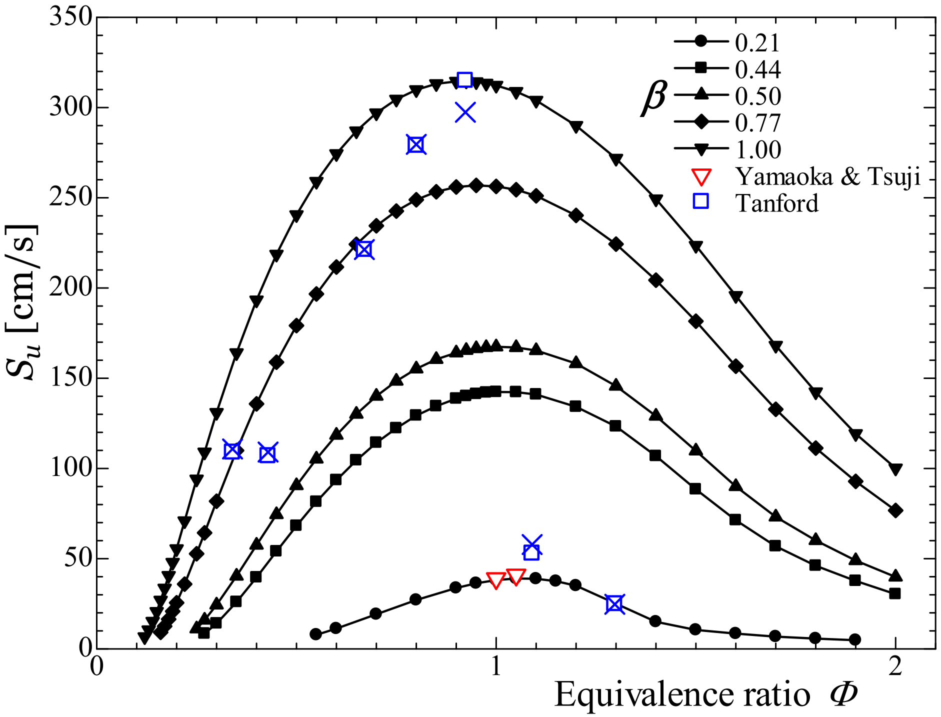
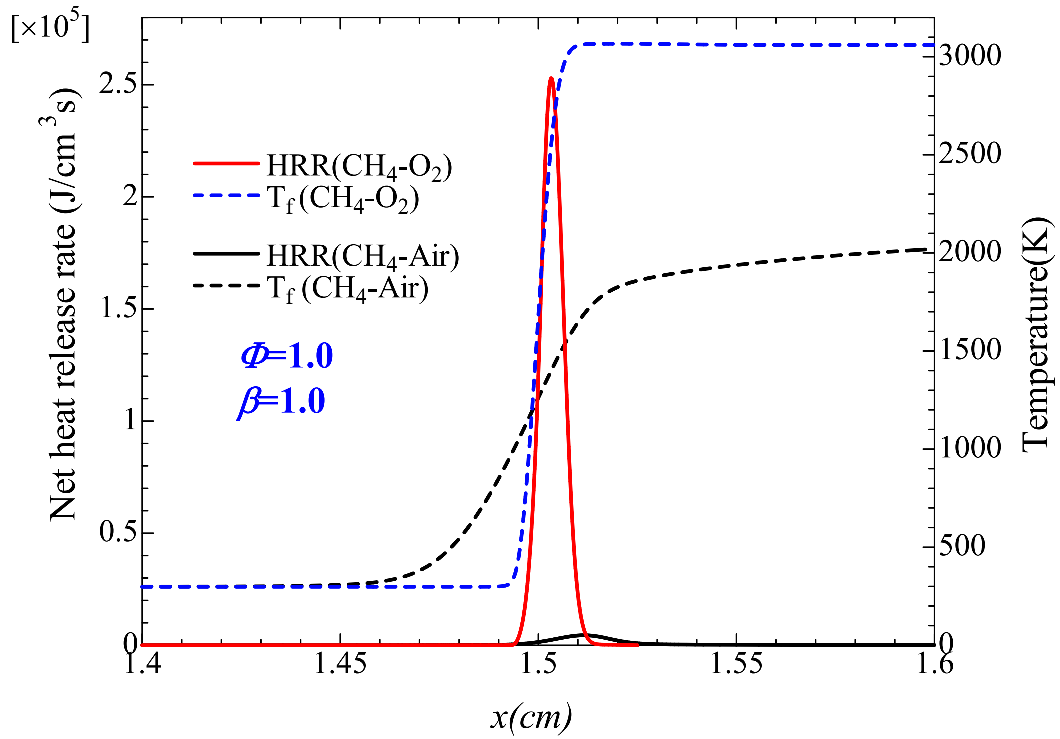
Calculated S_u for $CH_4/O_2/N_2$ flame(GRI 3.0)



Maximum S_u = 330 cm/s (at Φ=0.955, β=1)

Premixed CH_4/O_2 flame at **Φ=0.75-1.4**, $T_f \geq$ 3000 K



T_f: 3050 K (vs. 2220 K in air)

Peak of HRR: 2.54×10^5 $J/cm^3\cdot s$ (vs. 4.5×10^3 $J/cm^3\cdot s$ in air)

