第一届全国青年燃烧学术会议
2015年9月18-20日, 上海

层流火焰动力学研究进展及展望

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内容提要

1. 背景介绍
2. 代表性研究进展
3. 当前研究前沿
4. 总结展望

内容提要

1. **背景介绍**
2. 代表性研究进展
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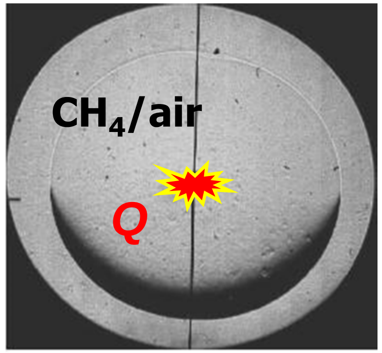
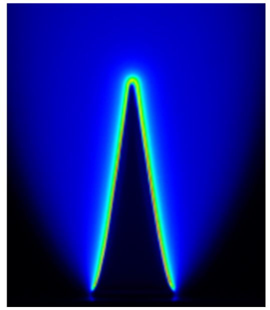
4. 总结展望

研究对象：基础燃烧过程

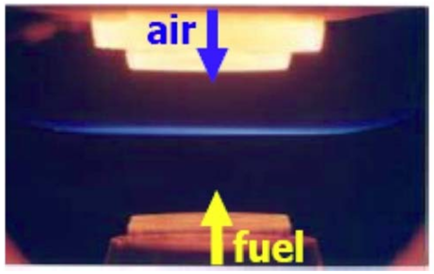
- **点火**
  - 最小点火能（球形传播火焰）
  - 点火温度/延迟时间（对冲火焰）



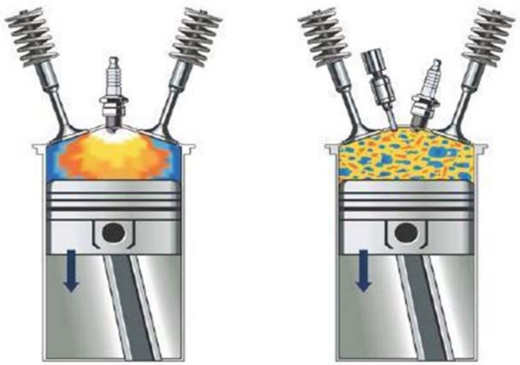
- **火焰传播**
  - 火焰速度（球形传播火焰、对冲火焰、平面火焰）
  - 火焰稳定性（球形传播火焰、平面火焰、热声耦合）
  - 火焰驻定（本森灯火焰、钝体稳定火焰）



- **熄火**
  - 熄火拉伸率（对冲火焰、球形传播火焰）
  - 可燃极限（球形传播火焰、管内传播火焰）



研究内容



研究与替代燃料和先进燃烧技术相关的基础燃烧问题：

- □ 基础燃烧理论研究
- □ 替代燃料燃烧特性研究
- ● 点火、火焰传播与熄火
- ● 近极限、多组元、高压、低温
- ● …… ……

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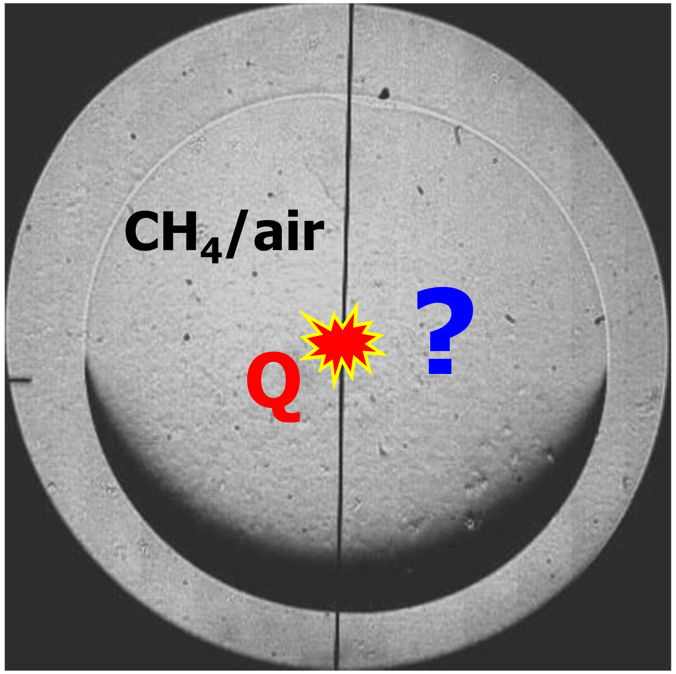
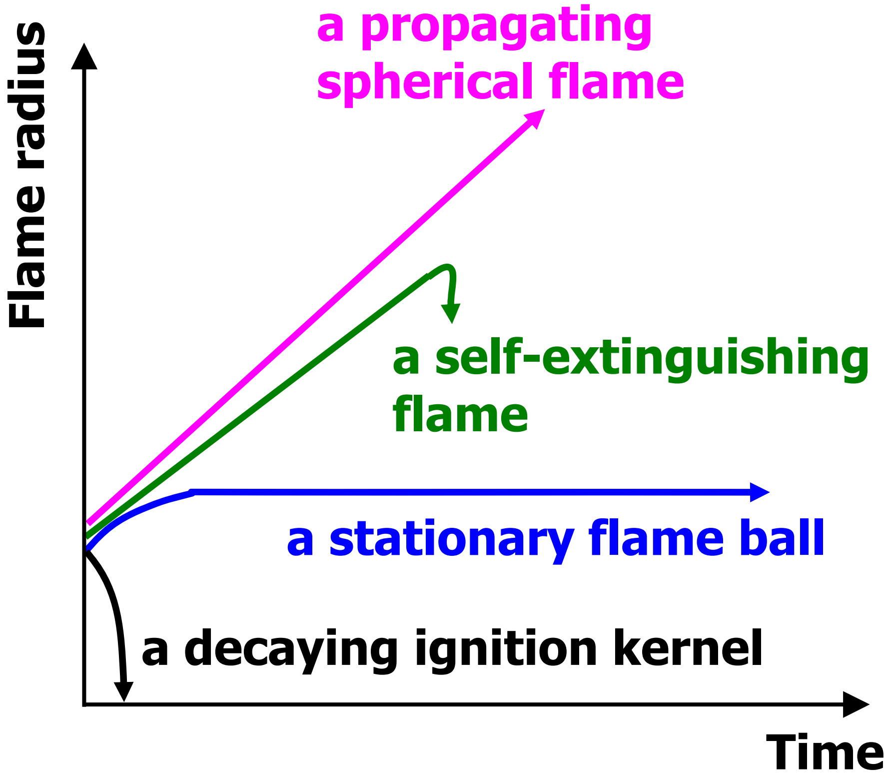
2.1 Flame ball and ignition theory

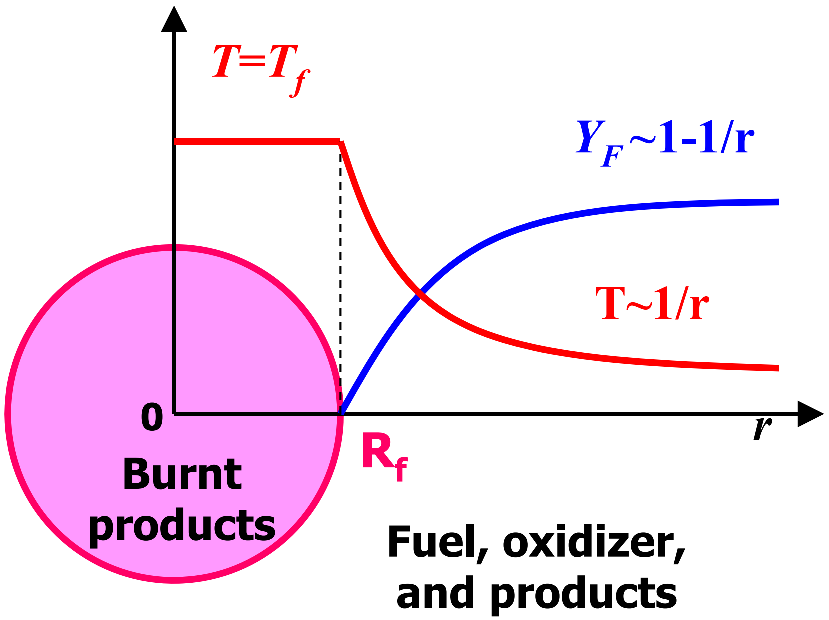
What happens after spark ignition in a premixture ?





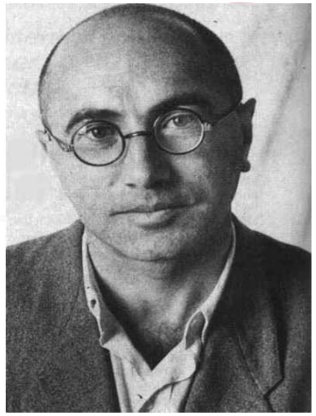
Depending on the mixture property and ignition energy, there are four possible outcomes.

What is flame ball ?



Zeldovich (1944):

- Purely diffusion-controlled stationary spherical flames
- Dynamics dominated by 1/r tail



Ya. B. Zel'dovich

Deshaies and Joulin (1984):

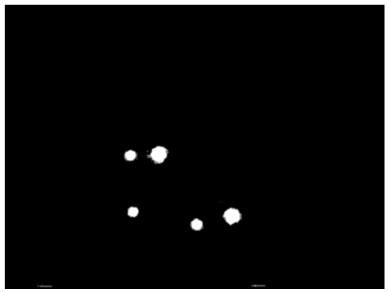
- Adiabatic flame balls are **unstable!**

?

Ronney (1990):

- Stationary flame balls
- Lean H_2-air mixtures

1.67 sec



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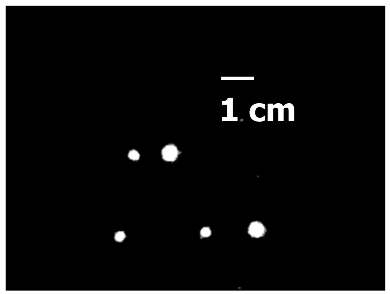

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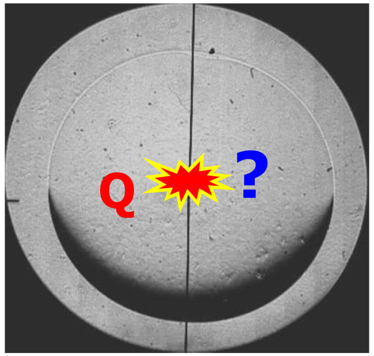
P. D. Ronney

Theory on critical ignition conditions

What is the controlling length scale for flame initiation ?

How is it related to the minimum ignition energy ?



