Dynamics of Near-Limit Cool Flames

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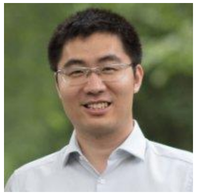
Acknowledgement



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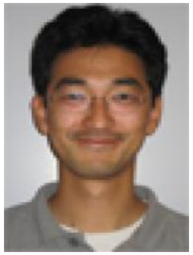

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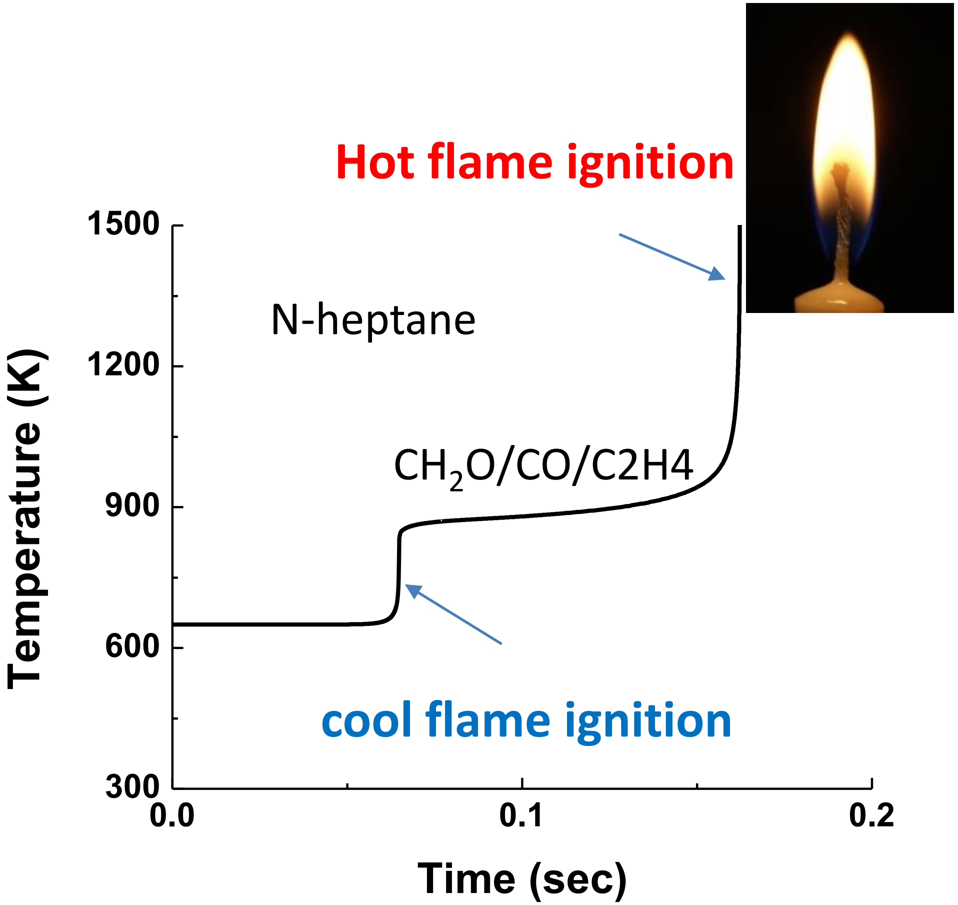
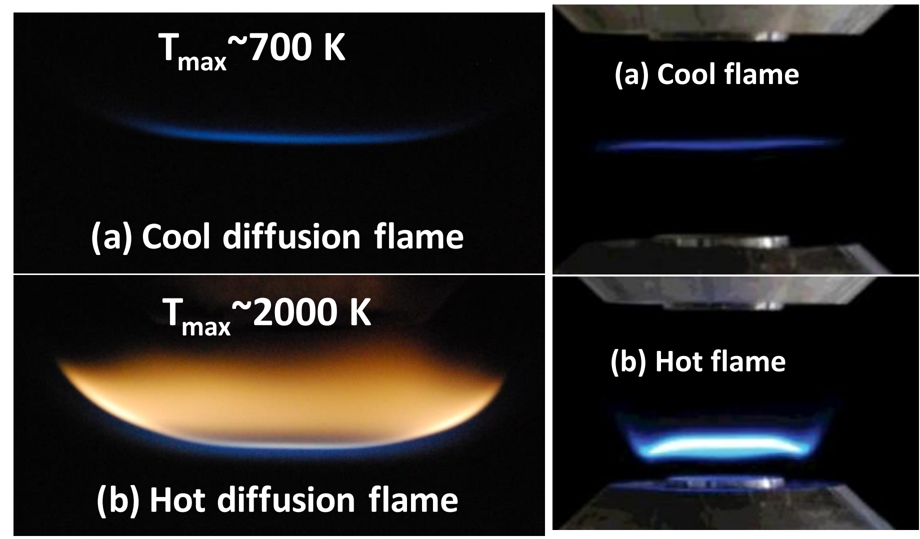
Cool flames vs. Hot flames



Ignition



Diffusion Flames **Premixed Flames**

Flames

Won & Ju et al., Proc. Combust. Inst. 35, 2015
Reuter, Won, & Ju, Proc. Combust. Inst. 36, 2017
Nayagam, D.L. Dietrich, P.V. Ferkul, M.C. Hicks, F.A. Williams, Combustion and Flame 159 (2012) 3583-3588.

- Cool flame is cool (600-900 K)
- No NOx and soot emissions

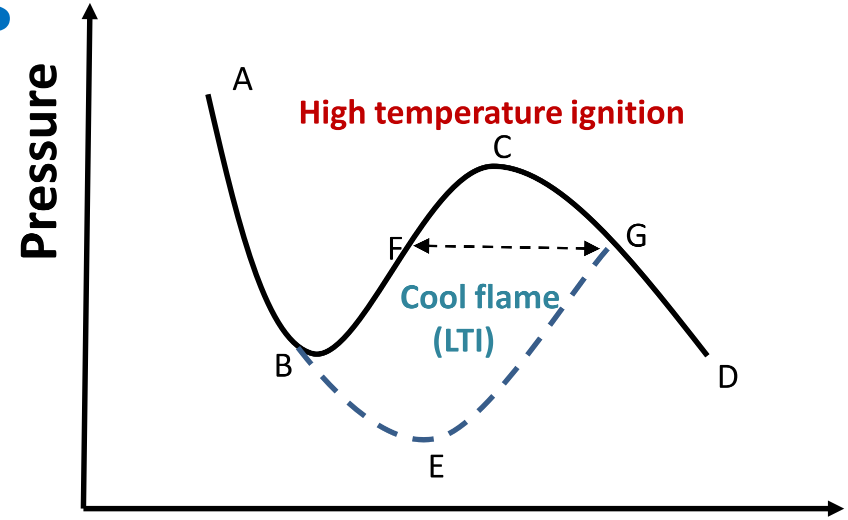
Content

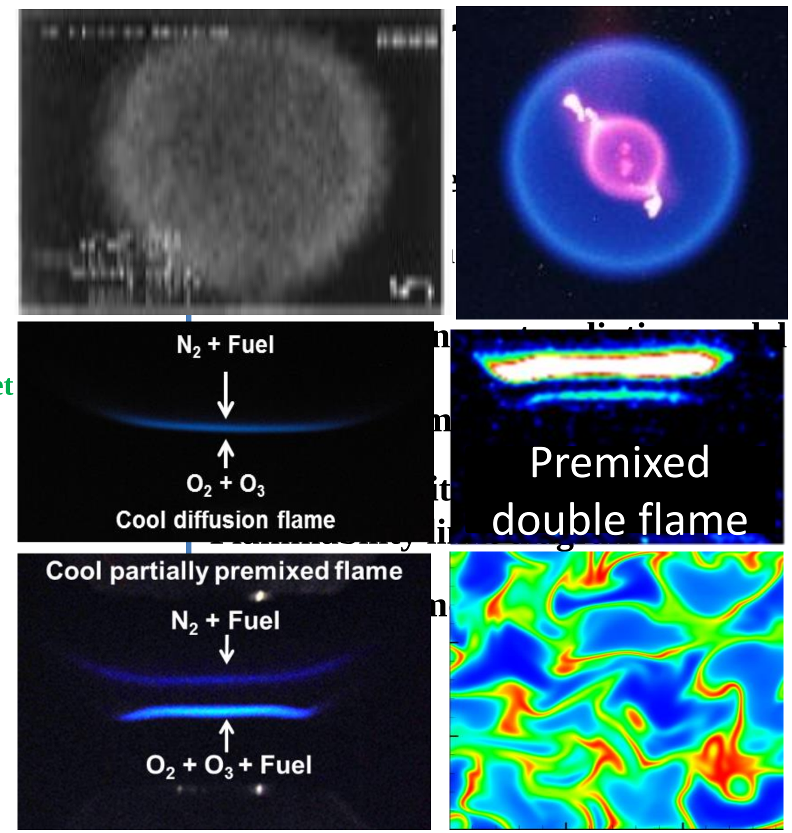
1. Dynamics and Regimes of Premixed Cool Flames
2. Dynamics and Regimes of Diffusion Cool Flames
3. Cool Flames as a platform for mechanism validation
4. Conclusion