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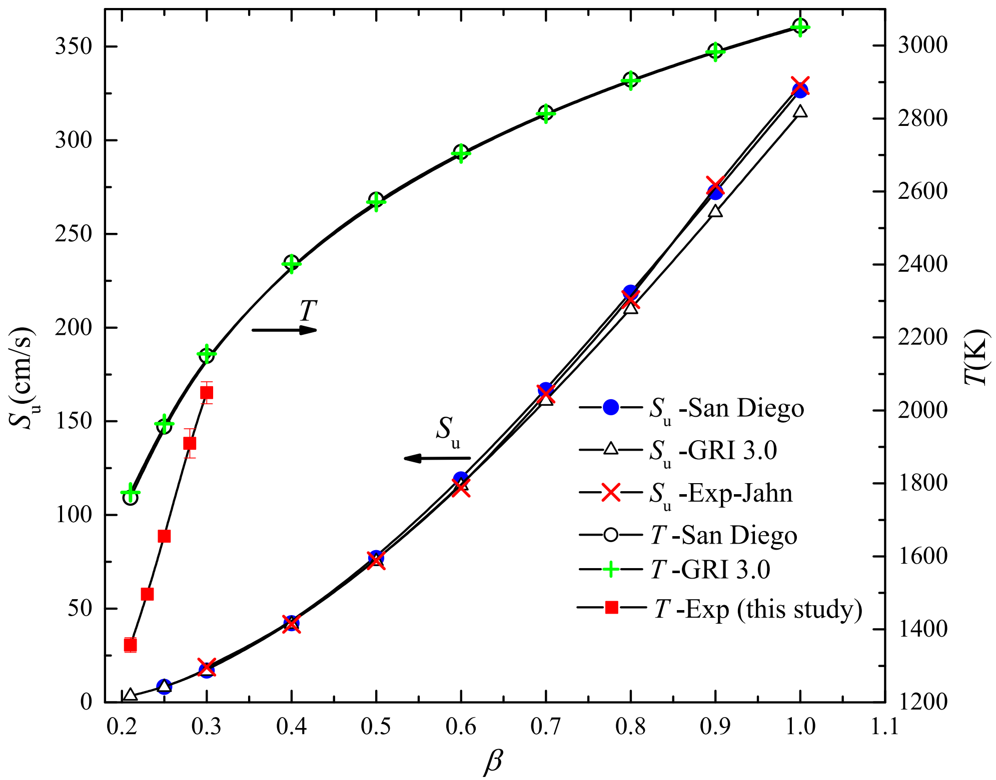
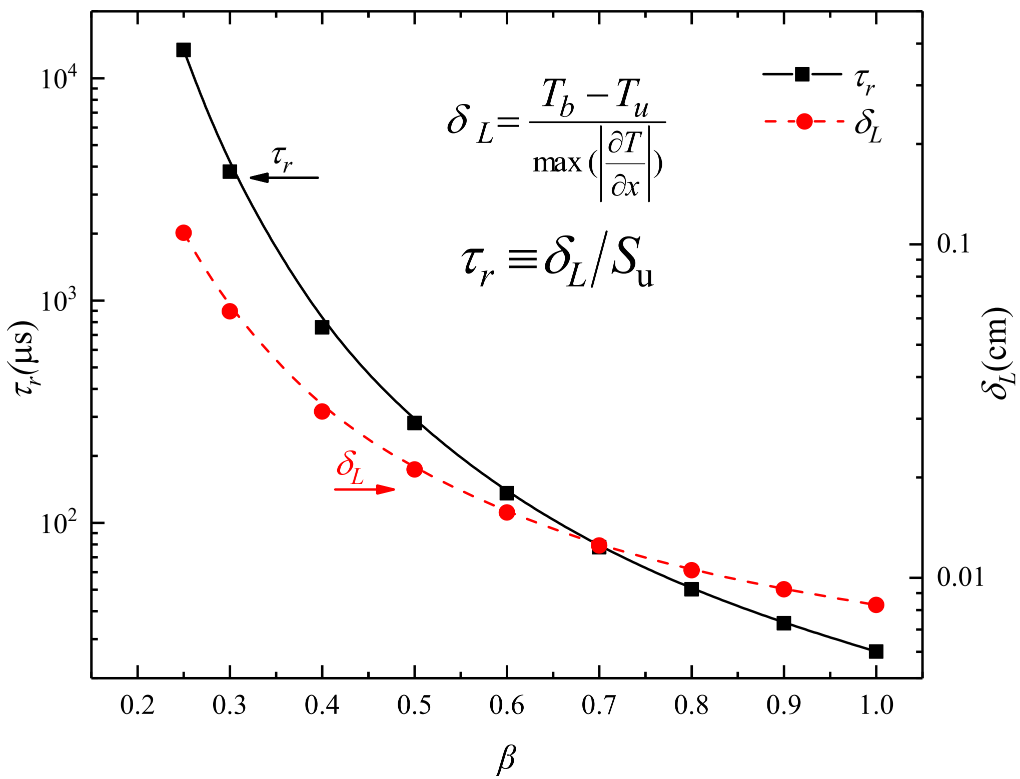
Ref. Shi, et al, Proc. Combust. Inst. 34 (2013) 3369-3377.

Theoretical analysis

Stoichiometric $CH_4/O_2/CO_2$ premixed flame



1 D premixed flame thickness and reaction time



Ref. Li, Shi*, et al., Energy 168 (2019) 151-159.

2 Theoretical analysis

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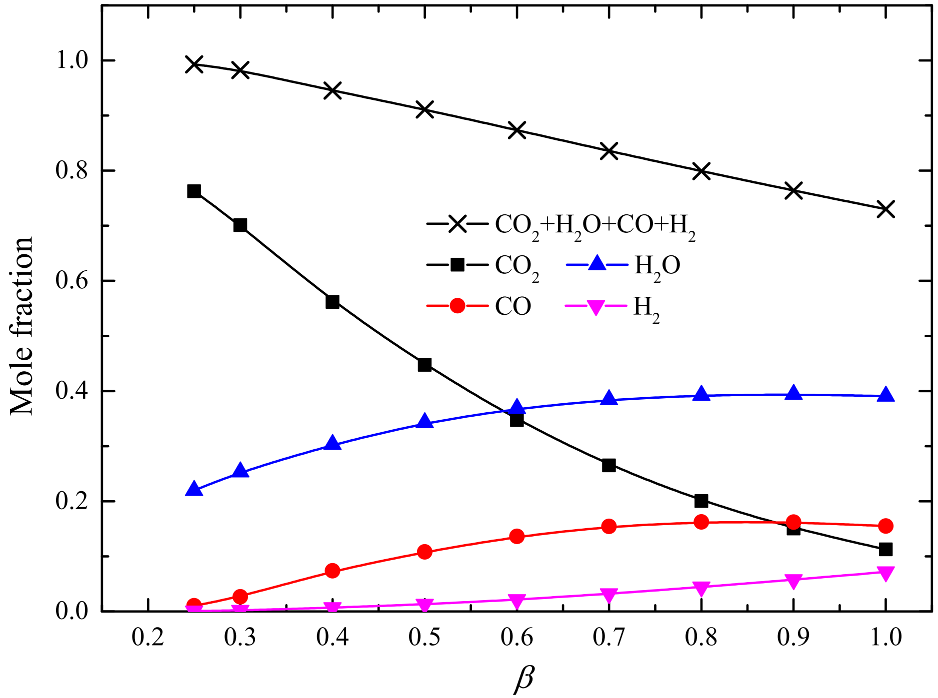
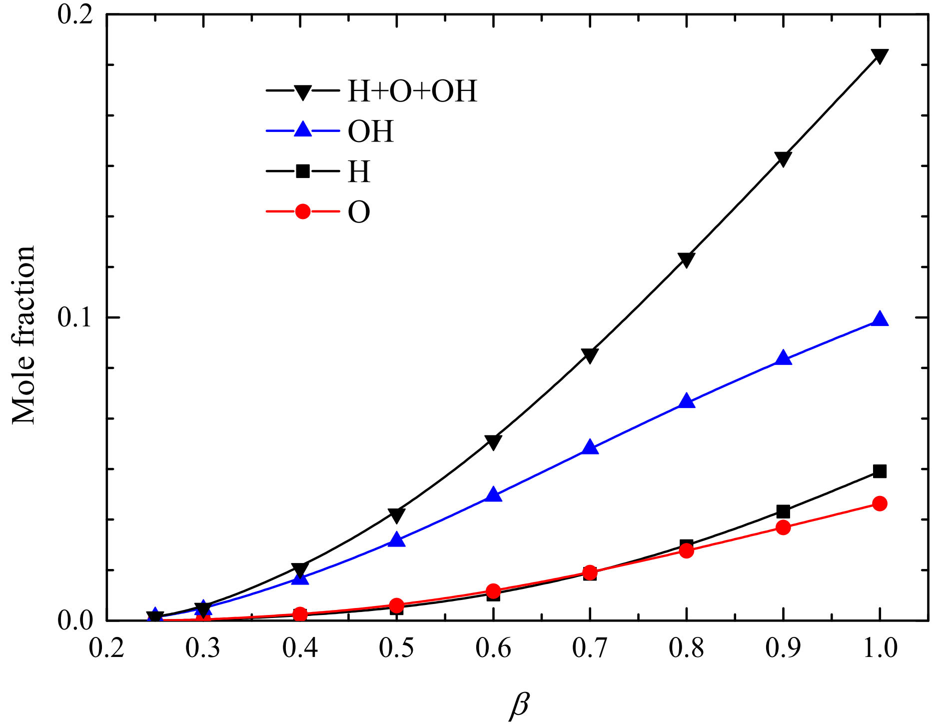
Stoichiometric $CH_4/O_2/CO_2$ premixed flame