- **Flame thickness**

  Lewis and Von Elbe (1961)

  - **Minimum flame kernel ~ flame thickness.**
  - **Minimum ignition energy ~ cube of flame thickness.**

- **Flame ball radius**

  Deshaies & Joulin (1984), Zeldovich et al. (1985), Champion et al. (1986)

  - **Adiabatic flame balls are unstable: collapse or expand.**
  - **Minimum flame kernel size ~ flame ball radius.**

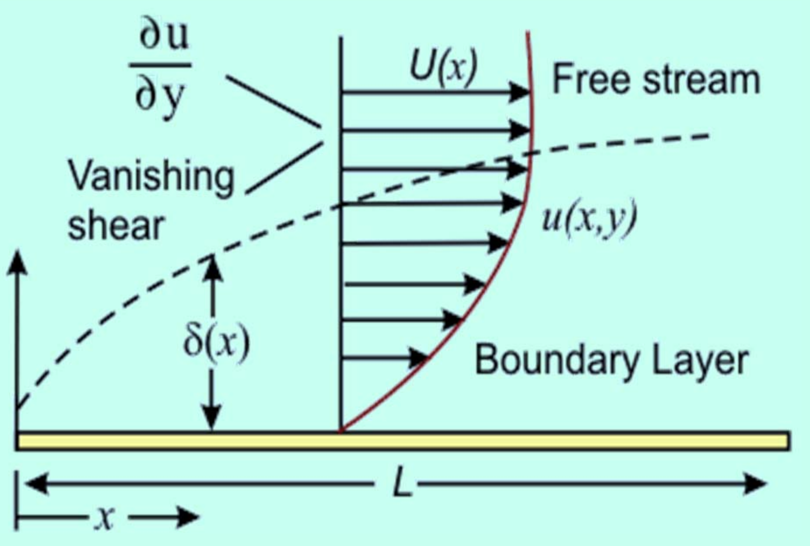
- **Minimum spherical flame radius**

  He (2001), Chen & Ju (2007CTM), Kelley & Law (2008CNF), Chen et al. (2011PCI)

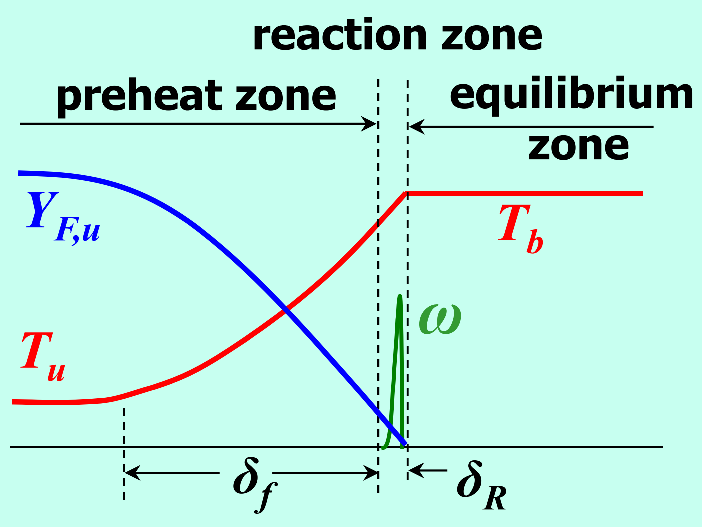
  - **Propagating spherical flame with radius less than flame ball radius exists.**
  - **Flame initiation might not be controlled by flame ball radius.**

2.2 Activation-energy asymptotics (AEA)

- **Fluids:** boundary layer theory (Prandtl): Re_x>>1
- **Flame:** large activation energy: E_a >>1
- **Math:** singular perturbation (matched asymptotics)



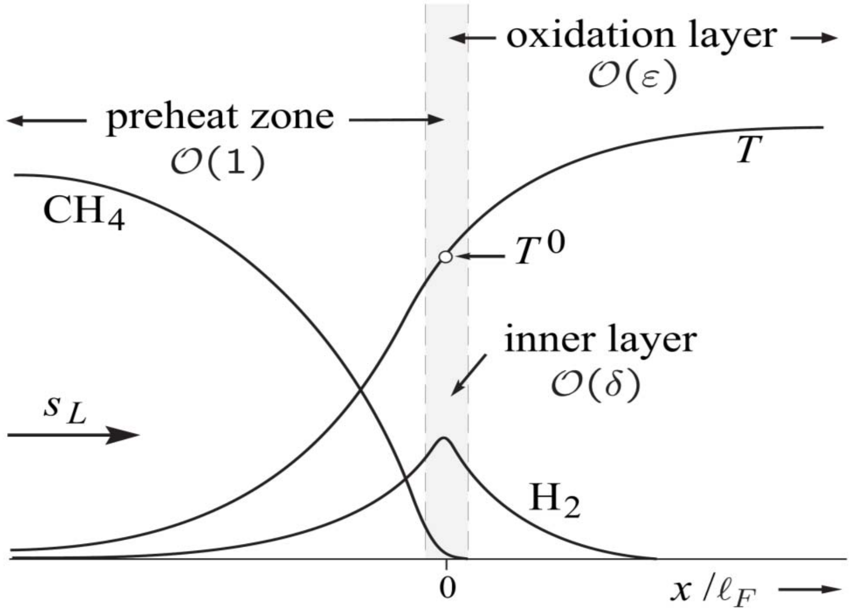
Boundary Layer



Premixed Flame

Reduced chemistry and flame structure

N. Peters



Premixed flame with four-step chemistry

$CH_4+2H+H_2O=CO+4H_2$

$CO + H_2O=CO_2+H_2$

$H + H + M=H_2 + M$

$O_2 + 3H_2 =2H+2H_2O$

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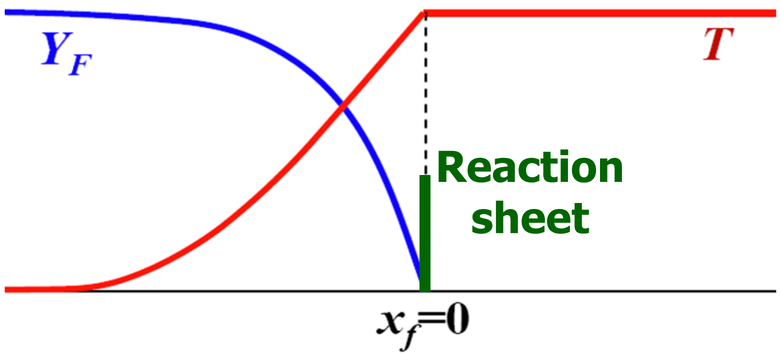
注：由于向一些国外同行咨询了相关建议，故该部分内容为英文

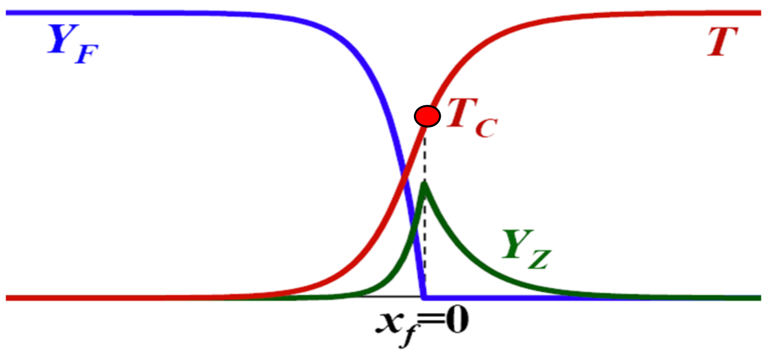
3.1 Laminar flame theory

Trend: from one-step chemistry to multi-step chemistry

Fuel → Product



Fuel → Radical → Product



Focus:
- ignition, extinction
- hydrodynamics & instability
- near-flammability limit
- ...

4-step chemistry (N. Peters)
- $CH_4+2H+H_2O = CO+4H_2$
- $CO+H_2O = CO_2+H_2$
- $H+H+M = H_2+M$
- $O_2+3H_2 = 2H+2H_2O$

Review papers:
- Matalon (2009), Smooke (2013) ... PCI
- Sanchez & Williams (2014), Pitz (2014), ...PECS
- Matalon (2007), Candel (2014) Linan (2015) Annual Rev. Fluid

3.1 Laminar flame theory

Two-step chemistry:

chain branching reaction

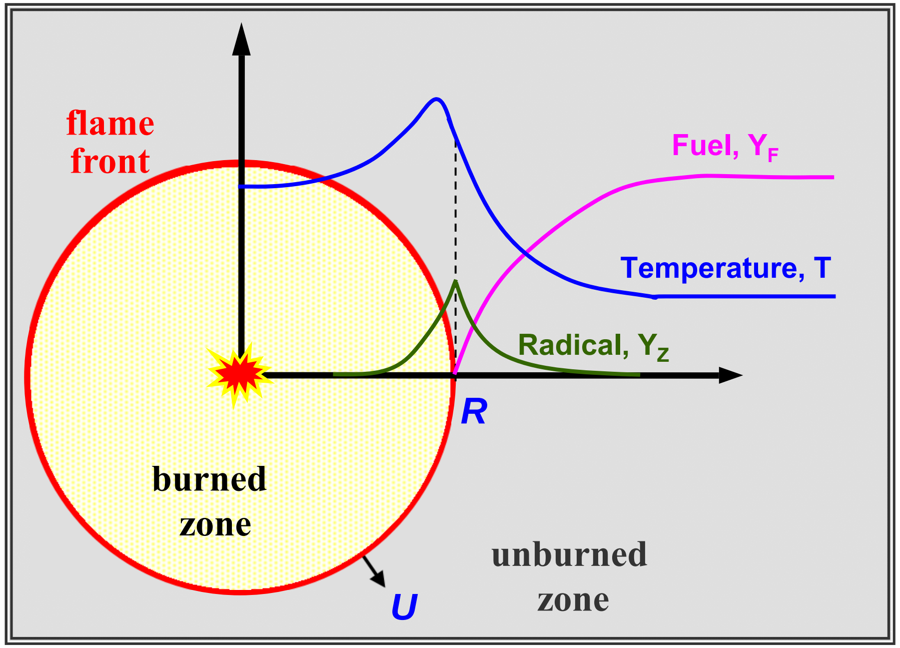
$$F + Z \rightarrow 2Z$$

chain termination reaction

$$Z + M \rightarrow P + M$$

Asymptotic analysis:

$$\boxed{f(U,\ R;\ q_t,\ q_r,\ Le_F,\ Le_Z,\ h) = 0}$$

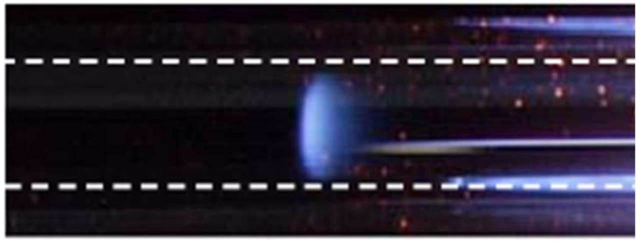


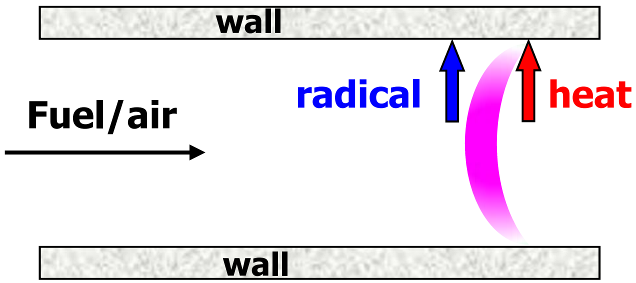
- **Effects of radical reaction and transport [1]**
- **Flame quenching [2,3]**
- **Thermal vs. chemical ignition efficiency [4]**

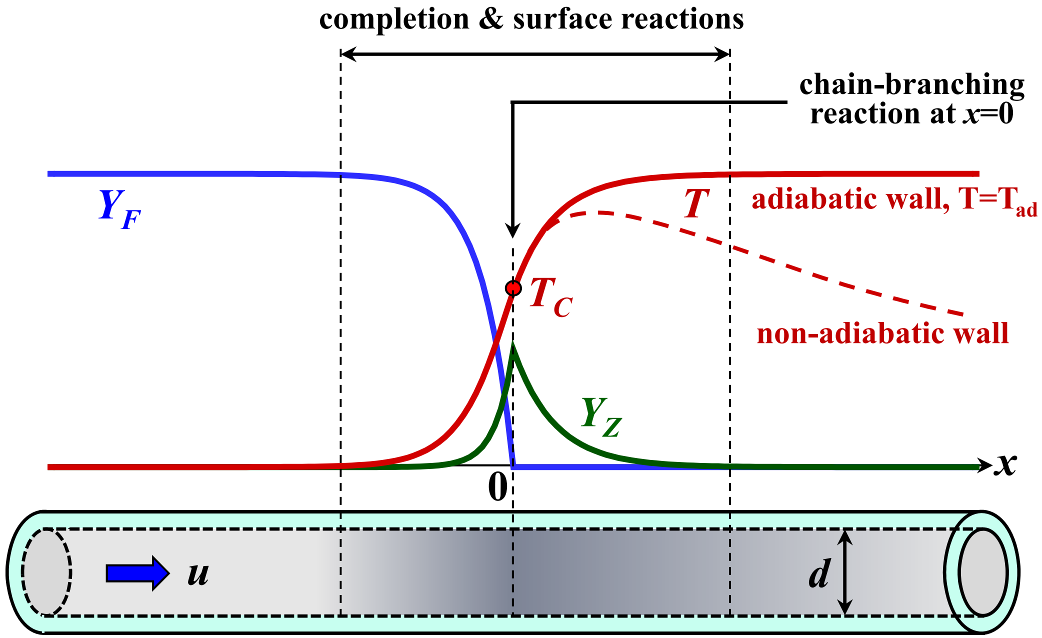
[1] H. Zhang, Z. Chen, Combustion and Flame, 158 (2011) 1520-1531.
[2] H. Zhang, Z. Chen, Combustion Theory and Modelling, 17 (2013) 682-706.
[3] H. Zhang, P. Guo, Z. Chen, Combustion Science and Technology, 185 (2013) 226-248.
[4] H. Zhang, P. Guo, Z. Chen, Proceedings of the Combustion Institute, 34 (2013) 3267-3275.