History of cool flame studies

Years	Experiments/Observation
Pre-1930	Observation of premixed cool flames in (flow tube, hot surface…) 1817 H. Davy
1950	P-T ignition diagram (unstirred closed reactor) Oscillatory cool flames
1970	Oscillatory cool flames in CSTR Rapid compression machine
1990	Cool flame ignition in RCM, shock tube…
2000	Micro-gravity premixed cool flames (Pearlman et al.) Micro-tube premixed cool flames (Maruta et al.)
2010	Micro-gravity droplet diffusion cool flames (Williams et Plasma/O_3 assisted stable diffusion cool flames Diffusion, premixed, partially premixed cool flames Diffusion cool flames for fuel reactivity studies Cool flames with high pressure fuel injection

(Ju, Law, and co-workers, 2010-2017)

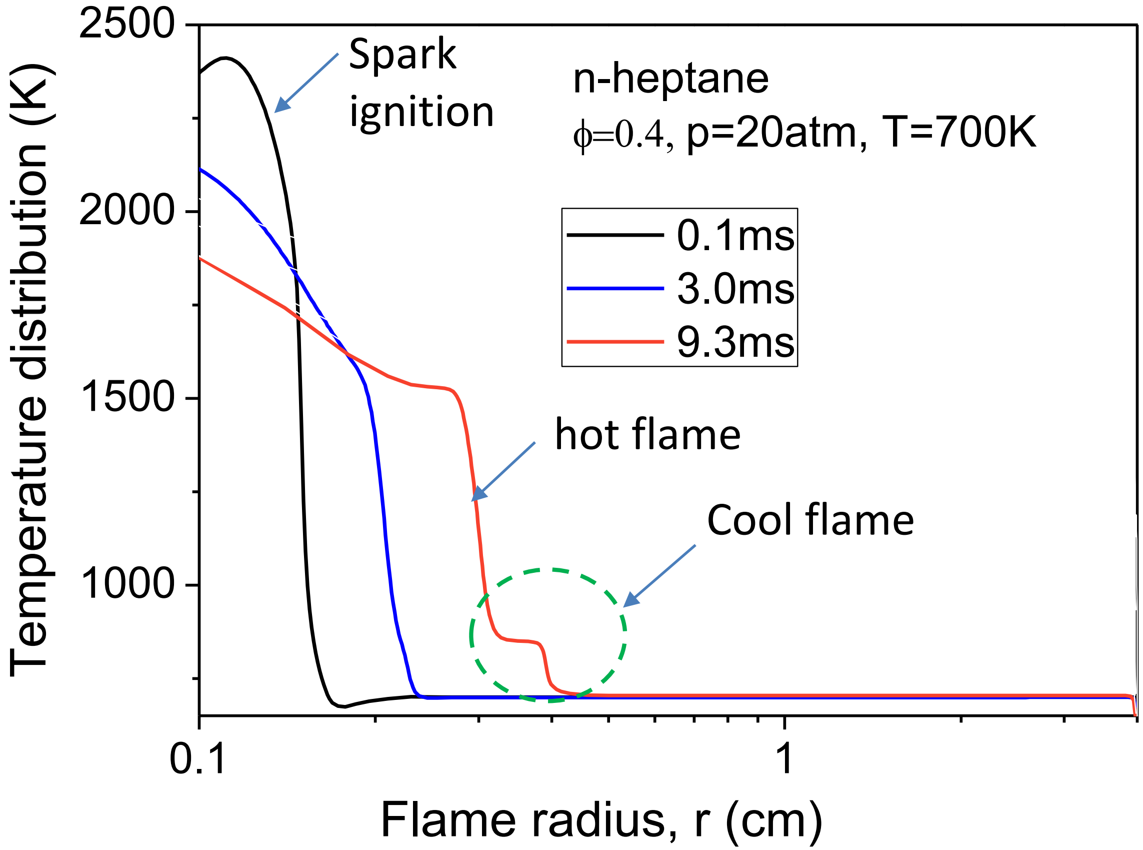




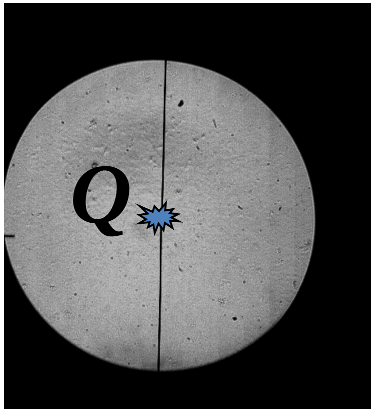
1. Dynamics and Regimes of Premixed Cool Flames

A puzzle on cool flame propagation at elevated temperature

Spark assisted HCCI flame propagation:
(High pressure, elevated temperature)



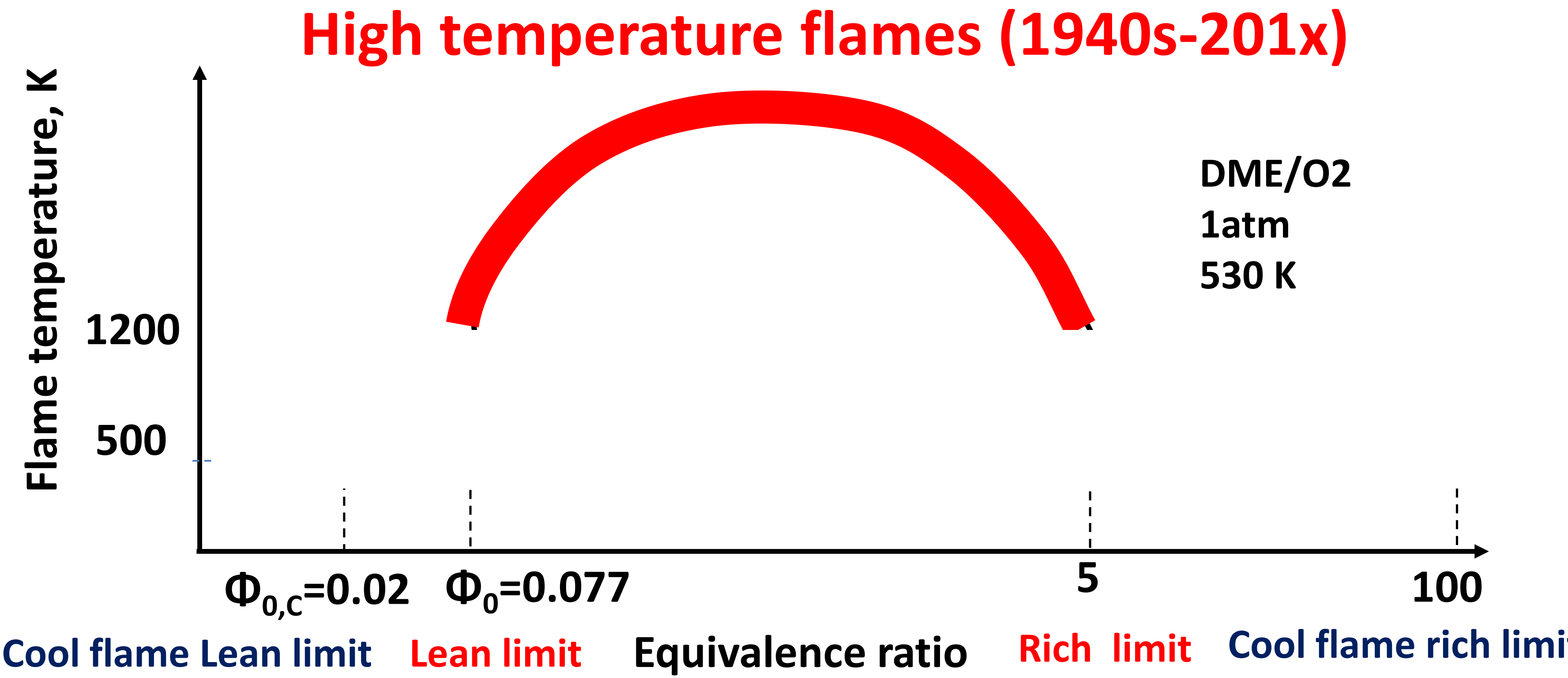
Hot flame by a spark
1 atm, 300 K



- **Why is there a double flame structure with coupled hot/cool flames?**
- **How fast and how can a cool flame can propagate?**
- **What is the effect of pressure on cool flame burning limit?**