Under high temperature CO_2 and H_2O cannot stably exist, yielding CO and H_2

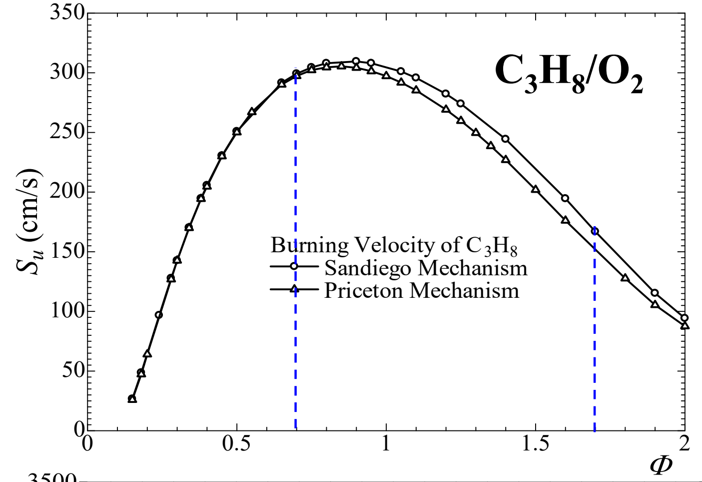


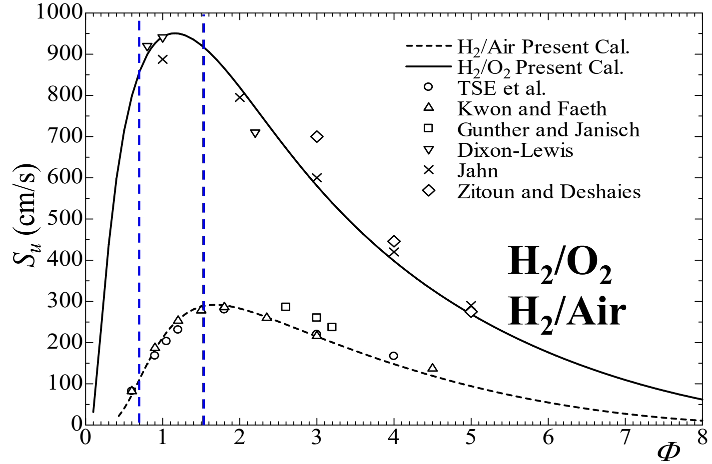
Formation of O, H and OH radicals **~ 20%**

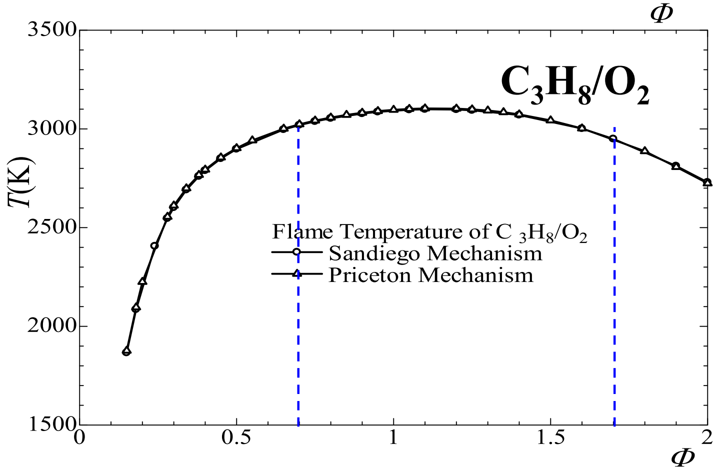
--Thermochemical heat release, reaction uncertainty

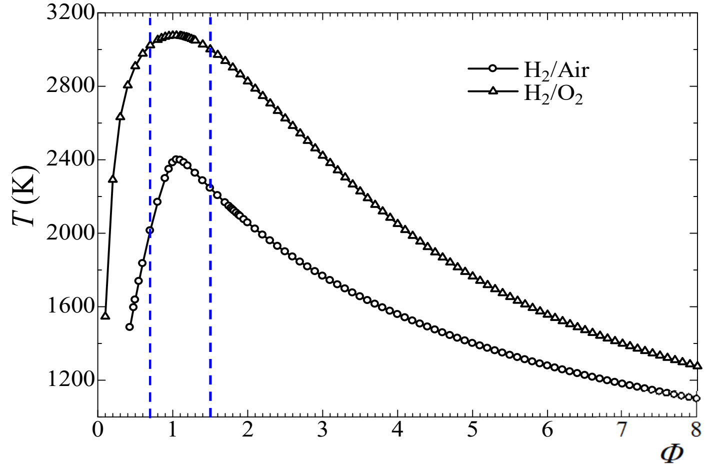
Ref. Li, Shi*, et al., Energy 168 (2019) 151-159.

2 Theoretical analysis





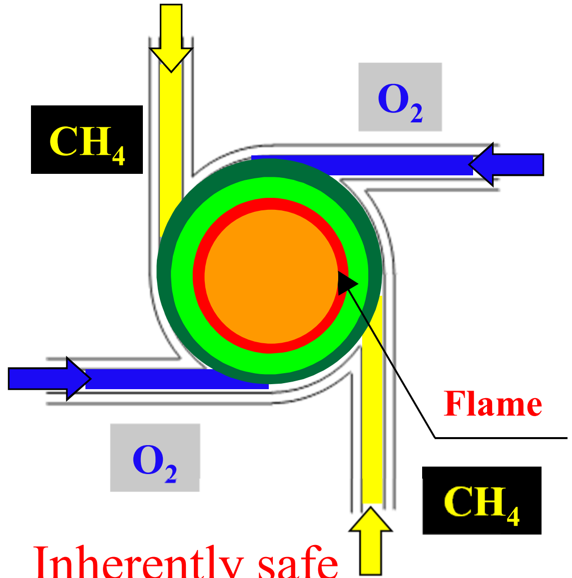




High S_u → flash back

High T → ablation

Attempt quashi-premixed combustion by adopting the technique of rapidly mixed tubular flame