3.1 Laminar flame theory

Theory on flame propagation in a tube







- **Two flame quenching mechanisms**
  - **Thermal quenching (heat loss)**
  - **Kinetic quenching (radical quenching)**
- **Effects of wall quenching of radicals [1]**
- **Heat recirculation, radical recirculation ?**

[1] B. Bai, Z. Chen, H. Zhang, S. Chen, Combustion and Flame, 160 (2013) 2810-2819.

3.2 Flame-chemistry

International Workshop on Flame Chemistry, 2012, 2014

Challenges in flame-chemistry:

- What are the new findings and the major knowledge gaps in understanding ignition and flame chemistry at extreme conditions?
- How to formulate theoretical and experimental strategies to narrow the knowledge gap and to develop better predictive kinetic models?
- What are the major differences in chemistry between homogeneous ignition and laminar and turbulent flames?
- How does low temperature chemistry affect ignition and combustion in high pressure HCCI, PPCI, RCCI, and gas turbine engines?
- How can we quantify the fidelity of high pressure flame chemistry and transport data?
- How can we extract constraining information for model construction from macro measure ignition delay, flame speeds, and extinction limits?
- What diagnostics can we apply to high pressure systems?
- How does turbulence and chemistry interact in high pressure and Reynolds flows?
- Can this workshop formulate collaborative relationship in research?

3.2 Flame-chemistry

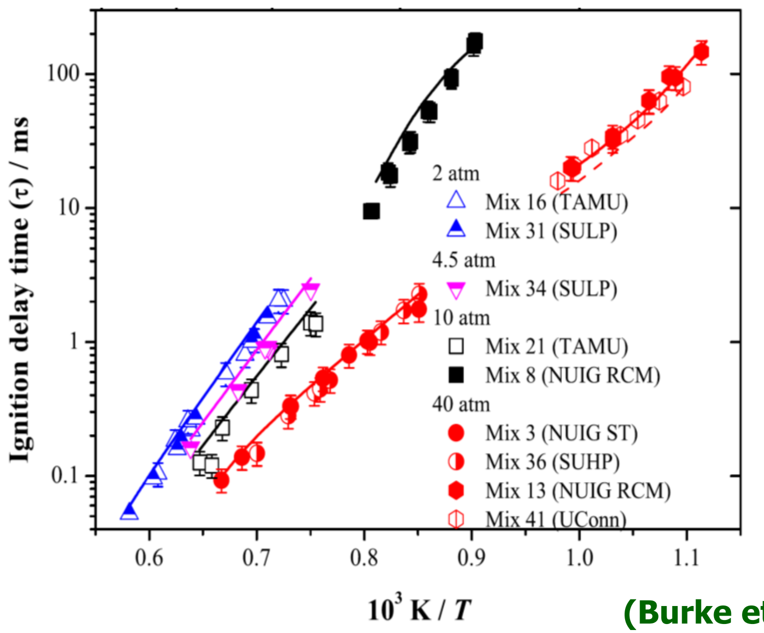
International Workshop on Flame Chemistry, 2012, 2014

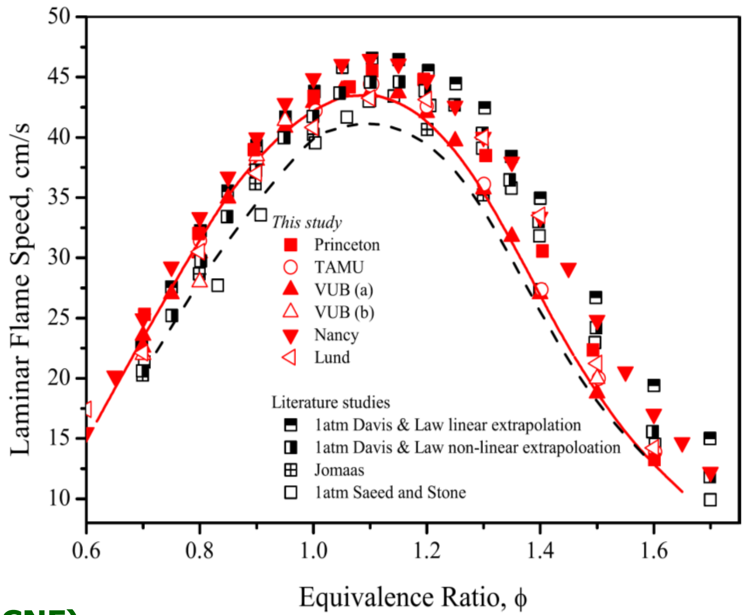
Collaboration: propene (2012), petane (2014)

An experimental and modeling study of propene oxidation.

- **Part 1: Speciation measurements in jet-stirred and flow reactors (2014 CNF)**
- **Part 2: Ignition delay time and flame speed measurements (2015 CNF)**

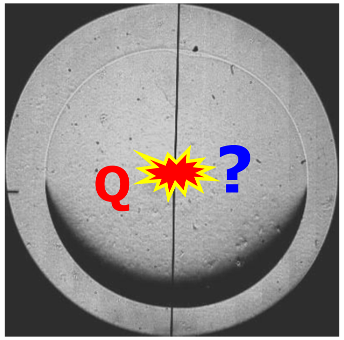
Authors: Battin-Leclerc, Curran, Dryer, Herbinet, Ju, Konnov, Nilsson, Oehlschlaegerc, Petersen, Sung …





(Burke et al. 2015 CNF)

3.3 Ignition — minimum ignition energy



Background:

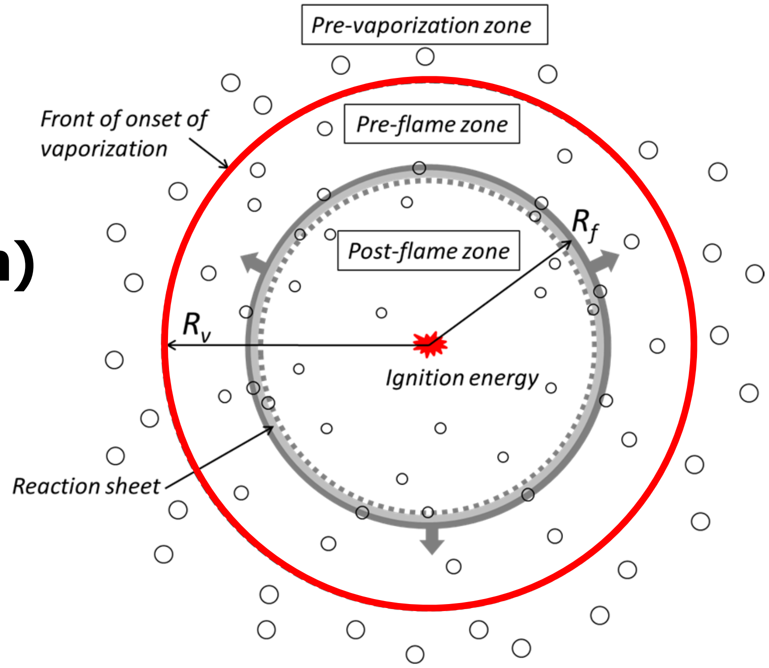
- High-altitude relight
- High-speed combustion
- Safety (fire, explosion)

Focus:

- Chemical effect (plasma)
- Turbulence (flow, transport)
- Diluents (H_2O, CO_2, ultra-lean)
- Spray (vaporization)
- Solid propellants (B, Al)

Review papers:

- Ju & Sun (2015) PECS
- Mastorakos (2009) PECS
- Aggarwal (2014) PECS
- Dreizin (2015) PECS



Ignition of spray flame

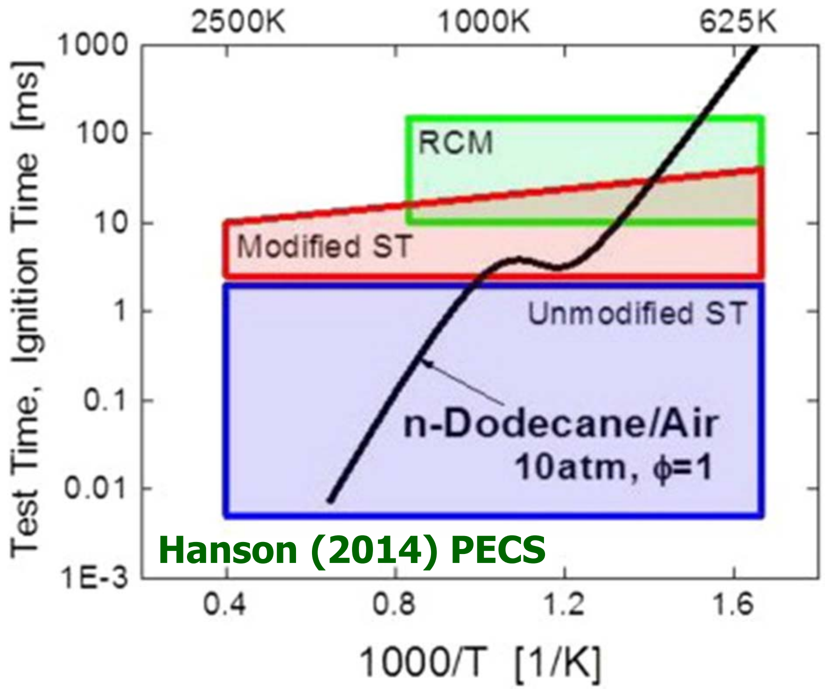
Han & Chen (2015) Combust. Flame

3.3 Ignition — ignition delay time

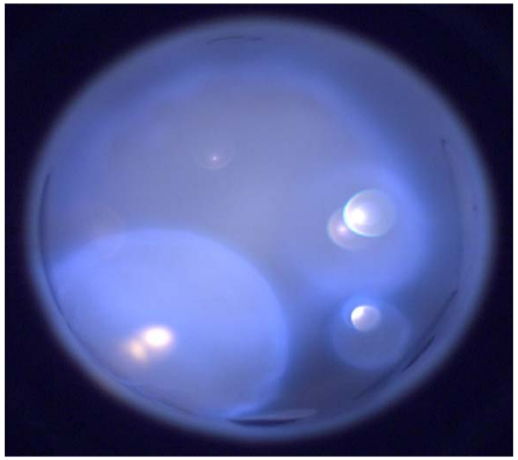
Background:
- **Data for chemical model development and validation**
- **High T: Shock tube**
- **Low T: RCM**

Focus:
- **Inhomogeneous ignition**
- **Strong/weak ignition**
- **ignition vs. flame**

Review papers & groups:
- **Hanson & Davidson (2014) PECS**
- **Sung & Curran (2014) PECS**
- **Grogan et al. (2015) CNF**
- **Wooldridge Group**
- **Ihme Group …**



Hanson (2014) PECS



Mansfield (2014) CNF

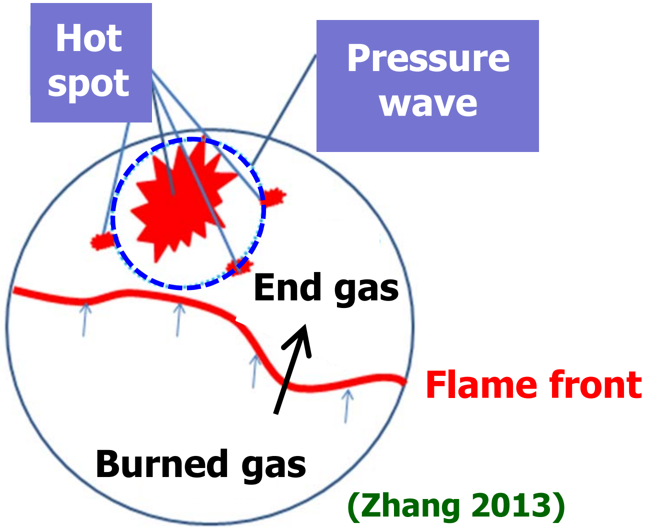
3.3 Ignition — Internal Comb. Engine

Background:

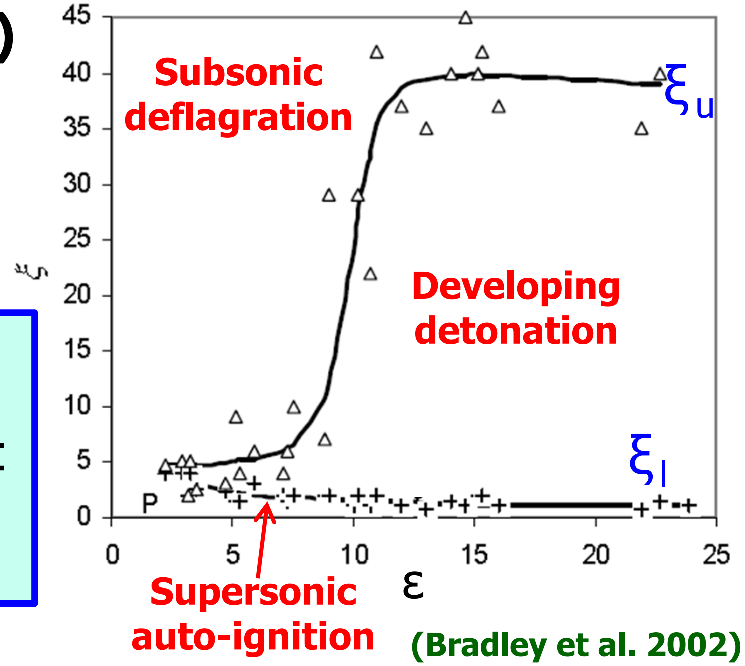
- Ignition control – HCCI, RCCI
- Engine knock

Focus:

- Fuel design/reactivity control
- End-gas autoignition (flame propagates in autoigniting mixture)
- Pre-ignition & super-knock
- Detonation development



(Zhang 2013)



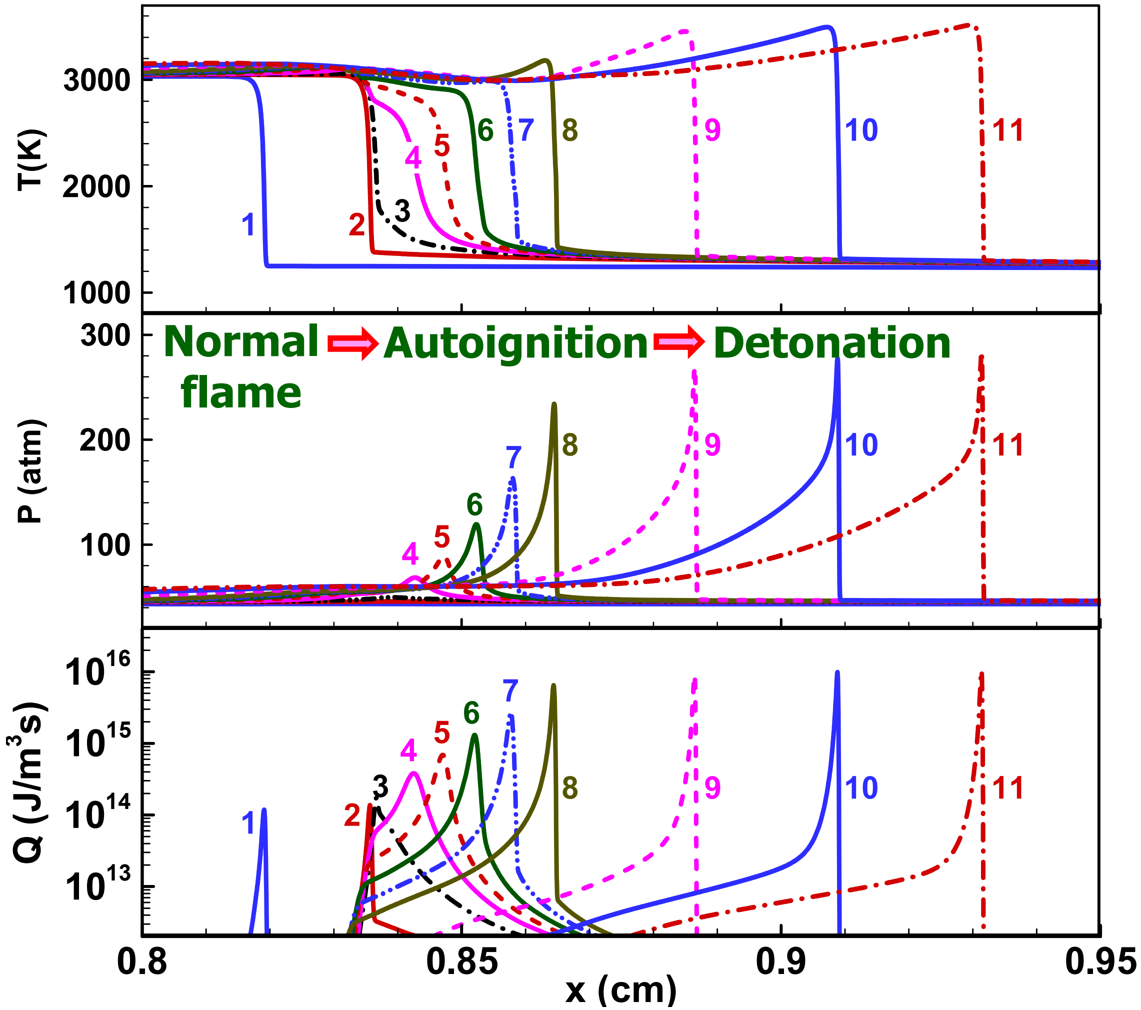
(Bradley et al. 2002)

Review papers & research groups:

- Yao (2009), Lu (2011), Saxena(2013) … PECS
- Drake (2007), Dec (2009), Kalghatgi (2015) PCI
- Kalghatgi (2014), Wang (2015) … IJER
- Bradley, Wooldridge, Wang, Wei, Chen …

3.3 Ignition — flame, autoignite/detonation

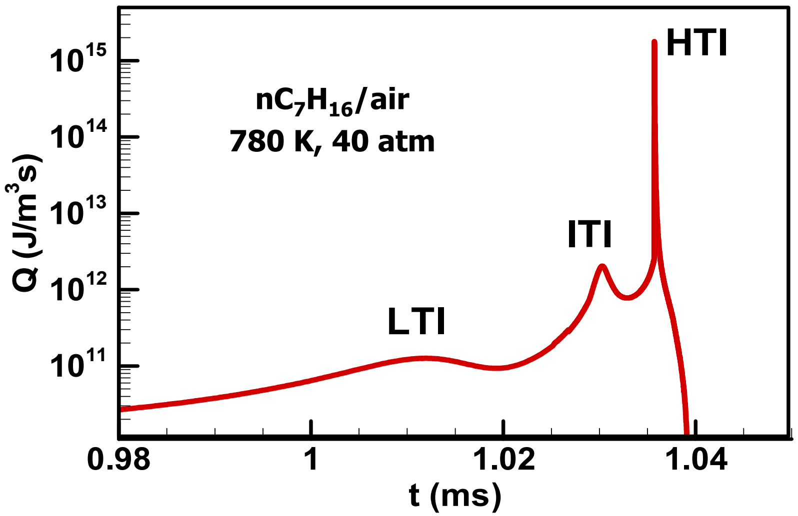
Focus: flame propagates in autoigniting mixture

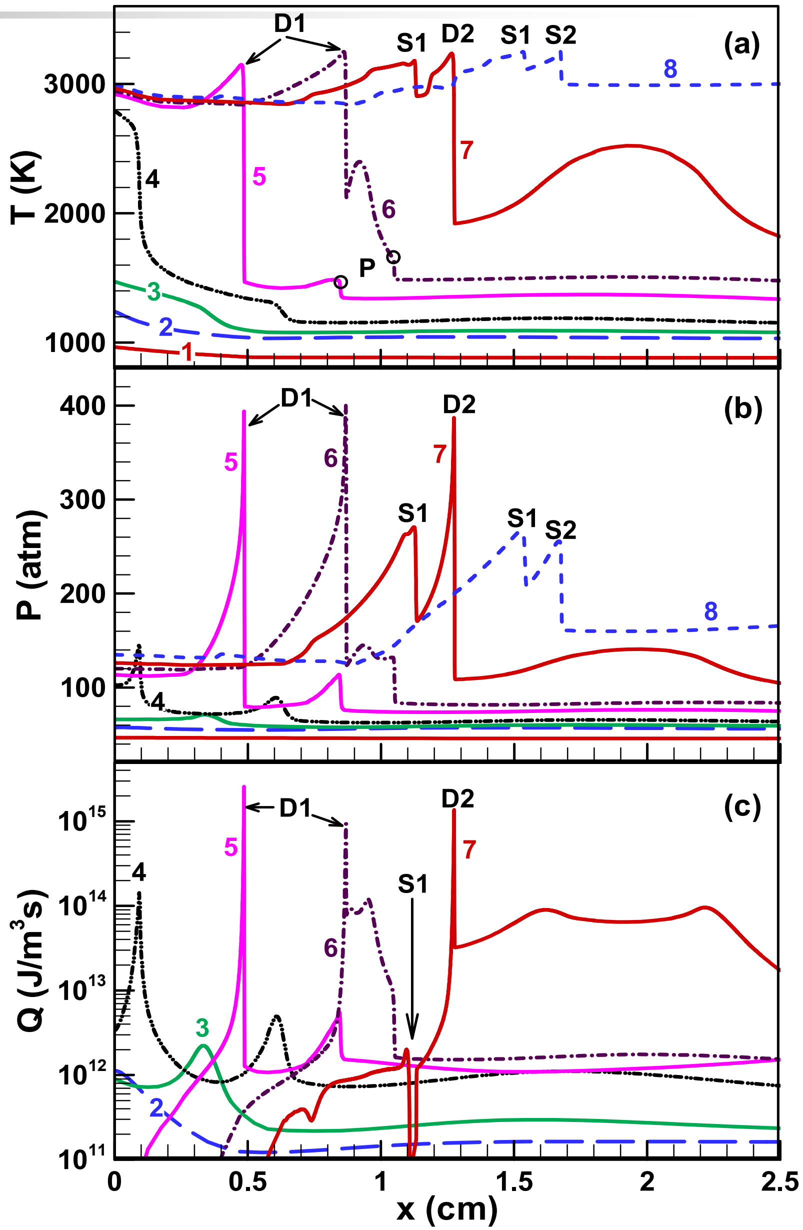


Simulation (Yu and Chen, 2015CNF)

Exp. (Qi, Wang ... 2015CNF)

Multi-stage ignition at low temperature

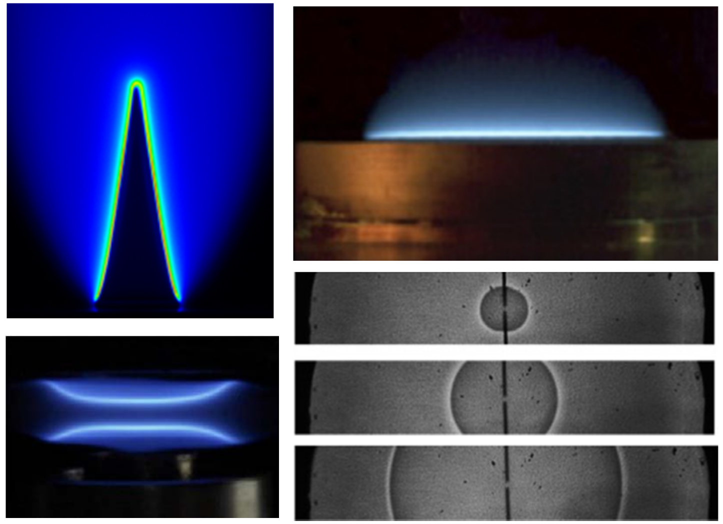




- For large fuels, multi-stage ignition occurs at low T.
- Heat release during different ignition stages might produce different pressure pulses.
- Complicated reaction-pressure wave interactions happen.