Y. Ju et al., Proc. of Combust. Inst., 33, 2011

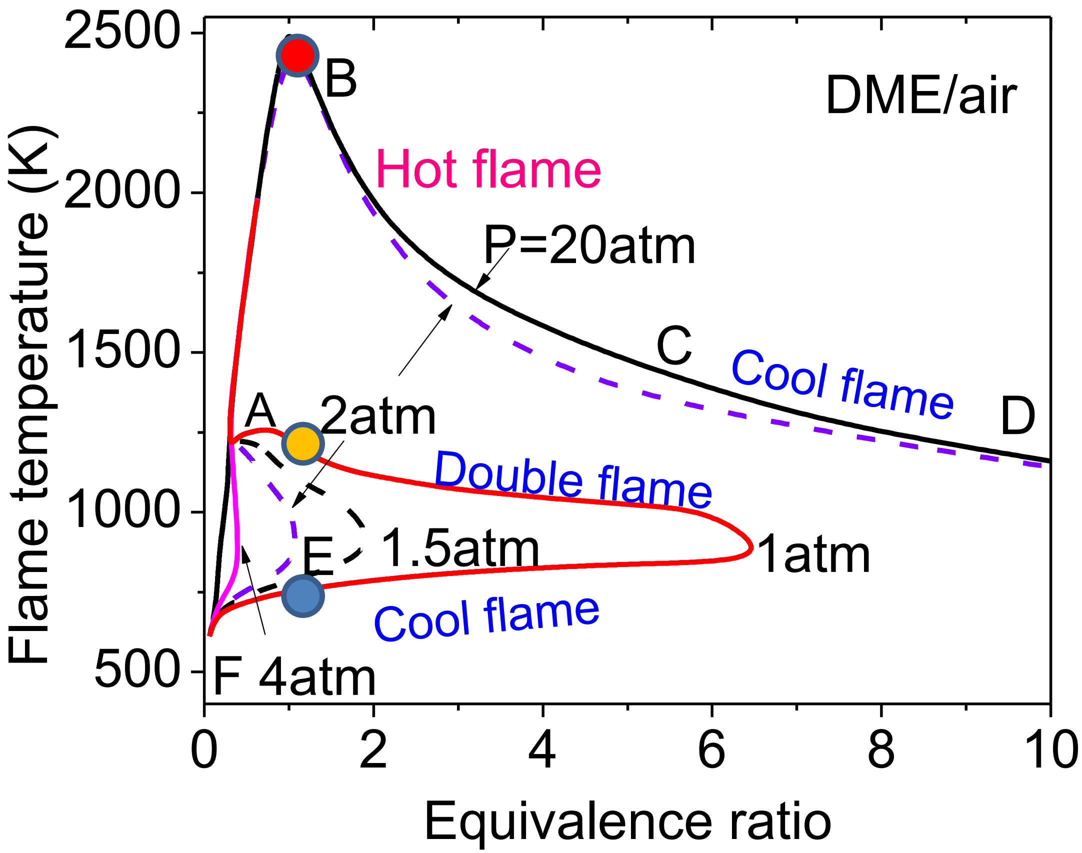
How fast a cool flame propagate?
How lean/rich can it burn?



Cool flame can burn much leaner and richer at hot flames at elevated temperature

Ju et al., Combustion and Flame, 2015.

How does pressure affect flame regimes and structure



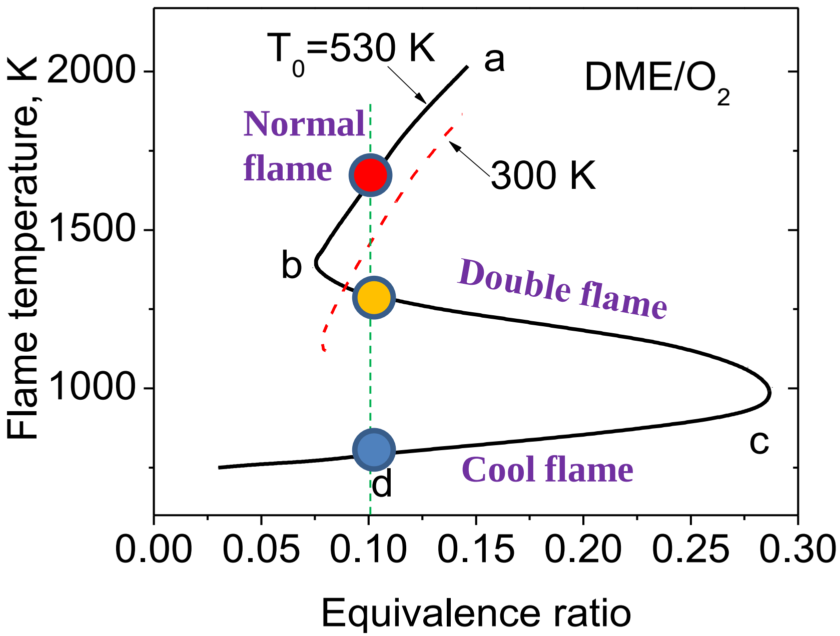
3 Questions?

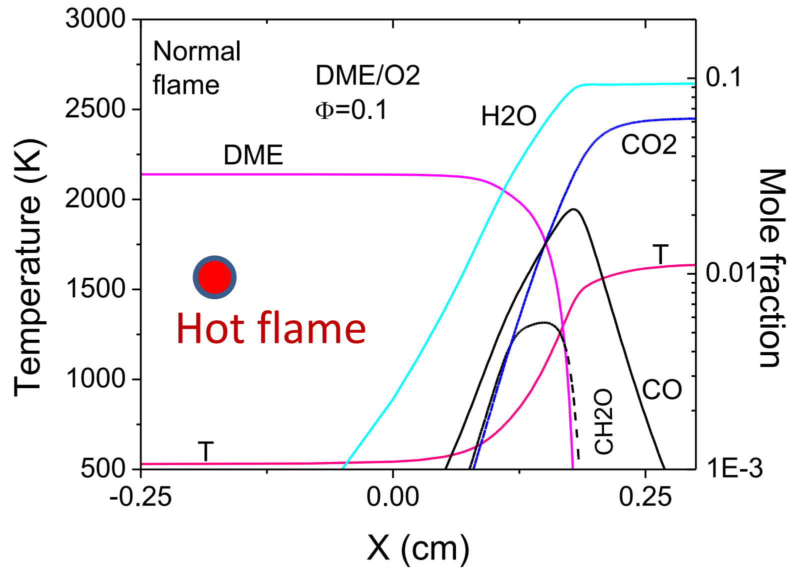
1. **Why do we have three different flame regimes on lean side?**
2. **What is the cool flame structure on the rich side?**
3. **Do we still have a cool flame at high pressure?**