Φ=0.7-1.7: T ≥ 3000 K

Φ=0.7-1.5: T ≥ 3000 K

Inherently safe

Ref. B. Shi, Ph.D dissertation; S. Ishizuka,et al., Proc. Combust. Inst.31 (2007)

3 Experimental investigation-Apparatus

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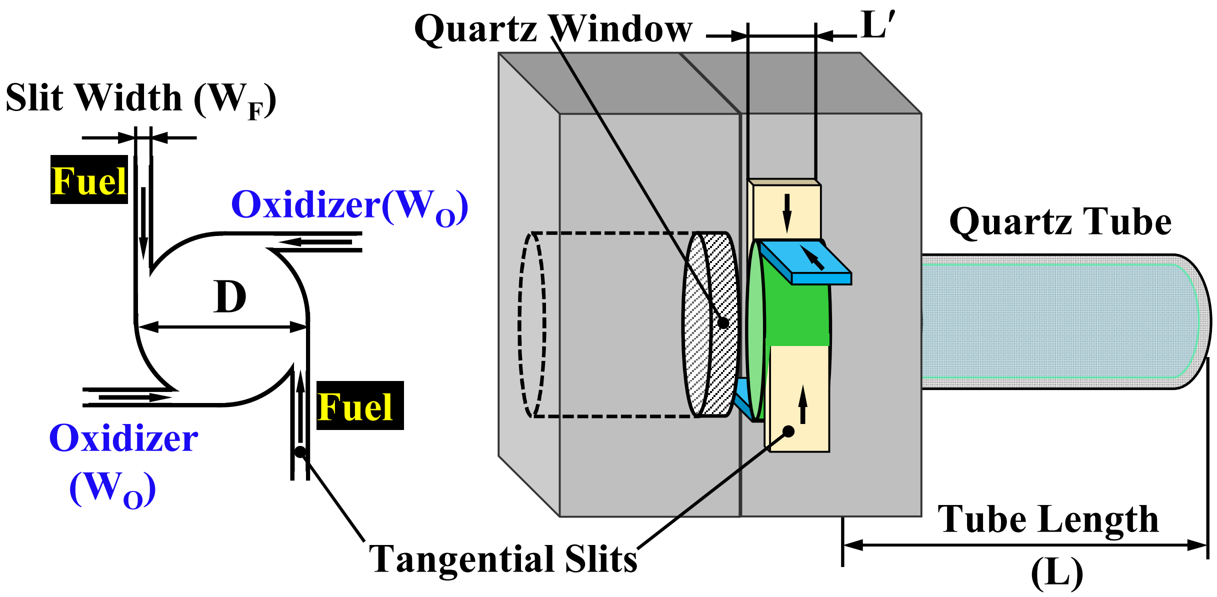
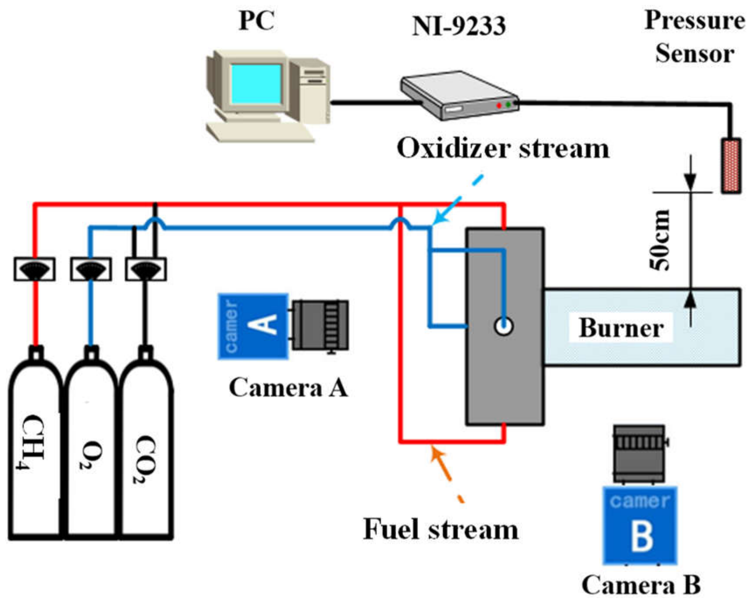


Tangential jet swirl burner



High Speed Camera: VRI, Phantom v7.3
FASTCAM- APXRS with HS-IRO intensifier and CH* filters
Pressure Sensor: BSWA TECH, MPA416

3 Experimental investigation-Methane/Air

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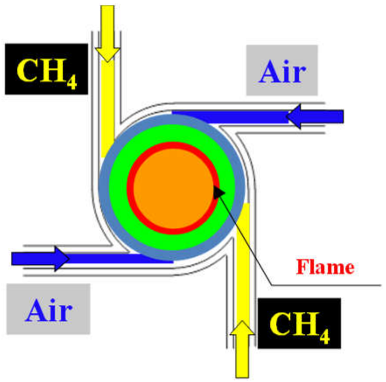
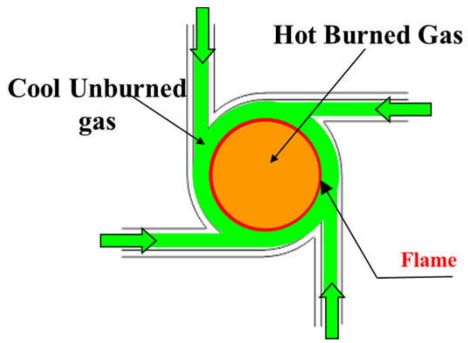
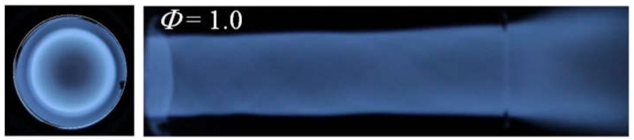
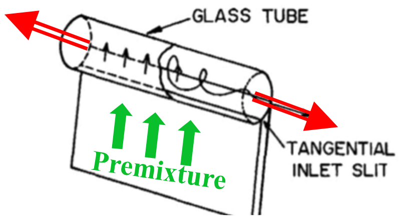


Rapidly mixed



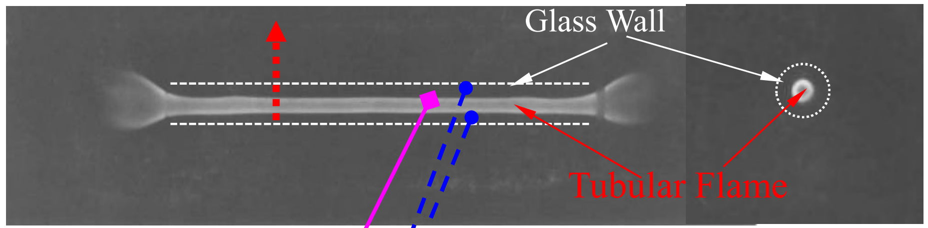
Premixed





Tubular Flame

S. Ishizuka: Proc. Combust. Inst. 20 (1984)



Stretched, laminar flame, tubular shape established in a rotating flow field.