P. Dai, Z. Chen, Combustion and Flame, (2015) online.

3.4 Flame propagation — S_u



Egolfopoulos et al. (2014) PECS

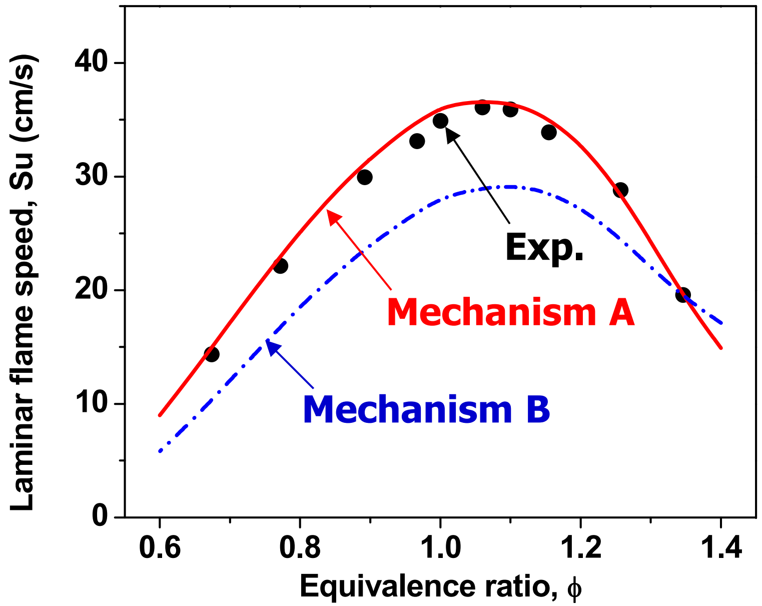
Workshop on Laminar Burning Velocity (2012, 2015 France)

Background:

- **Data for chemical model development and validation**
- **Input for turbulent premixed flame modeling**

Focus:

- **Accuracy/uncertainty**
- **High pressure/temperature**

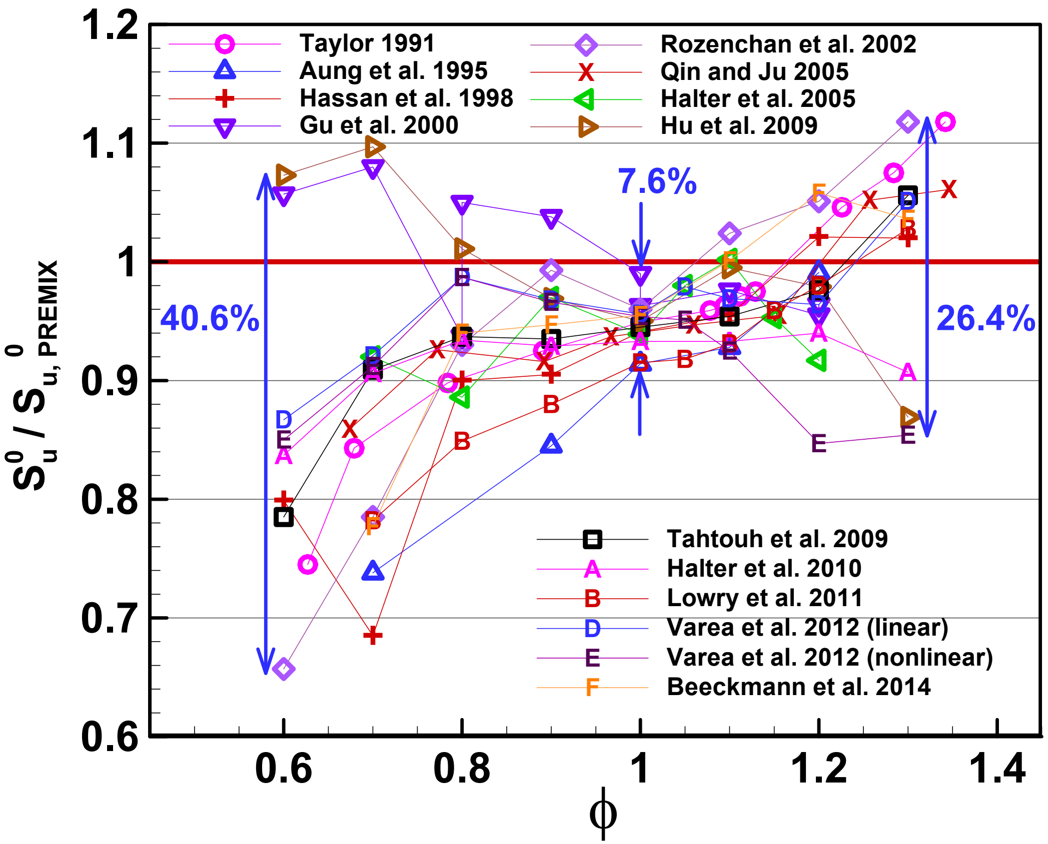


Review papers:

- **Egolfopoulos et al. (2014) PECS**
- **Ranzi et al. (2012) PECS**

3.4 Flame propagation — S_u

Measurements for the same mixture by different groups



CH_4/air at NTP

Normalized by prediction of GRI Mech 3.0

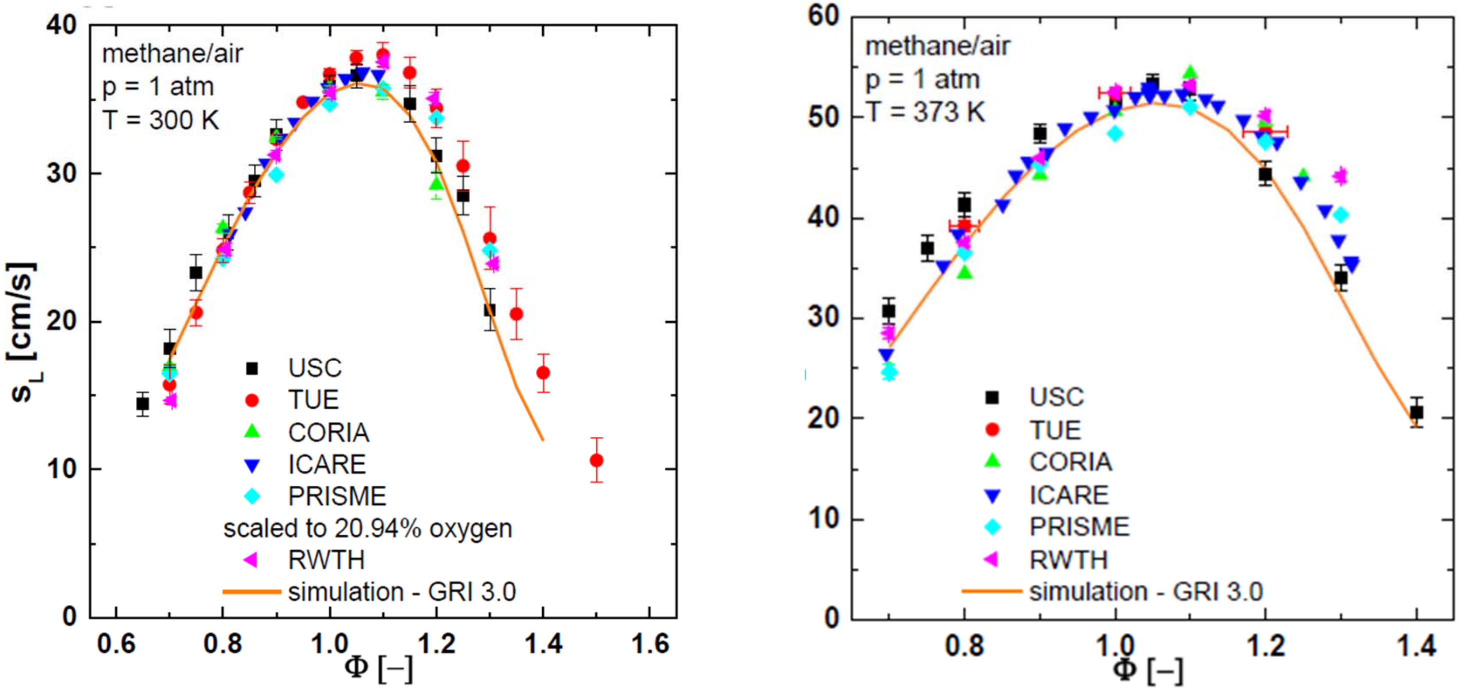
Z. Chen (2015) CNF

- **Very large discrepancy at very lean or rich condition**
- **Useless for restraining the uncertainty of chemistry**

Collaborative Study for Accurate Measurements of Laminar Burning Velocity

J. Beeckmann[*1], N. Chaumeix[2], P. Dagaut[2], G. Dayma[2], F. Egolfopoulos[3], F. Foucher[4], P. de Goey[5], F. Halter[4], A. Konnov[6], C. Mounaïm-Rousselle[4], H. Pitsch[1],B. Renou[7], E. Varea[7] and E. Volkov[5]

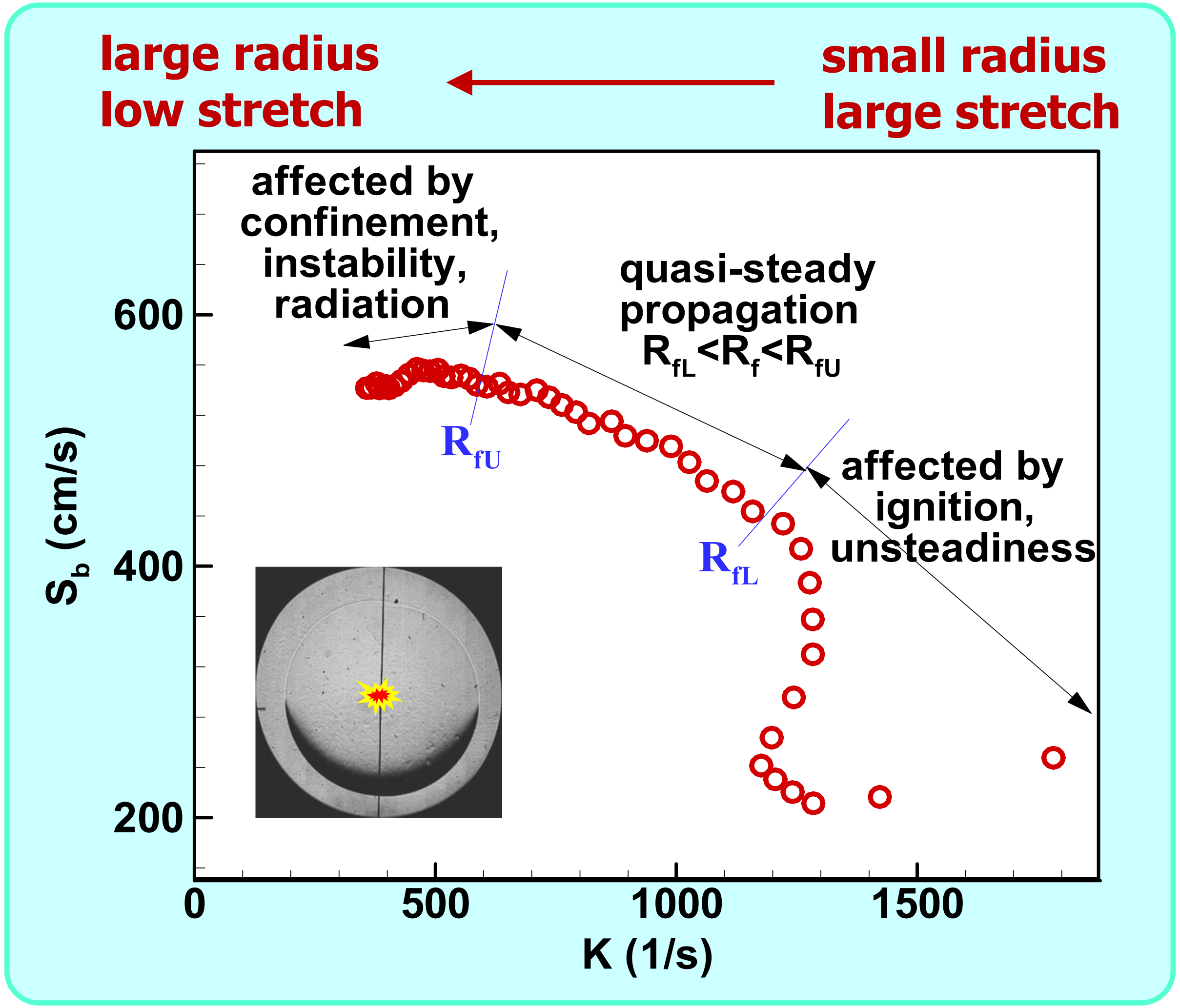
[1]*Institute for Combustion Technology, RWTH Aachen University, Aachen, Germany*
[2]*CNRS-ICARE, Orléans, France*
[3]*University of Southern California, Los Angeles, United States of America*
[4]*PRISME, Université d'Orléans, Orléans, France*
[5]*University of Technology Eindhoven, Eindhoven, Netherlands*
[6]*Division of Combustion Physics, Lund University, Lund, Sweden*
[7]*CORIA - INSA de Rouen, Rouen, France*



Collaborative work after the 1st (2012) Workshop on Laminar Burning Velocity

3.4 Flame propagation — S_u

Possible causes for the uncertainties in S_u measurement:



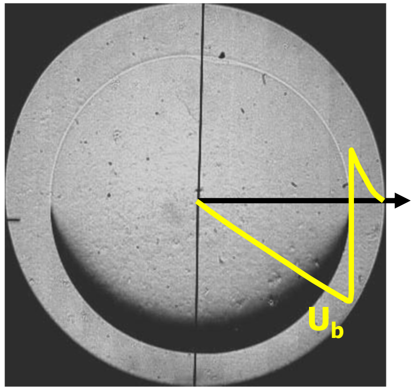
- **Mixture: ϕ , P, T_u**
- **Ignition**
- **Buoyancy**
- **Instability**
- **Confinement**
- **Radiation**
- **Nonlinear stretch**
- **Extrapolation**

...