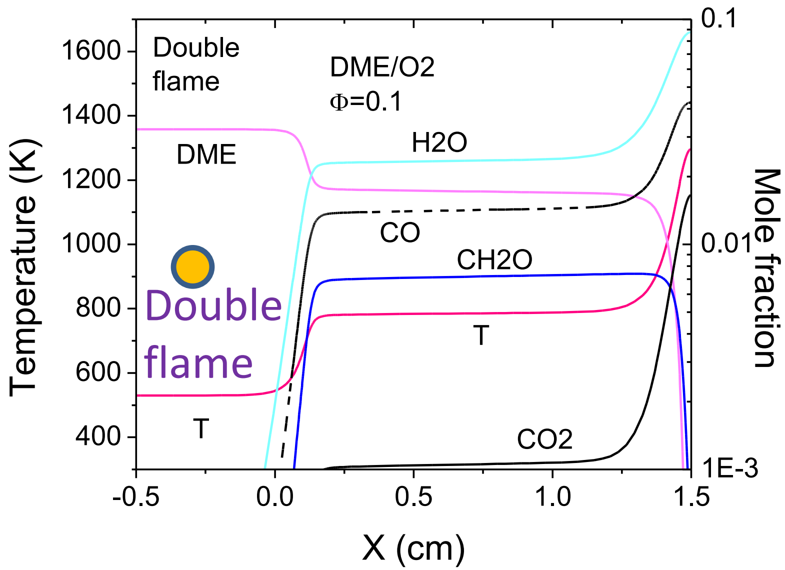
- Pressure dramatically changes flammable region of lean cool flames, but not the rich cool flame
- The cool flame to hot flame transition limit is sensitive to pressure.

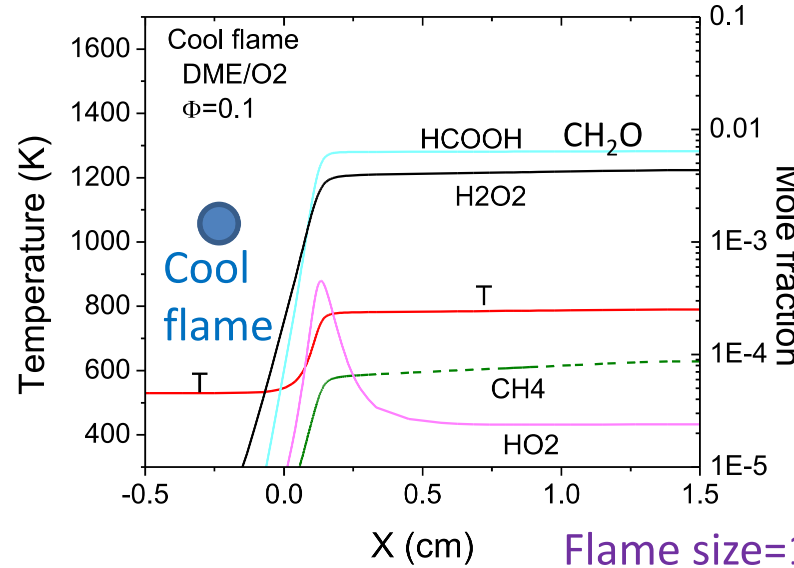
Y. Ju, Combustion and Flame, 2017

Different flame structures (2 atm)