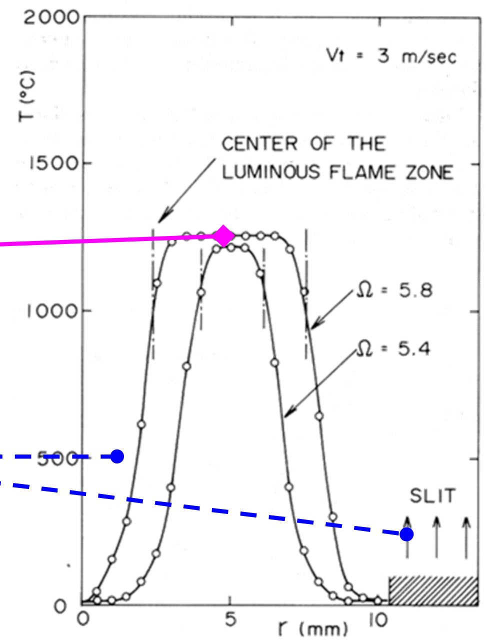
Inside：high temperature, burned gas with low density

Outside：low temperature, unburned gas with high density

Rayleigh stability：**aerodynamically stable**

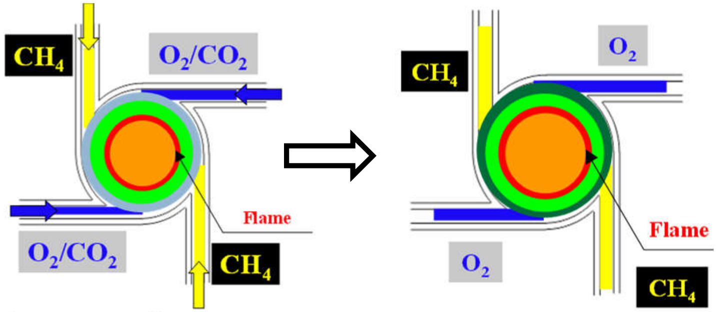
T distribution: **thermally stable**

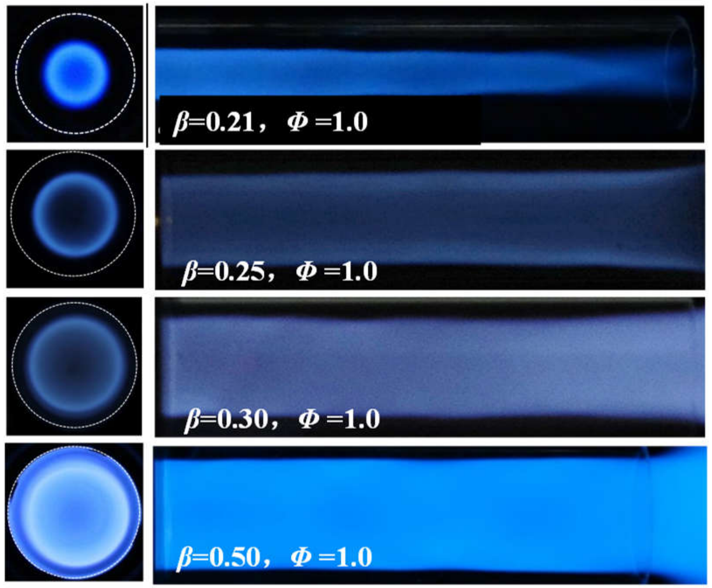
Possible for **long time operation/high T_f**



Radial temperature distribution

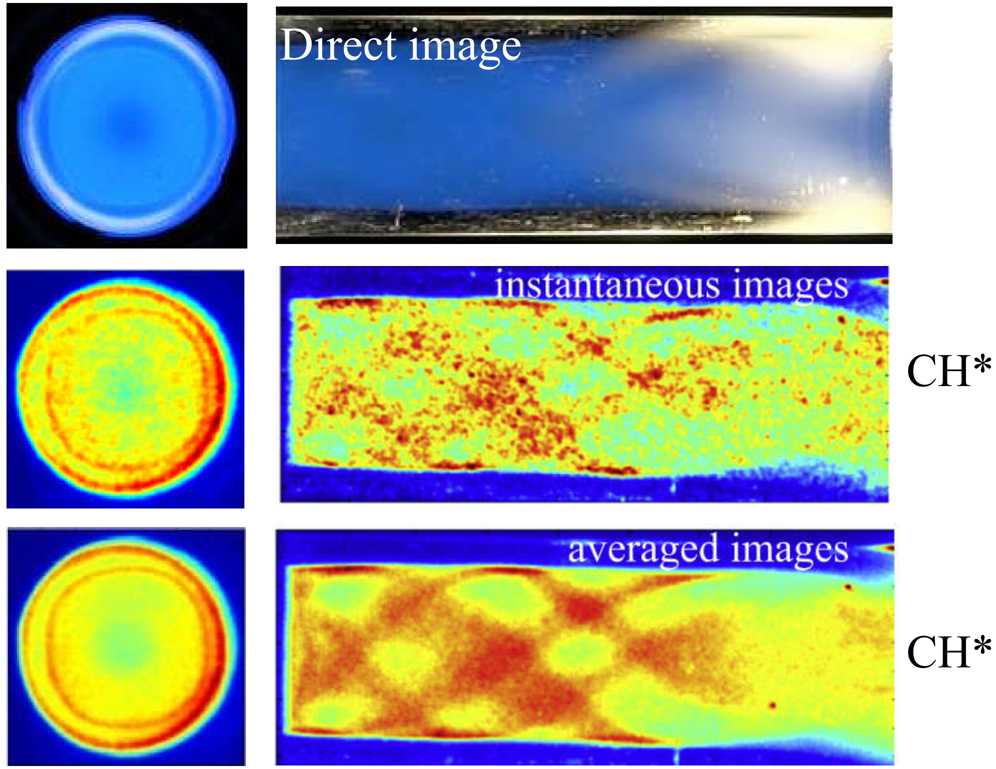
3 Experimental investigation-Oxy-methane