Z. Chen (2015) CNF

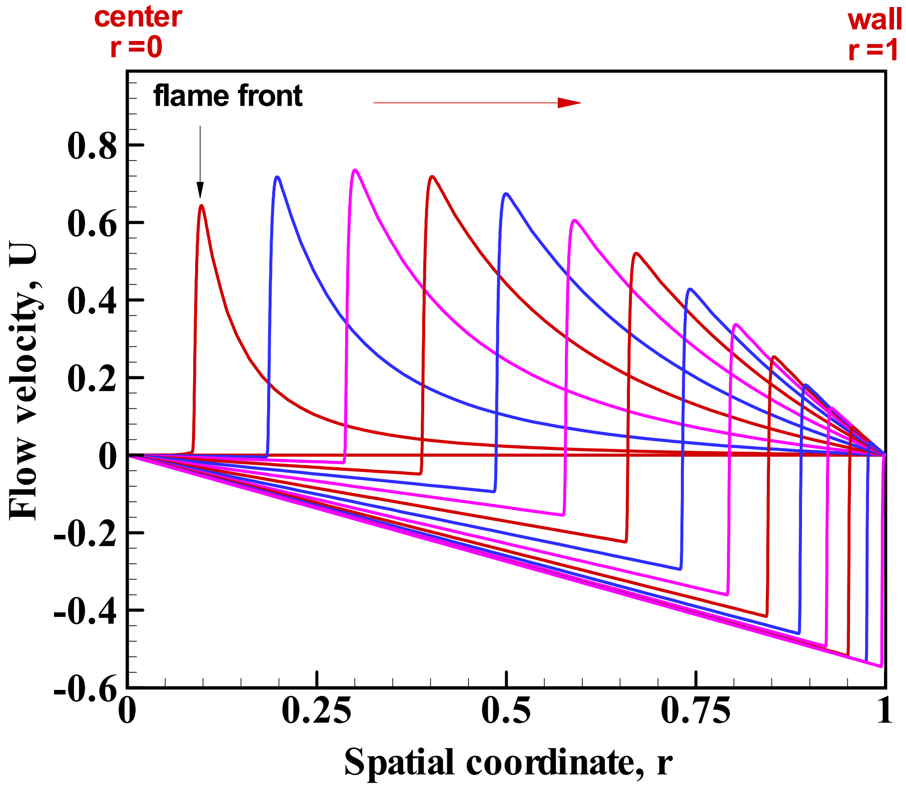
Confinement: P rise and compression

Z. Chen, M.P. Burke, Y. Ju, Combust. Theory Modell. 13 (2009) 343-364.
Z. Chen, Combust. Flame 157 (2010) 2267-2276.



$$S_b = \frac{dR_f}{dt} - \cancel{u_b}$$

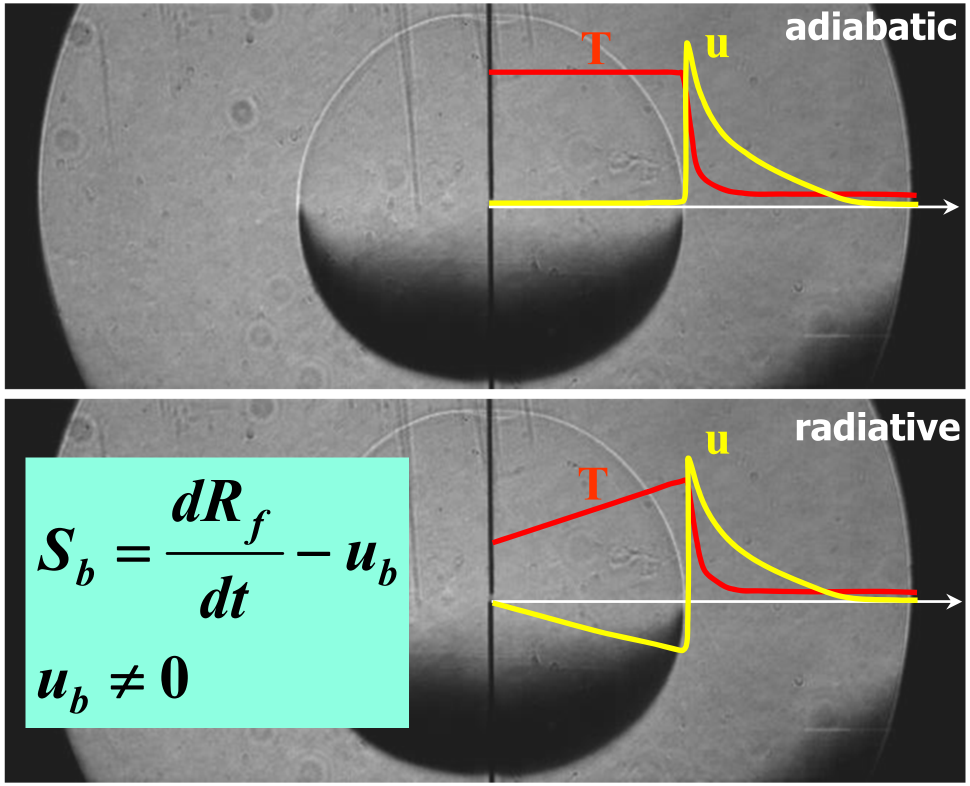
$$u_b \neq 0$$



- **Flow effect:** to induce inward flow and slow flame propagation
- **Thermal effect:** to increase T_u and flame propagation speed

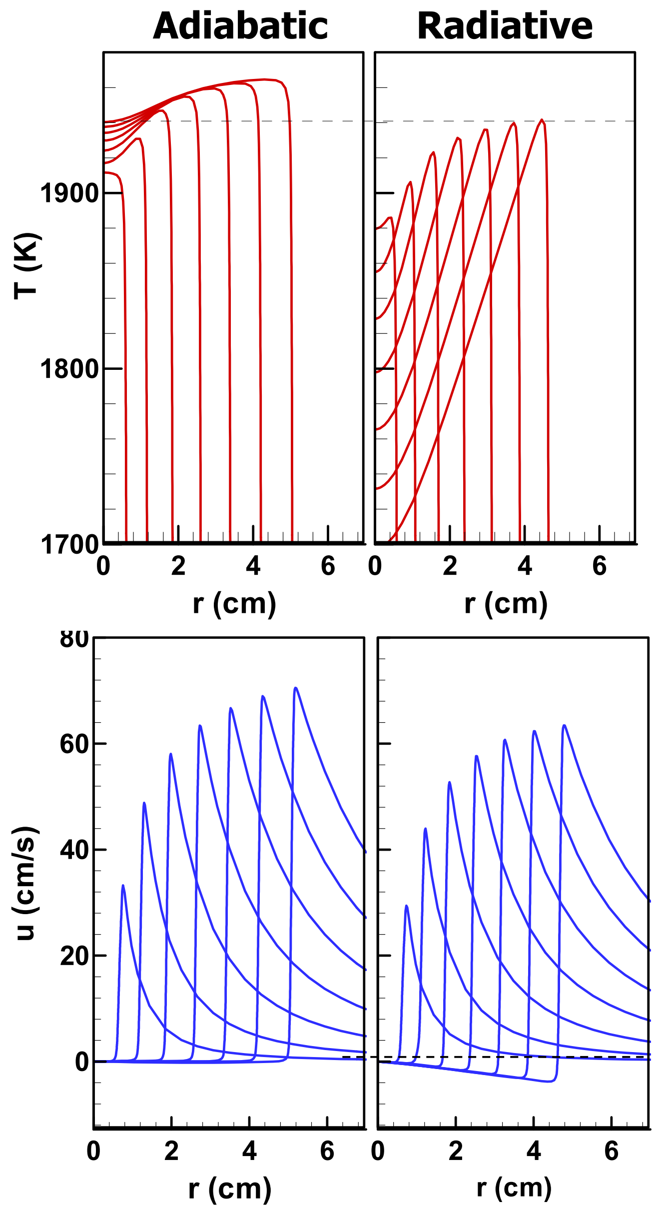
Radiation: thermal & flow effects

Z. Chen, Combust. Flame 157 (2010) 2267-2276.



$$S_b = \frac{dR_f}{dt} - u_b$$

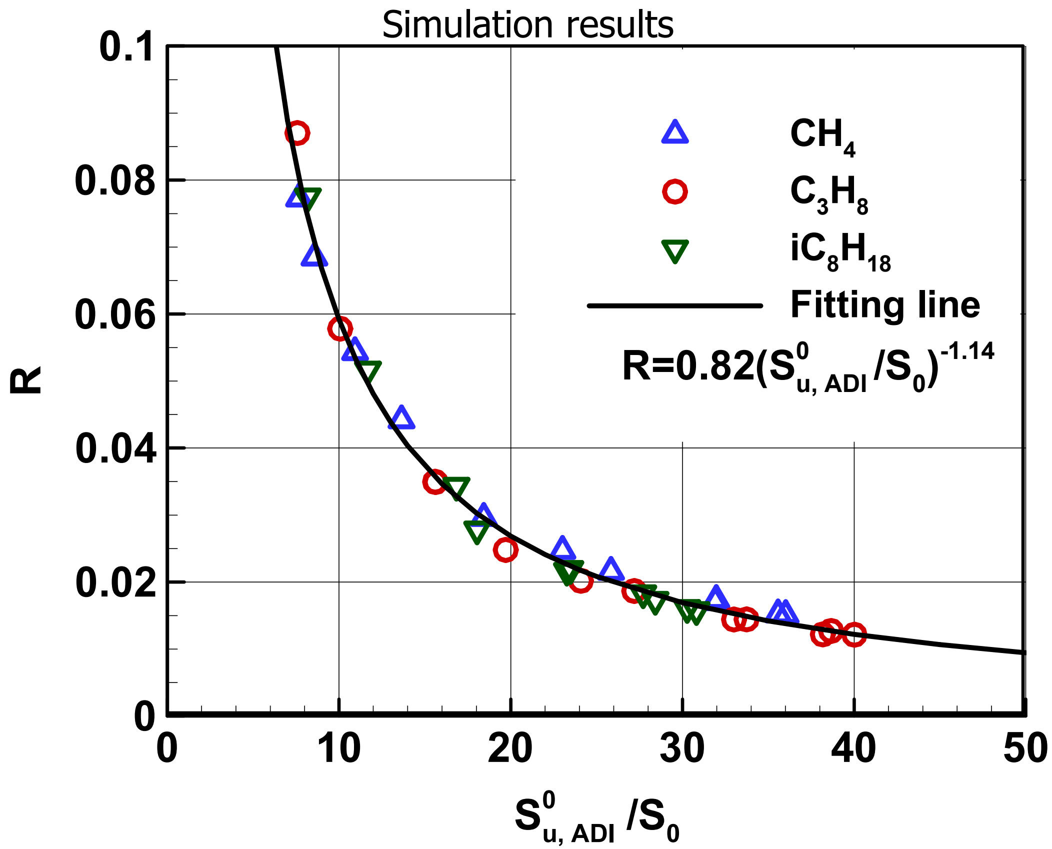
$$u_b \neq 0$$



- **Thermal effect:** to decrease the flame temperature & flame propagation speed
- **Flow effect:** to induce inward flow and slow flame propagation