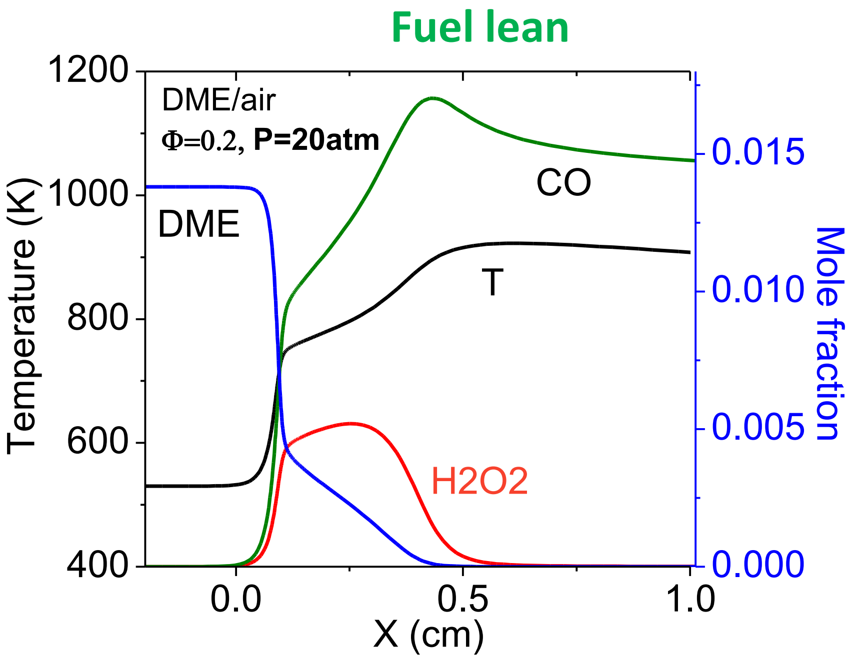


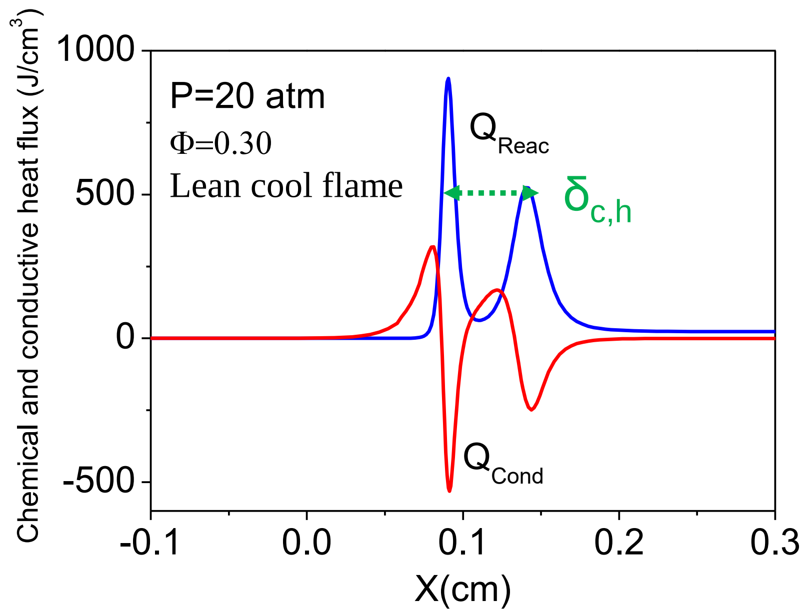


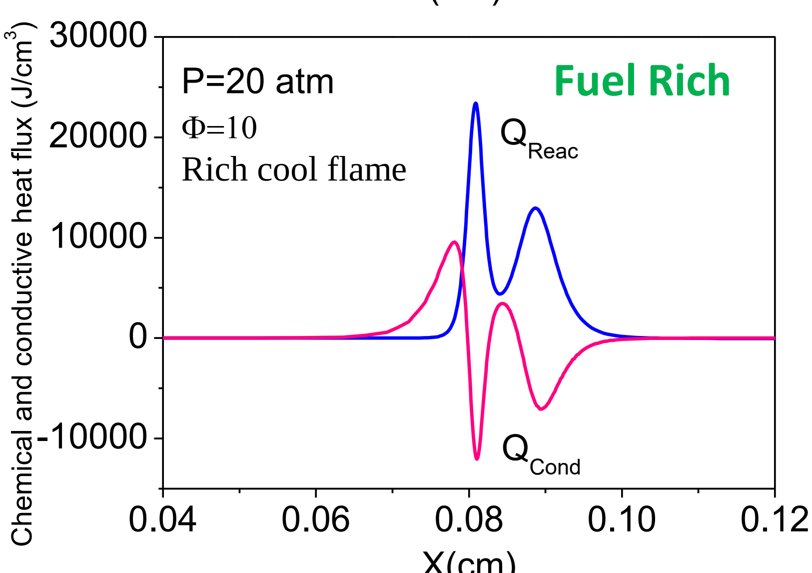


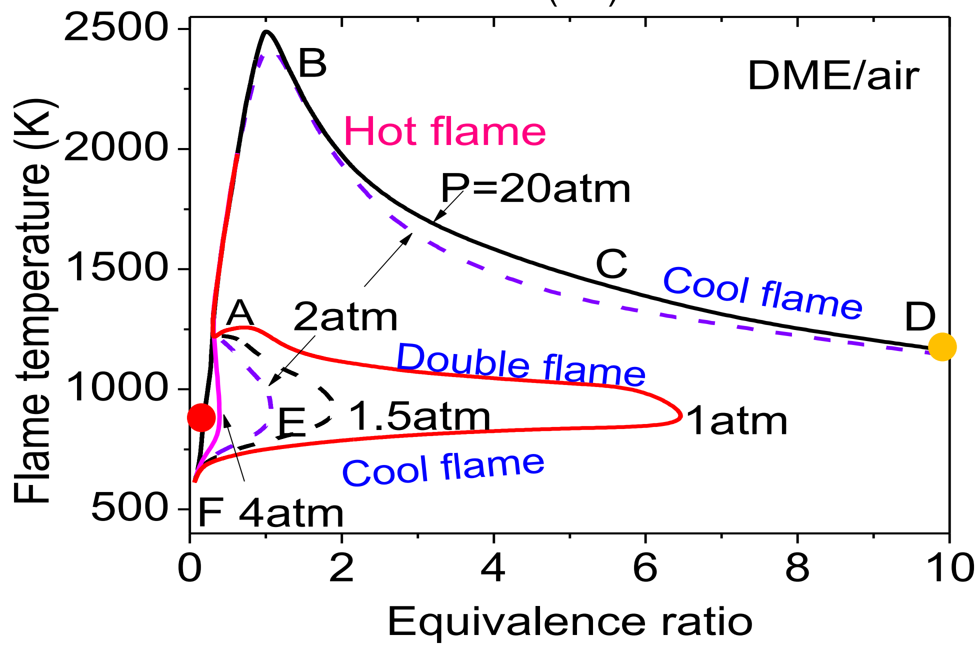
Flame size=1.5cm

Double flame structure of high pressure lean/rich cool flames

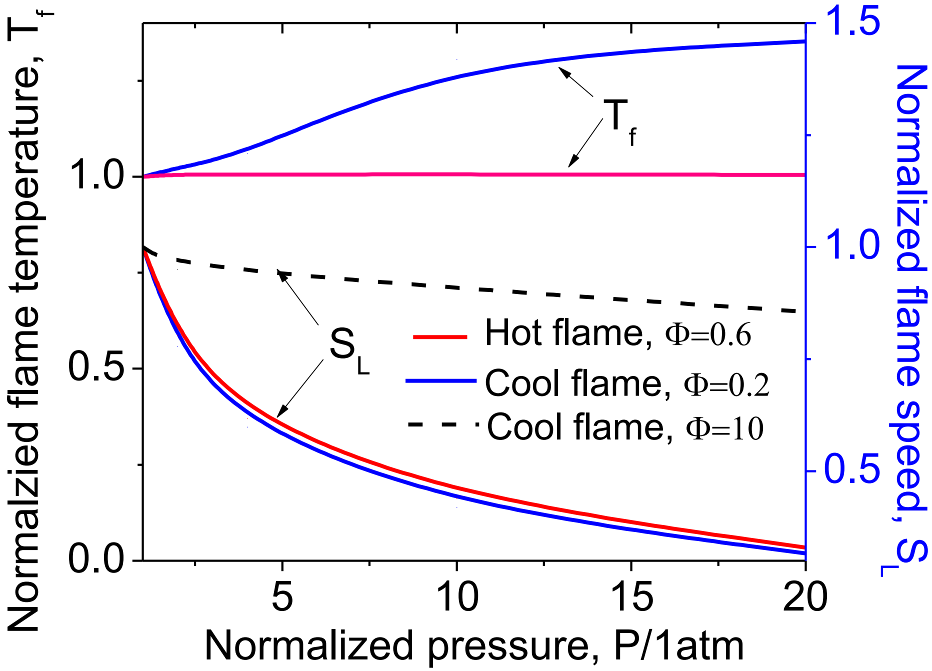






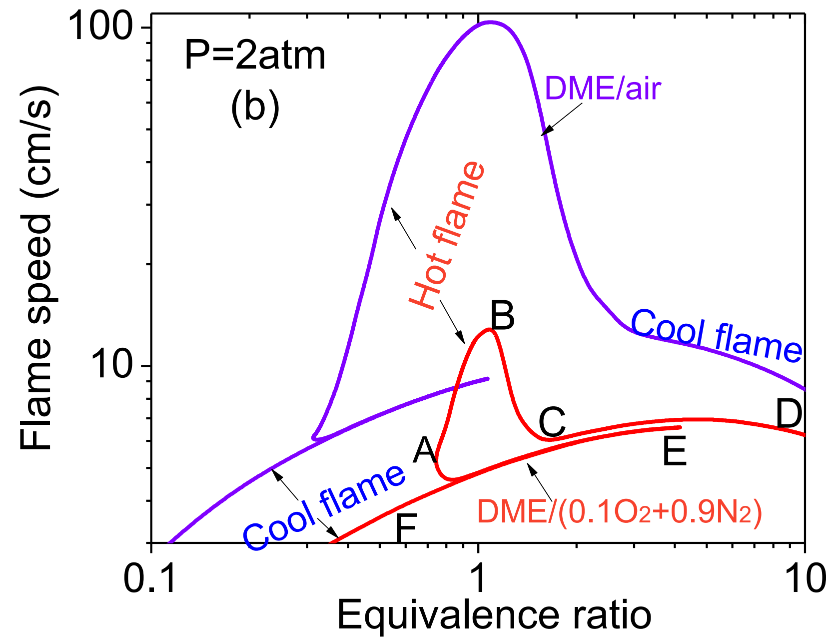


Effects of pressure and mixture dilution on cool flame speeds and burning limits



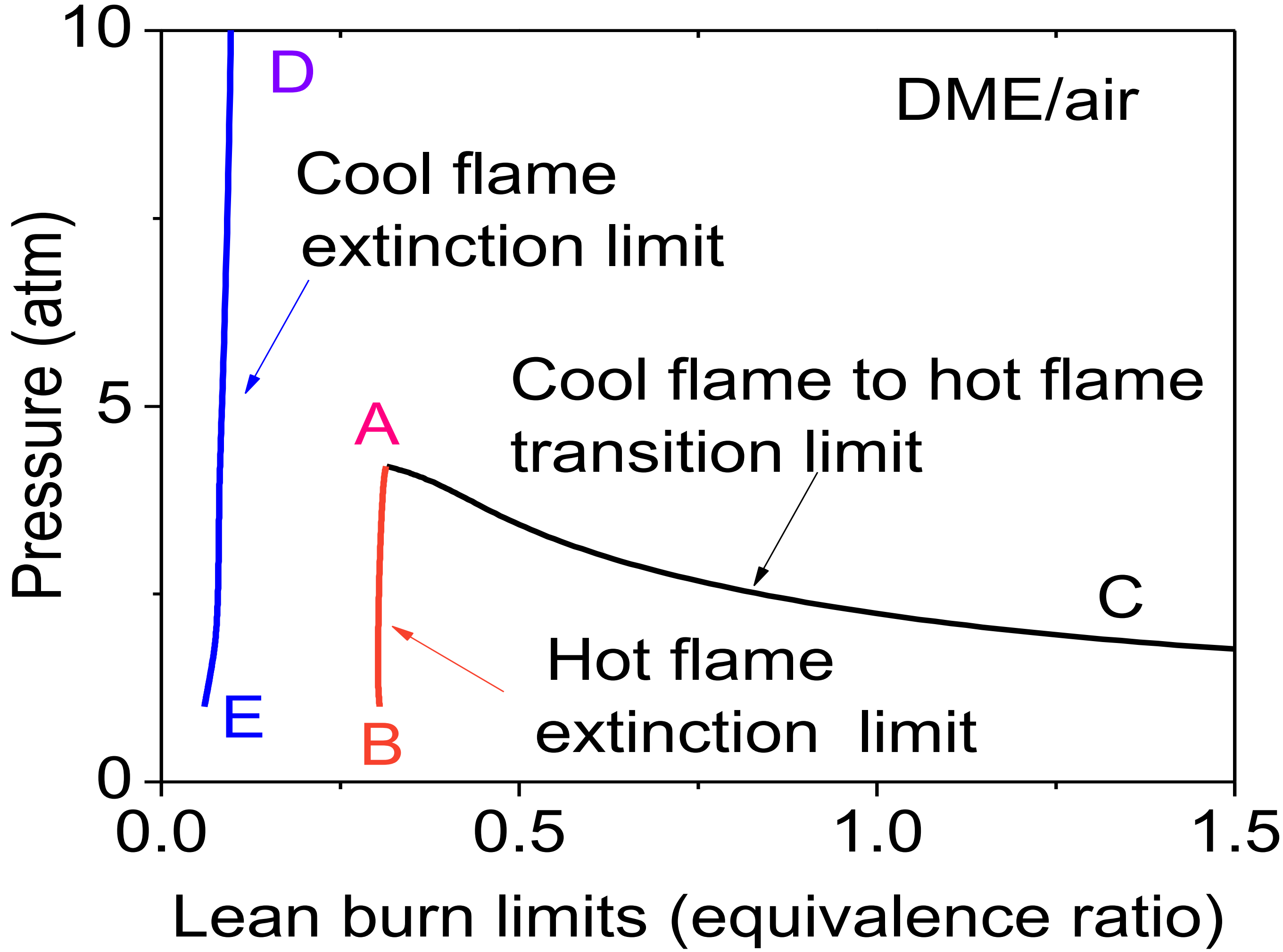
- **Lean and rich cool flame speed and temperature have distinctive pressure dependence due to the NTC effects.**