Oxygen mole fraction $\beta \leq 0.5$

Steady, uniform, laminar flame

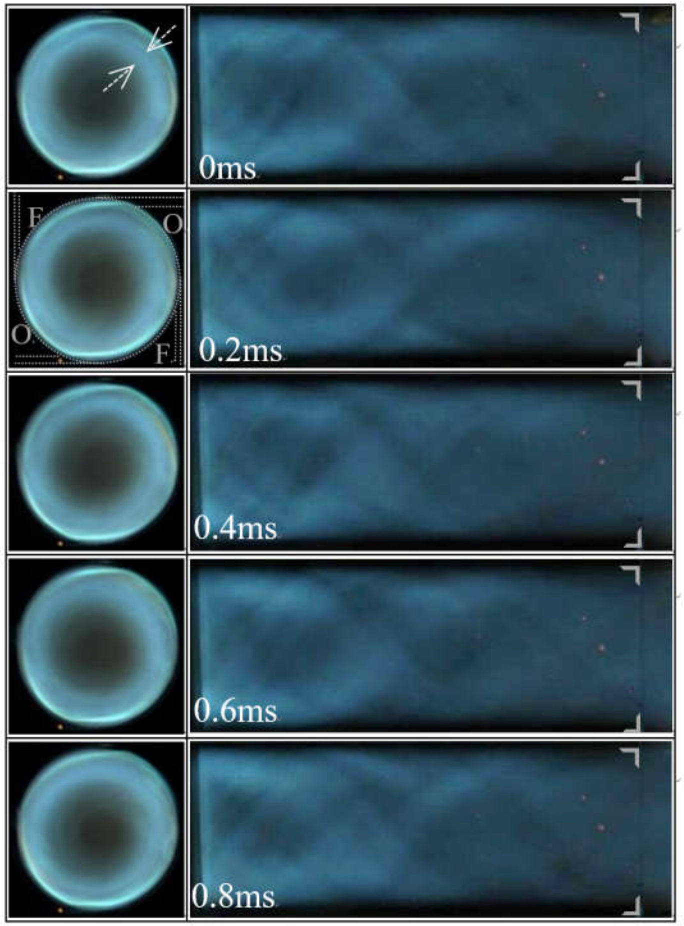


Steady laminar flame, $\beta = 0.67$, $\Phi = 1.0$

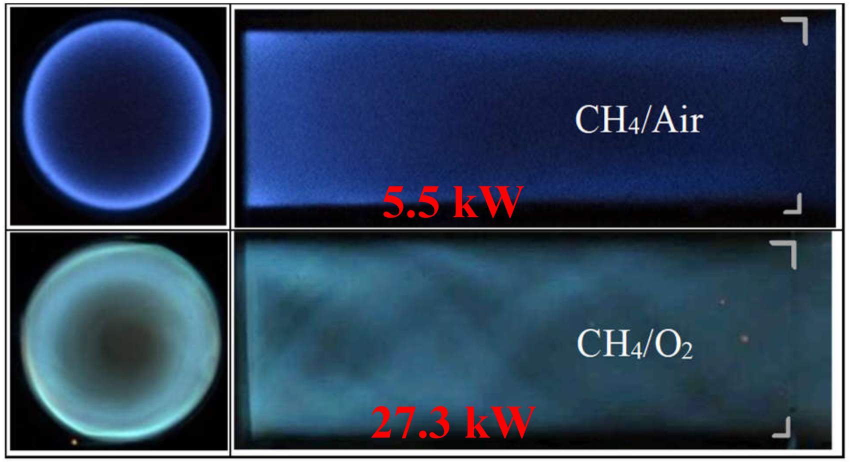
$\beta \geq 0.6$, **non-uniform** laminar flame

Ref. Shi, et al., Combust. Flame 162 (2015) 420-430.

3 Experimental investigation-CH_4/O_2



***β* = 1.0, *Φ* =1. 0**, steady laminar flame

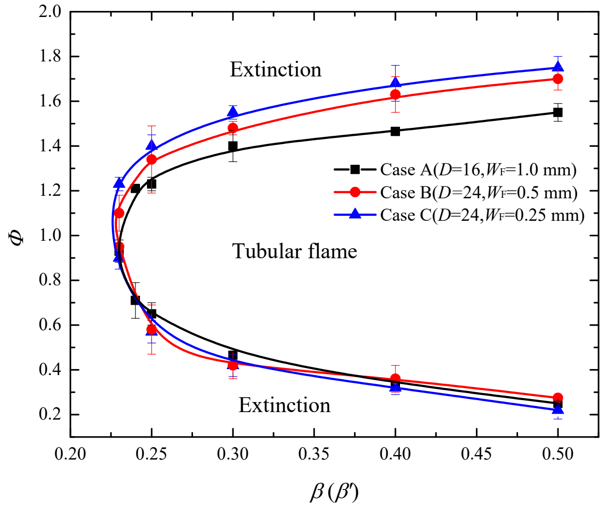


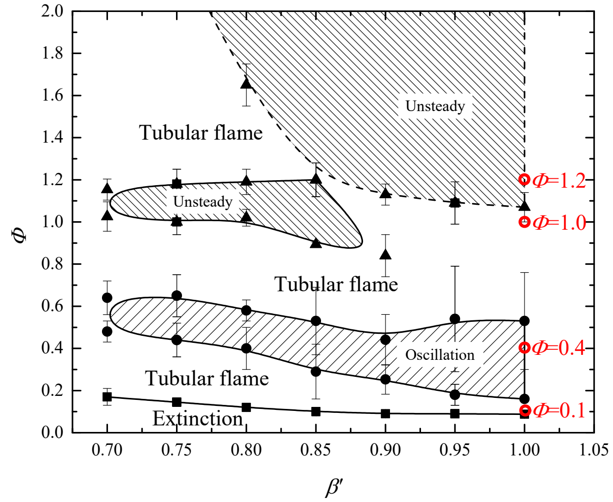
Q_O **=6.0 m³/h, *Φ*=1.0**

CH_4/Air	**CH_4/O_2**
T=**2220** K	**T=3050 K**
λ=**0.25**W/m·K	**λ=2.8 W/m·K**
HRR=**4.5x10³** J/cm³·s	HRR=**2.54x10⁵**J/cm³·s
	Reaction time≈22μs

Ref. Li, Shi*, et al., Energy 168 (2019) 151-159.