Radiation: correction for fuel/air

H. Yu, W. Han, J. Santner, X. Gou, C.H. Sohn, Y. Ju, Z. Chen, Combust. Flame 161 (2014) 2815-2824



Under-prediction due to radiation:

$$R = 1 - \frac{S^0_{b,\,\mathrm{radiative}}}{S^0_{b,\,\mathrm{adiabatic}}}$$

$$R = 0.82\left(\frac{S^0_{u,\,\mathrm{ADI}}}{S_0}\right)^{-1.14}$$

$$S_0 = 1\ \mathrm{cm/s}$$

- Within 2% for S_u^0>25 cm/s; within 5% for S_u^0>12 cm/s
- Empirical correlation, $R=R(S_u^0)$, for different fuel/air
- Radiation-corrected flame speed

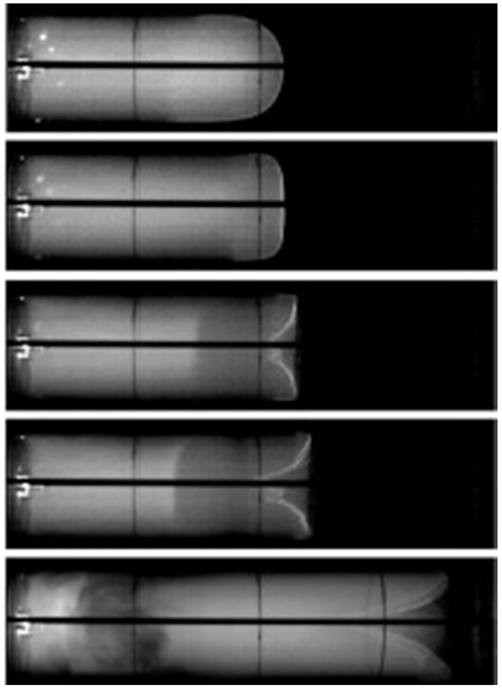
3.4 Flame propagation — instability

Background:

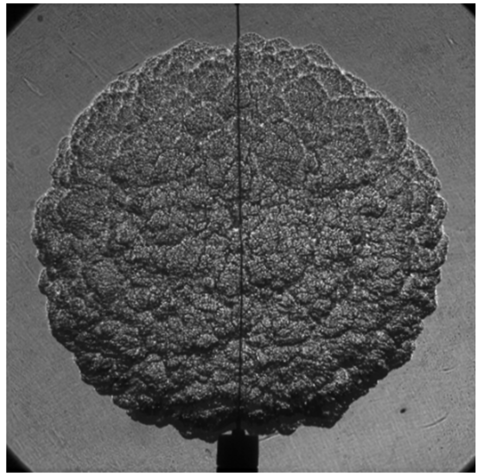
- flame properties
- turbulent combustion
- …

Focus:

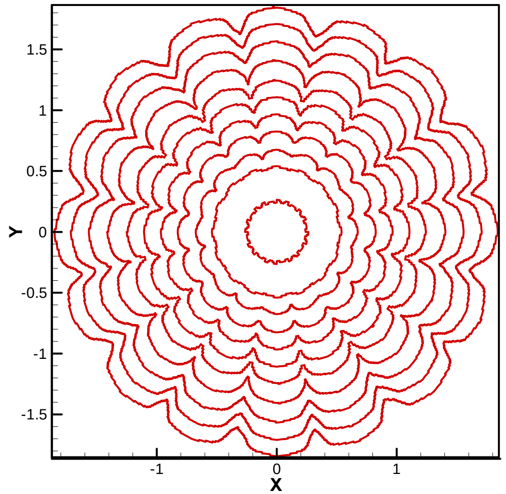
- Flame acceleration
- Channel flame
- Tulip flame
- …



Ponizy et at. (2014)



Jomassa & Law (2013)



Z. Chen (2014)

Review papers and groups:

- Kadowaki (2005) … PECS
- Matalon (2009), Smooke (2013) PCI
- Matalon (2007), Candel (2014) Annual Rev. Fluid
- Bradley, Law, Ronney, Sun …
- Matalon, Oran, Bychkov, Liberman…

3.5 Flame & chemistry of fuel blends

Background:

- Ignition control (RCCI)
- Alternative fuels (alcohol)
- Surrogate fuel model

Focus:

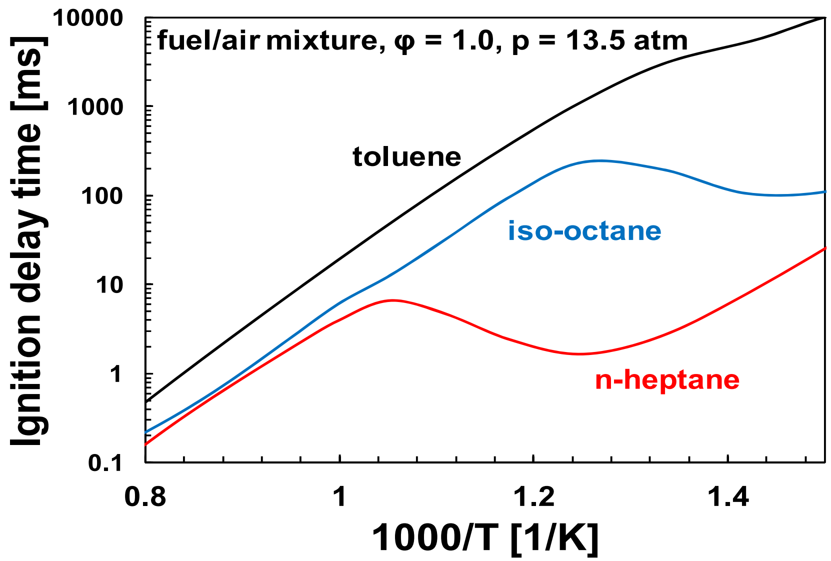
- Ignition delay, flame speed
- Chemical mechanism
- Chemical interaction
- Transport/thermal effects

Review papers and groups:

- Lu (2011), Reitz (2015) ... PECS
- Dooley (200) CNF ...
- Zuohua Huang, Xingcai Lü, ...

Fuel blends:

- Gasoline + diesel
- Natural gas + H_2
- Gasoline + ethanol
- PRF + toluene
- Syngas (H_2+CO) ...



3.6 Plasma assisted combustion

Background:

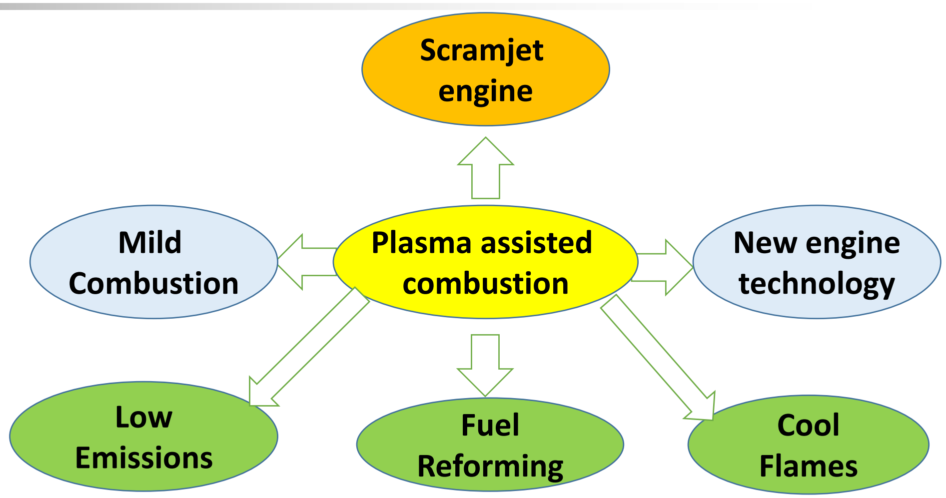
- PAC: a new way to control combustion, emissions, and fuel reforming

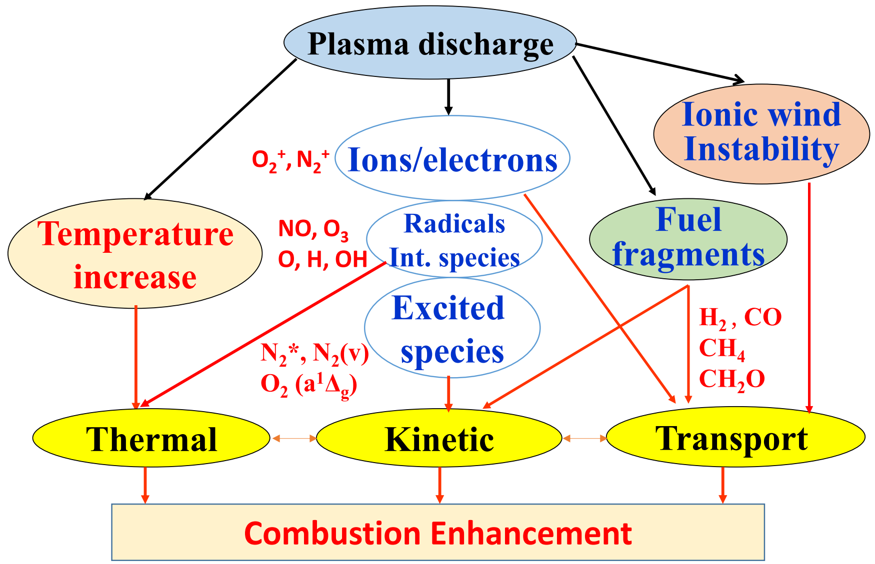
Focus:

- Combustion control via PAC
- Plasma mechanism
- Plasma/combustion interaction
- PAC at high P / low T
- Neat experiments for modelling

Review papers:

- Ju & Sun (2015), Starikovskiy (2013) PECS
- Starikovskiy (2015) ???,
- Starikovskaia (2006) JPD-AP
- Starikovskii (2005) PCI