- **Dilution and EGR enhance cool flames and suppress hot flames**



Y. Ju, Combustion and Flame, 2017

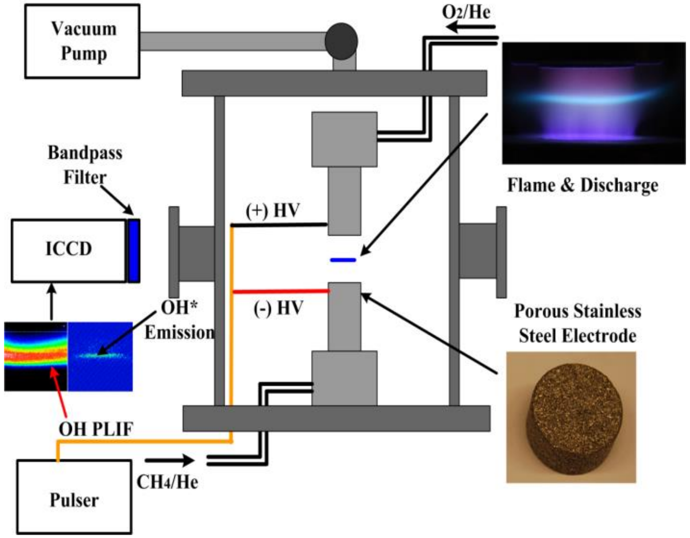
A generic flammability limit diagram: the K-Curve (premixed flames) for both cool and hot flames at elevated pressure

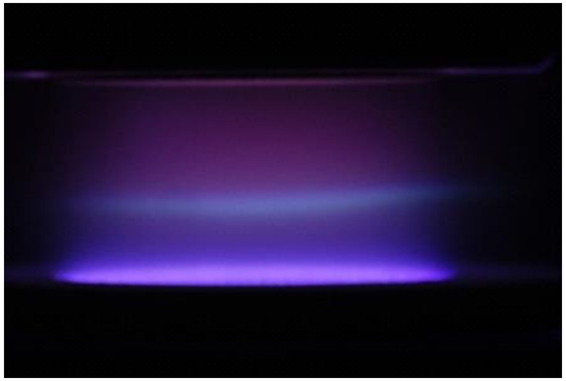


Y. Ju, Combustion and Flame, 2017

Recent experimental studies of cool flames (w plasma & ozone sensitization)

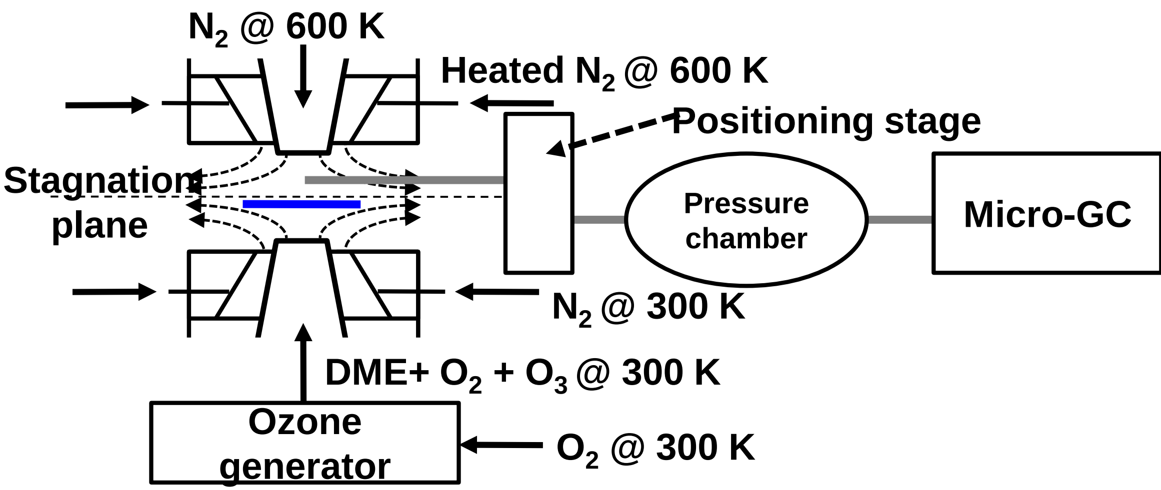
Nano-sec plasma assisted cool flames

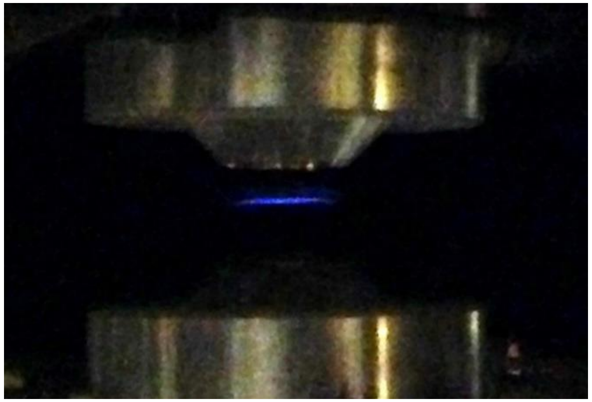




Sun, W., Won, S.H. and Ju, Y., 2014. *Combustion and Flame*, *161*.