Experimental investigation-Stability



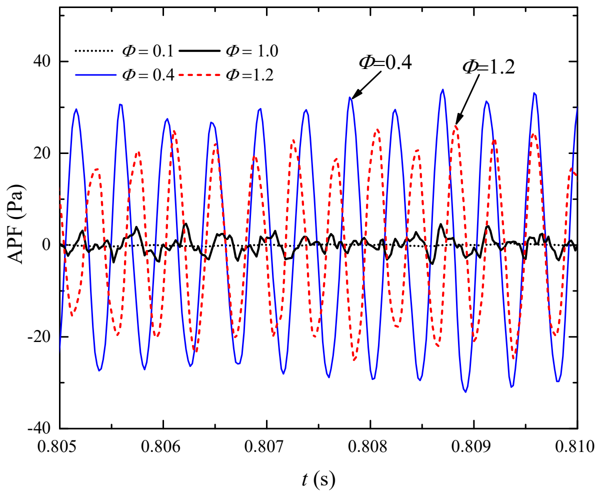


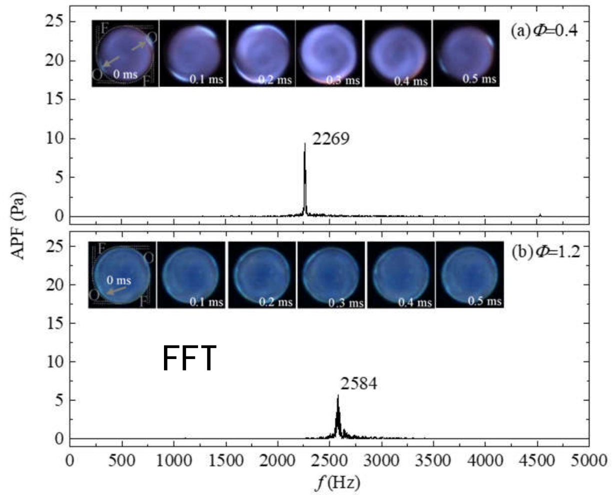
Premixed CH_4/O_2 flame

Φ=0.75-1.4, $T_f \geq 3000$ K

Combustion instability

e.g., **Φ=0.4, 1.2**





High frequency oscillation,

Axial mode thermal acoustic

$f_z=(2n_z+1)c/4(l+\Delta l)$

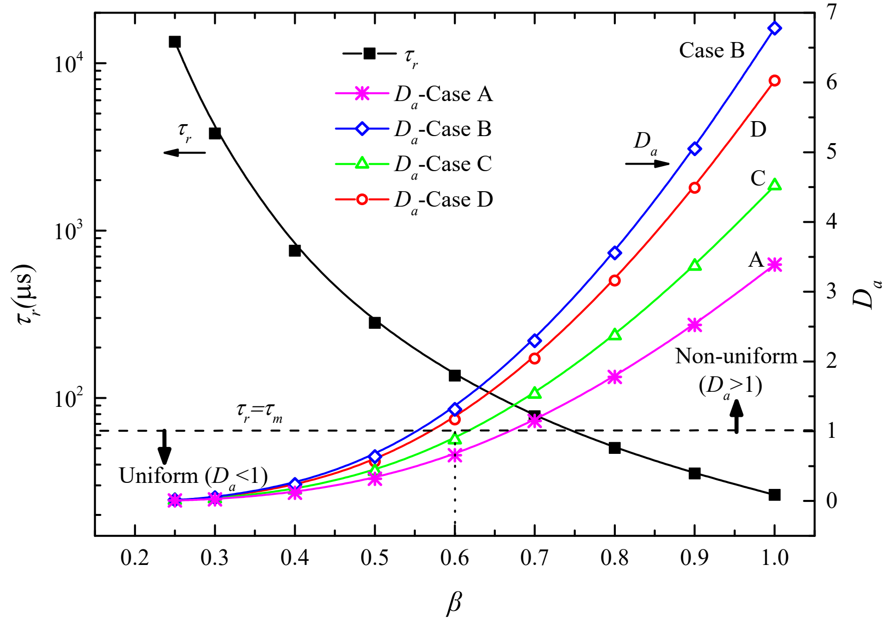
owing to **poor mixing**

Ref. Shi, et al, Combust. Flame 162 (2015) 520-530.
Li, Shi, et al， Exp. Therm. Fluid Sci. 90 (2018) 115-124.

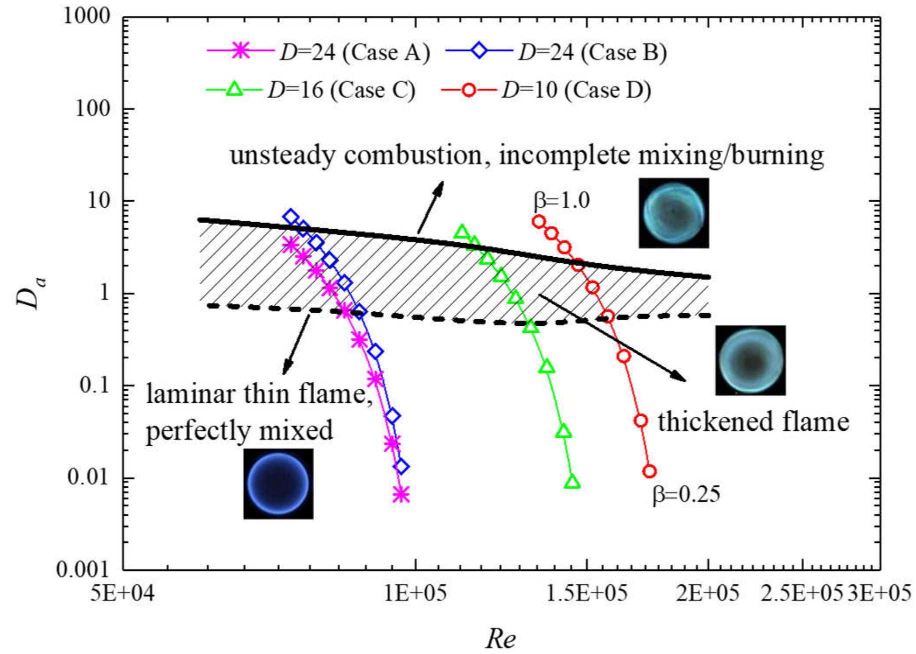
Experimental investigation-D_a

$$D_a \equiv \frac{\tau_m}{\tau_r} = \frac{mixing \ \ time}{reaction \ \ time} \leq \text{or} \approx 1 \qquad \tau_m \equiv \delta_m^{\ 2} / D_{mass} \qquad \tau_r \equiv \delta_L / S_u$$

Mixing of fuel/oxidizer should be completed before onset of reaction



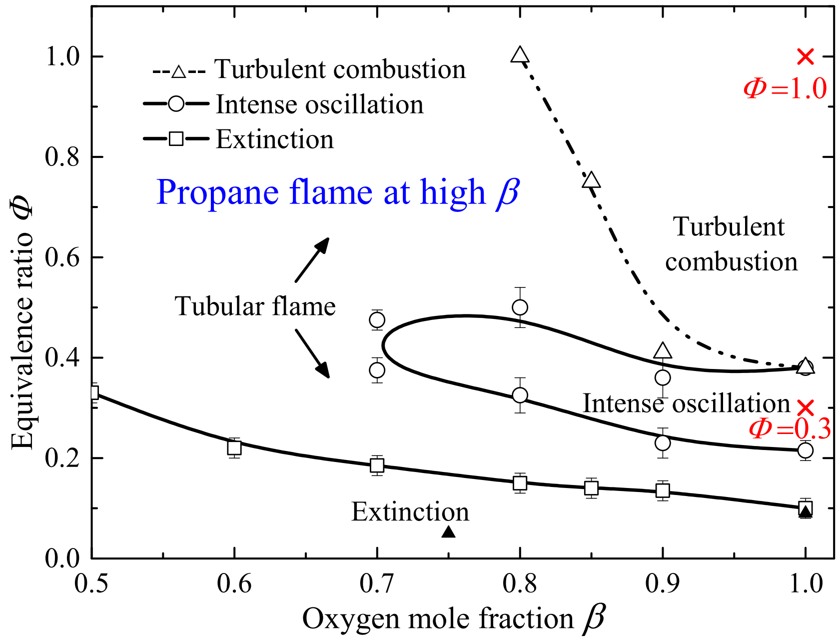
D_a in a variety of tests



Borghi graph (considering diameter, inlet size, flow rate)