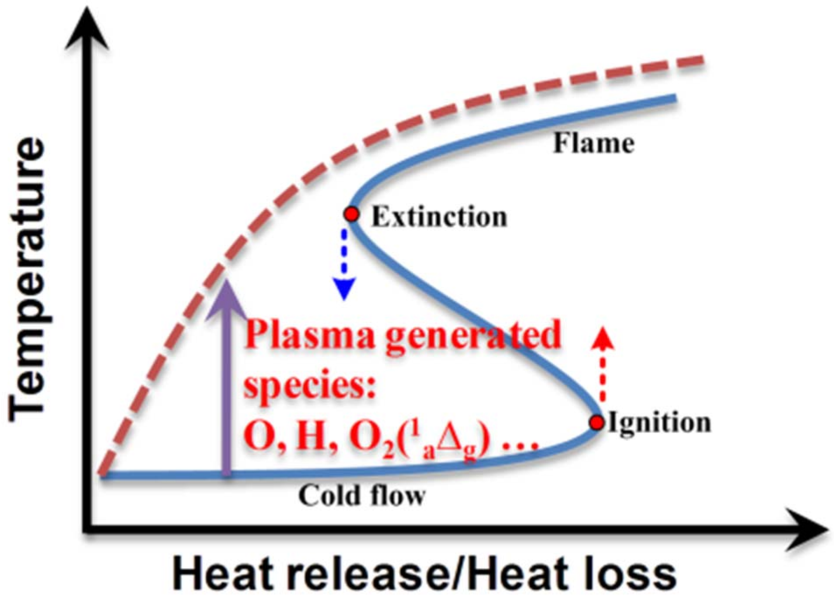




Ju & Sun (2015) PECS

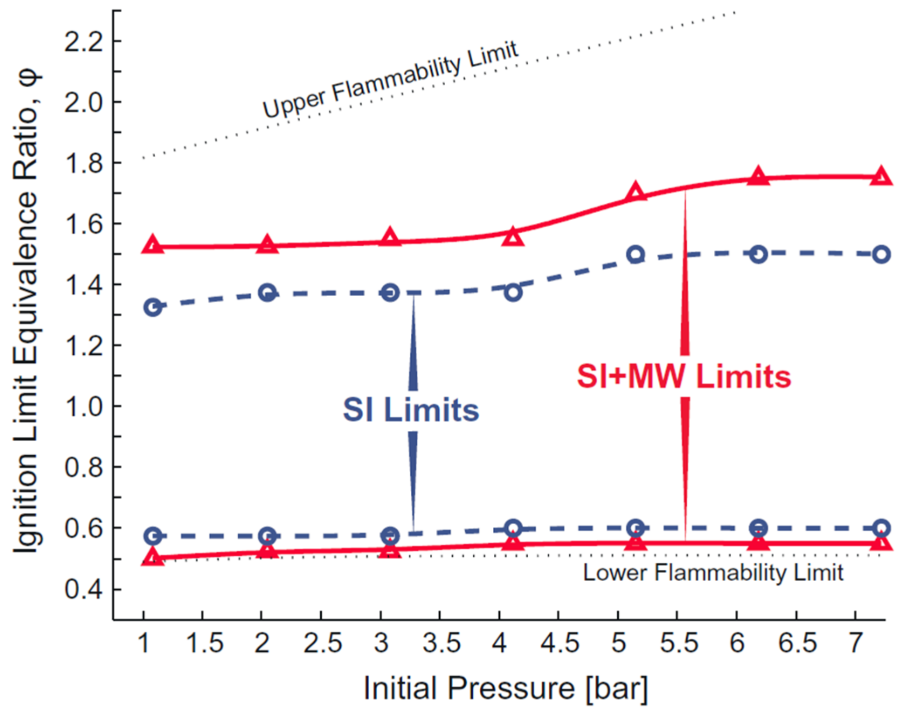
3.6 Plasma assisted combustion

S-curve (ignition & extinction)



Sun et al. (2013) PCI

Flammability limits

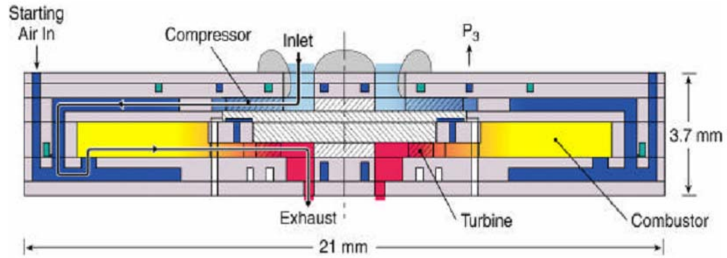


Wolk et al. (2013) CNF

3.7 Meso-/microscale combustion

Background:

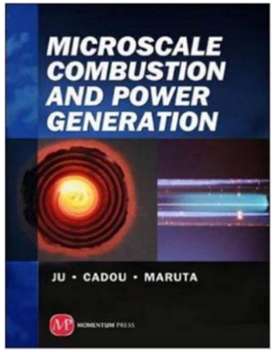
- Micropower for MEMS
- High energy density
- Increased loss, friction …

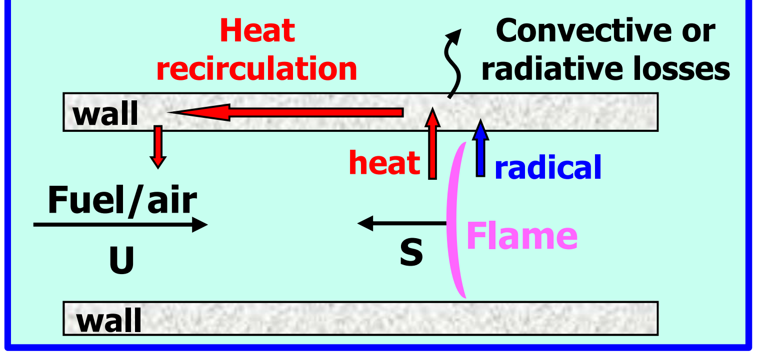


MIT micro-gas turbine (Epstein et al. 1997)

Focus:

- Heat recirculation
- Surface reaction/quenching
- Flame quenching & stabilization
  - Heat loss
  - Radical loss
- Flame/wall interaction
  - Thermal
  - Chemical
- Catalytic combustion
- Liqud-gas mixing, fuel injection



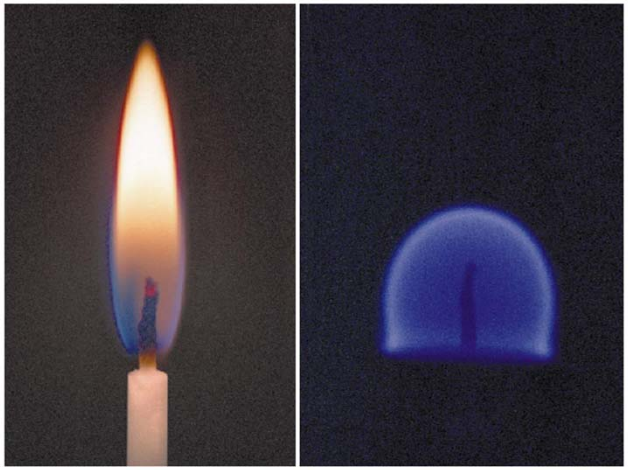


Review papers:

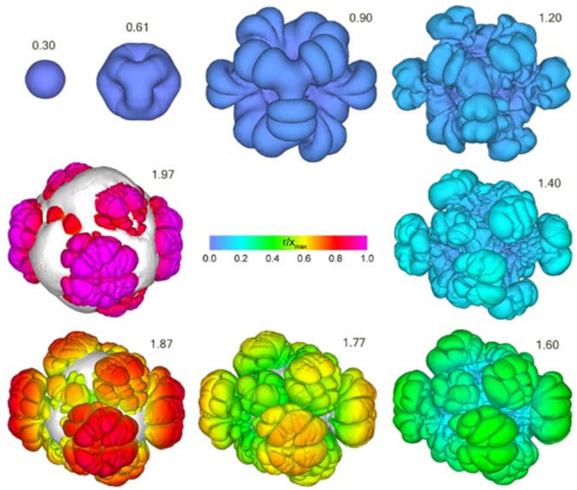
- Ju, Cadou, Matura (2015) Book
- Kaisare & Vlachos (2012) PECS
- Ju & Maruta (2011) PECS
- … ….
- Maruta (2011) PCI

3.8 other topics

- **Supersonic combustion**
- **Microgravity combustion**
- **Mild combustion**
- **Cosmic combustion/supernova**
- **Catalytic combustion**
- **Multi-phase combustion**
- **Nano-particles, flame synthesis**
- **Detonation**
- **Fire**
- **… …**



From internet



Gamezo et al. (2004) PRL

内容提要

1. 背景介绍
2. 代表性研究进展
3. 当前研究前沿
4. **总结展望**

4. 总结与展望

- 理论分析：从“热”（单步反应）到“反应”（多步反应）；从气相到多相（喷雾、粉尘、表明催化…）；从准定常到非定常；从定性到定量…
- 极端条件（高压、超临界、近可燃极限、近稀释极限、富氧、高速、微重力等）下的着火、火焰传播、失稳、熄火等基础燃烧过程及临界燃烧状态之间的转换机理
- 关键自由基的输运特性和关键基元化学反应对着火、火焰传播、熄火等基础燃烧过程的影响及控制作用，冷焰与低温化学反应

4. 总结与展望

- 辐射与火焰的相互作用
- 火焰与流动的相互作用
- 火焰与壁面的相互作用

- 超临界条件下的基础燃烧特性
- 低温等离子体促进点火与强化燃烧的规律及机理
- 液雾动力学及其与化学反应/流动的耦合作用

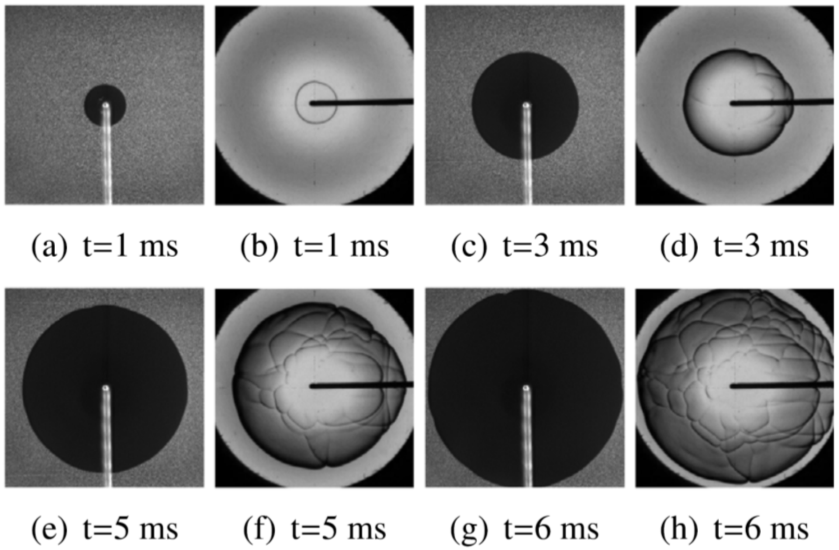
- 催化燃烧
- 火焰合成
- 爆震敲缸

……

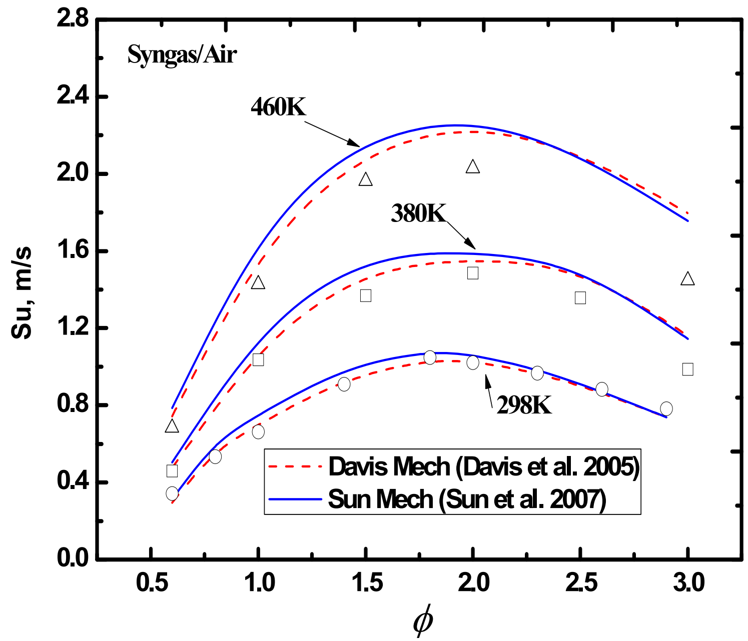
合作方向：球形传播火焰测量层流火焰速度

本课题组为该方面的实验提供基于详细化学反应机理的一维球形传播火焰模拟结果，用于跟实验测量结果进行对比。已有合作单位和成果

- **Ju, Law @ Princeton [1]**
- **Pitsch @ RWTH Aachen [2]**
- **Bruno @ CORIA-CNRS [2]**
- **Halter @ ICARE-CNRS [3]**
- **Kong @ IET-CAS [4]**



Visualization sequence (tomography and Schlieren) of H_2/air (E.R.=0.5, P= 0.1 MPa, T = 300 K) [2]



H_2/CO/air, high P and T_u [5]

[1] F. Wu, W. Liang, Z. Chen, Y. Ju, C.K. Law, Proc. Combust. Inst. 35 (2015) 663-670.
[2] E. varea, J. Beeckmann, H. Pitsch, Z. Chen, B. Renou, Proc. Combust. Inst. 35 (2015) 711-719.
[3] L. Courty, K. Chetehouna, Z. Chen, et al., Combustion Science and Technology, 186 (2014) 490-503.
[4] M. Han, Y. Ai, Z. Chen, W. Kong, Fuel, 148 (2015) 32-38.

谢谢大家！

感谢基金委的支持和齐飞老师发起并组织该会议！

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欢迎大家过来交流、相互学习！