Ozone assisted cool flames



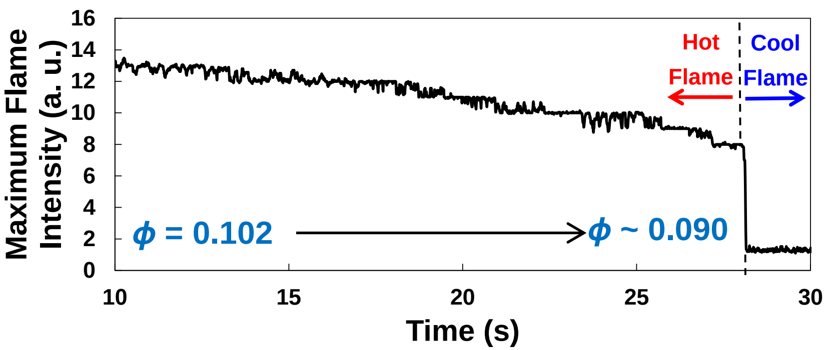


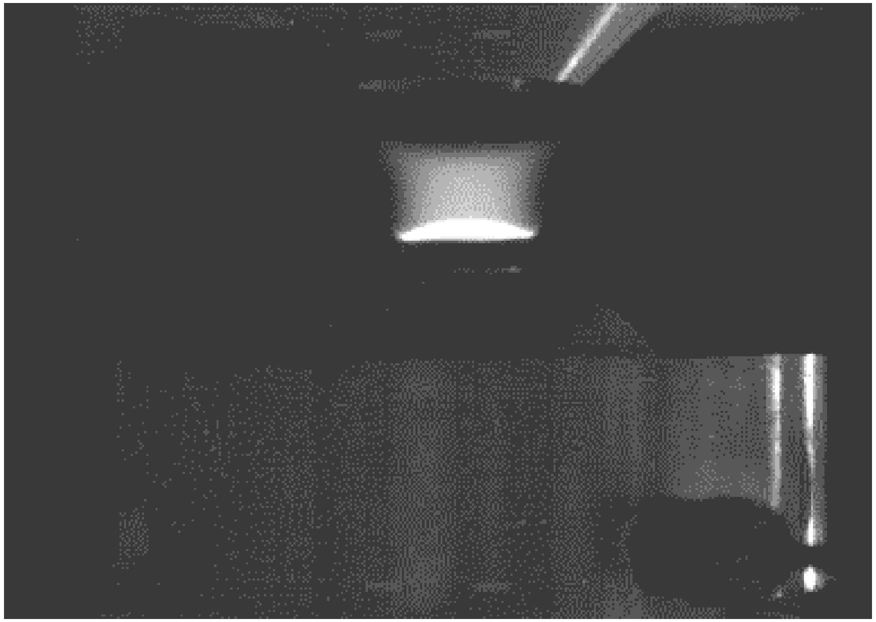
Won, S.H., et al., 2015, *Proceedings of the Combustion Institute*, *35*.

Hot Flame to Cool Flame Transition: 3 flame regimes

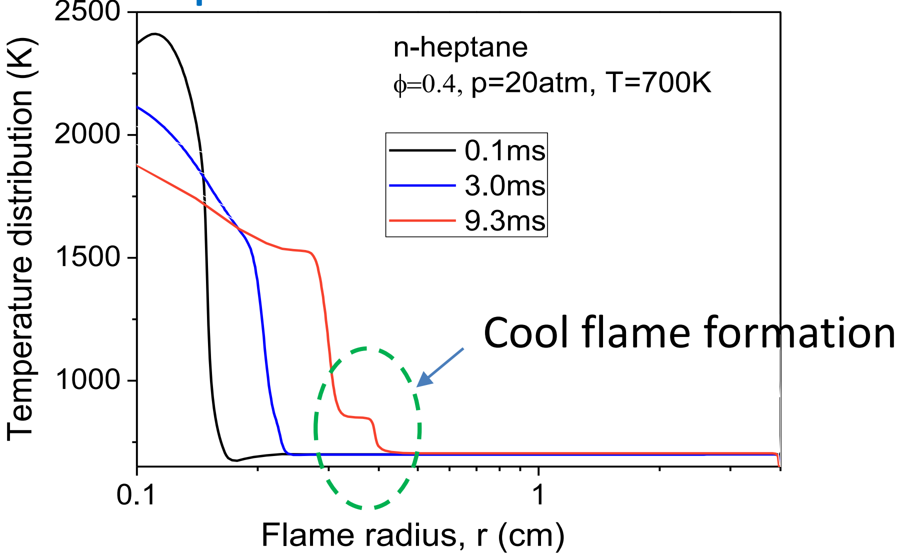
Premixed Flame Extinction transition from hot flame to cool flame

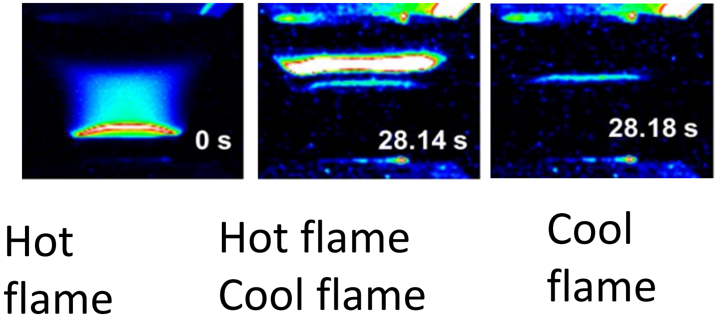
- Constant strain rates
- Reducing fuel concentration





Spark assisted HCCI combustion

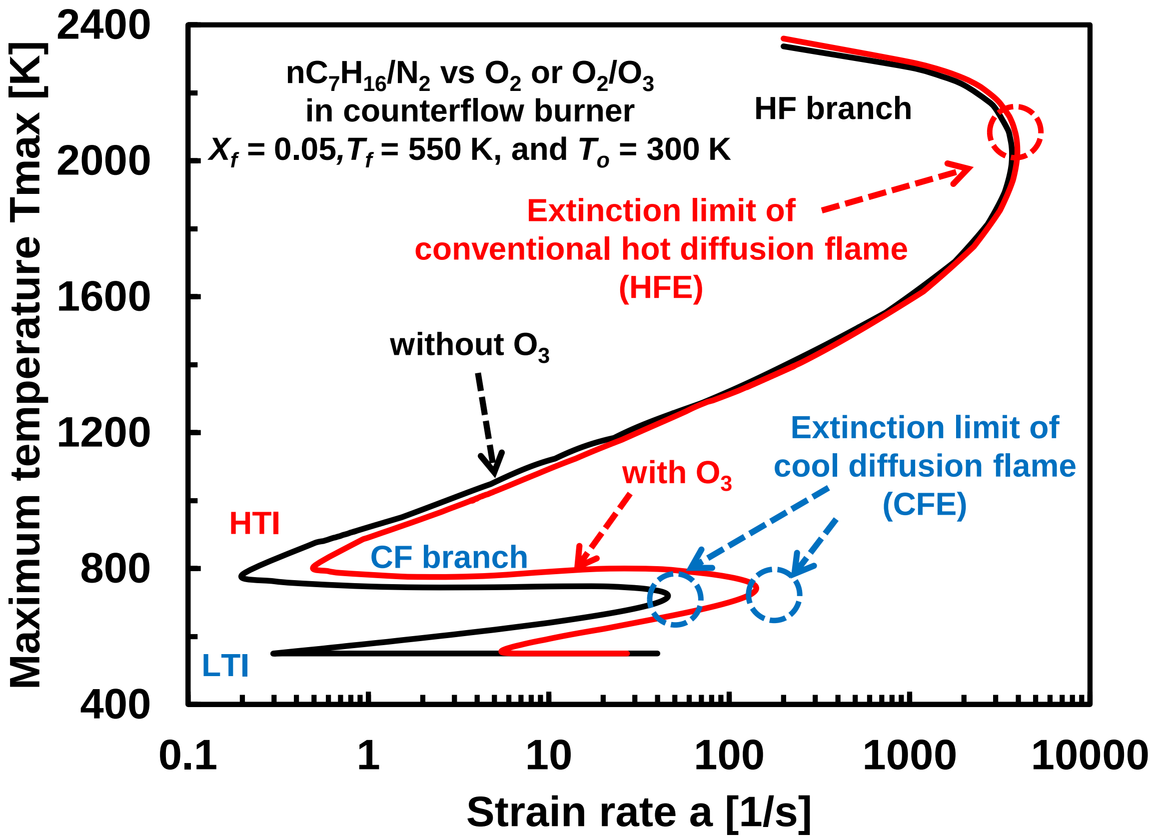


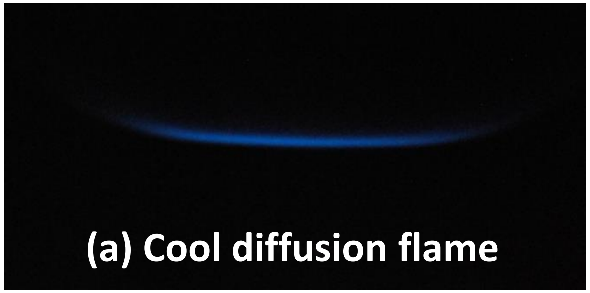


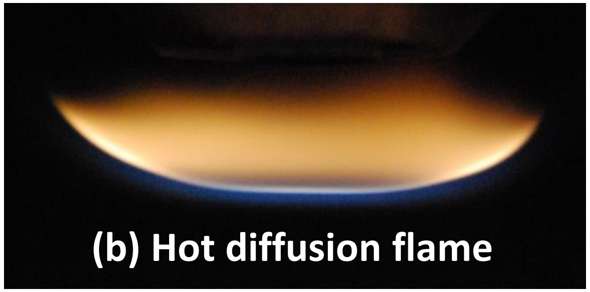
Reuter, C.B., Won, S.H. and Ju, Y., 2016. *Combustion and Flame*, *166*, pp.125-132.