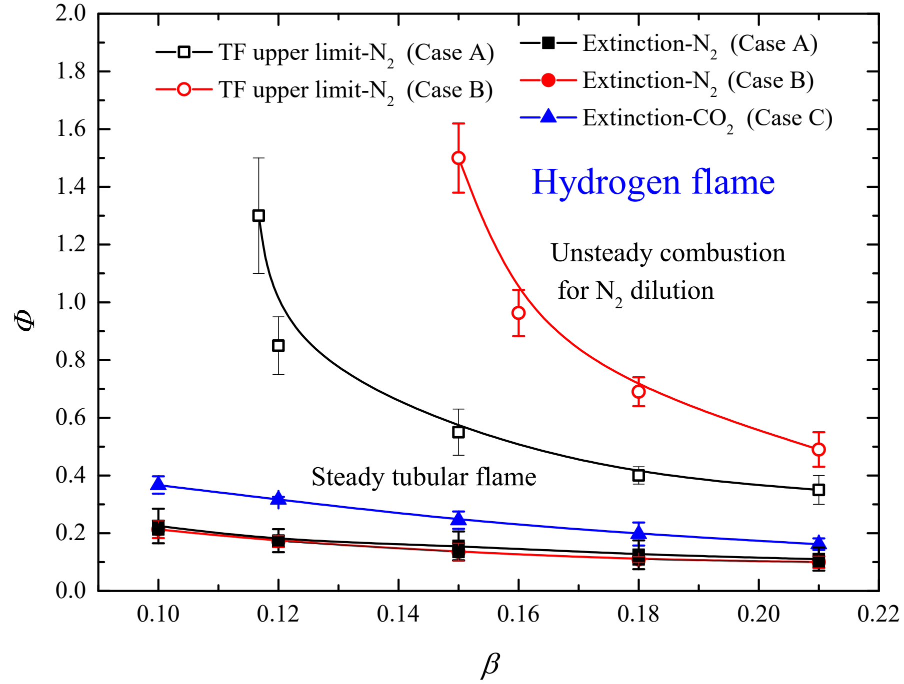
Ref. Shi, et al, PCI. 34 (2013) 3369-3377; Shi, et al, Combust. Flame 161(2014) 1310-1325; Li, Shi, et al, Energy 168 (2019) 151-159.

Experimental investigation-C_3H_8, H_2



β=1.0, Φ=0.3

β=1.0, Φ=1.0



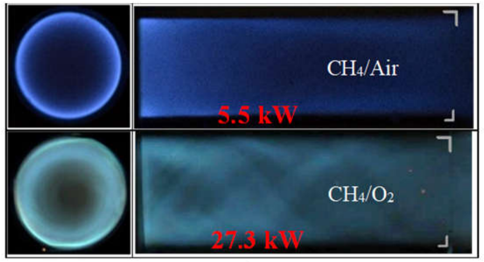
Combustion modes of hydrogen

Limited range of β for steady combustion

High burning velocity?

Ref. Shi, et al, Proc. Combust. Inst. 36 (2017) ; Shi, et al, Int. J. Hydrogen Energy 43 (2018) 14806-14815.

4 Summary

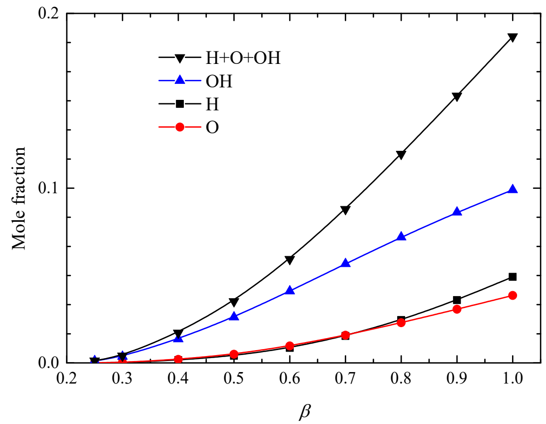


Q_O=6.0 m³/h, Φ=1.0

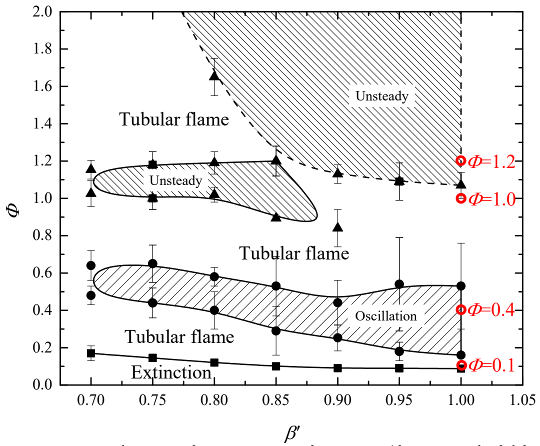
CH_4/Air	CH_4/O_2
T=2220 K	T=3050 K
λ=0.25W/m·K	λ=2.8 W/m·K
HRR=4.5x10³ J/cm³·s	HRR=2.54x10⁵J/cm³·s

Benefits of ultrahigh temperature combustion in industry

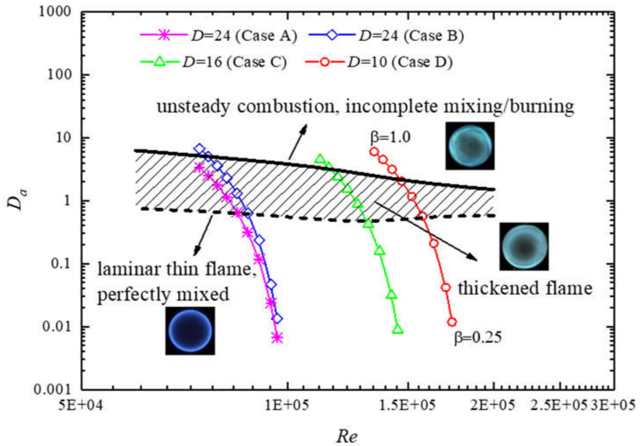
- Capacity increase
- Fuel saving
- CO_2 , NO*x* reduction
- Reduce scaling losses
- Quality improvement



Plenty of active radicals (*β*=1.0)



Combustion regime (instability)

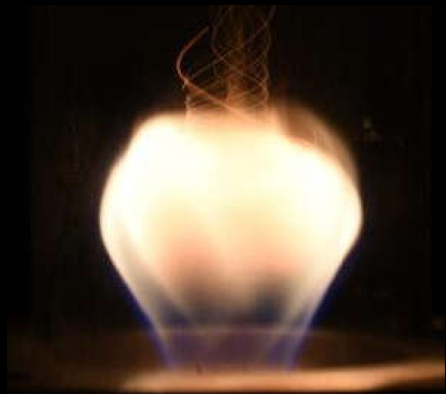


Borghi diagram

Challenges in measurement:

- Detailed flame structure,
- O, H, OH radicals,
- Temperature,
- Emissions…

Acknowledgement

NSFC: No. 51676016 , 91641204

Prof. Ishizuka & my team members！