2. Dynamics of Diffusional Cool Flames

- Existence of cool diffusion flames in counterflow configuration with n-heptane
  - cool flame regime exists regardless of addition of ozone
  - Addition of ozone extends cool flame regime.



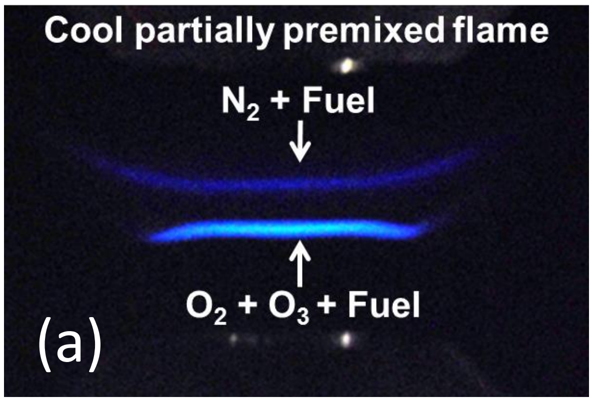


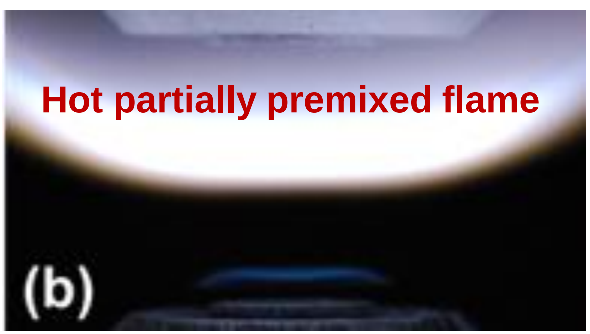


Won, S.H., et al., 2015, *Proceedings of the Combustion Institute*, *35*.

Self-Sustaining partially premixed Cool Flames

- **Cool partially premixed flames: DME/O_2/O_3**

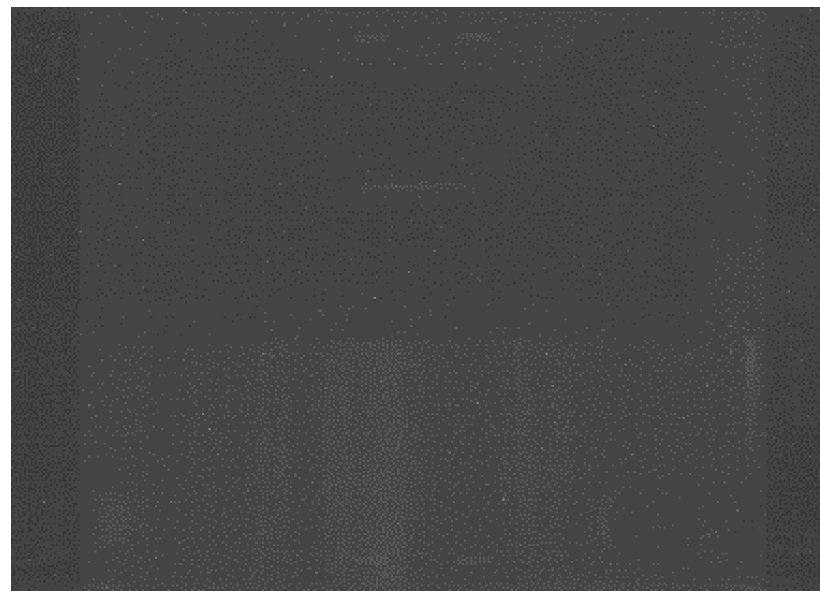




Reuter et al., *Proc. Combust. Inst.* 2017

Transition from cool flames to hot flames

- Start w/ partially premixed cool flame at a = 73 s^{-1}, ϕ = 0.11, X_F = 0.44
- Gradually add fuel to diffusion side up to X_F ~ 0.48

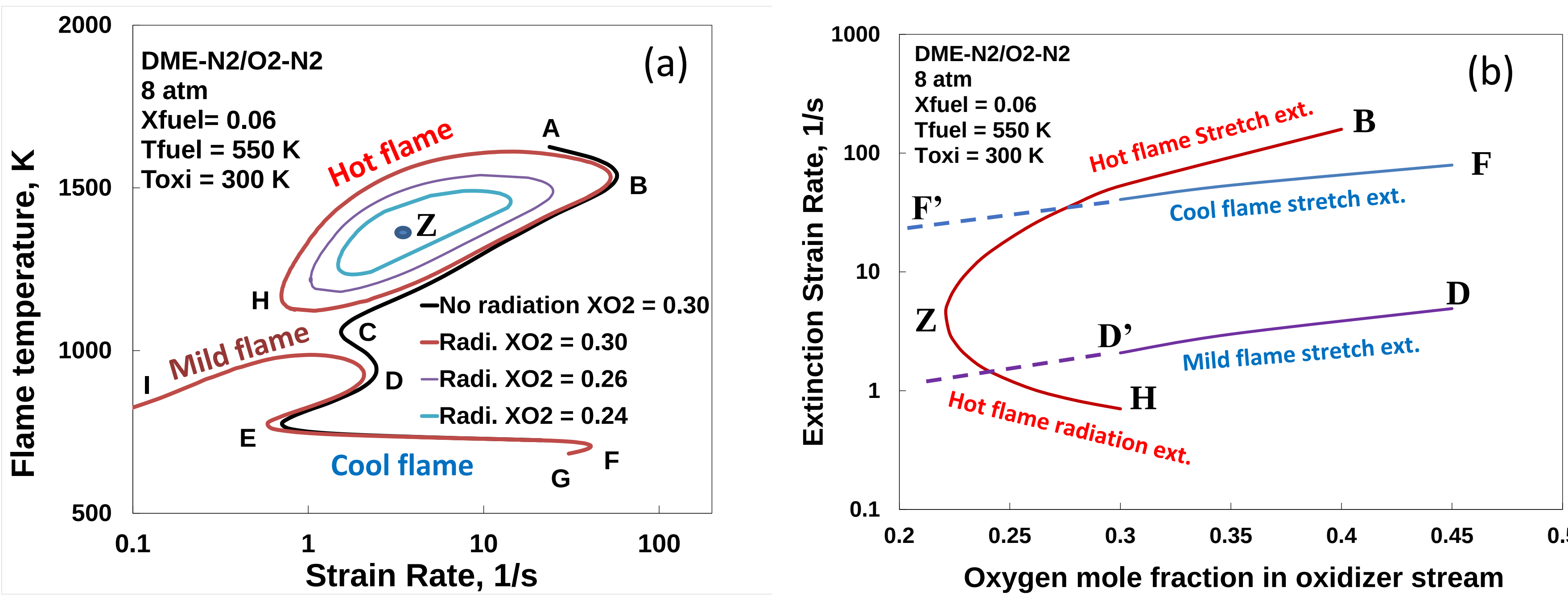


- At a higher fuel concentration cool flame transfer to hot flames

2. Dynamics of Regimes of Diffusion Cool Flames

Diffusion flame flammability limit diagram: € - Curve:

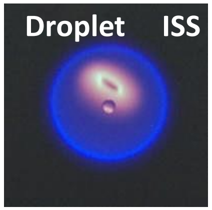
for cool, mild, and hot flames at elevated pressure

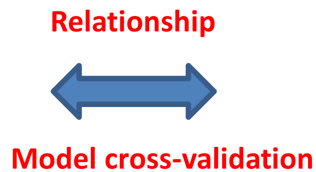


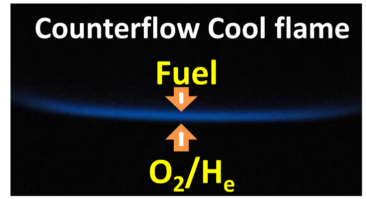
A "mild flame" regime may exist at very low stretch rate?

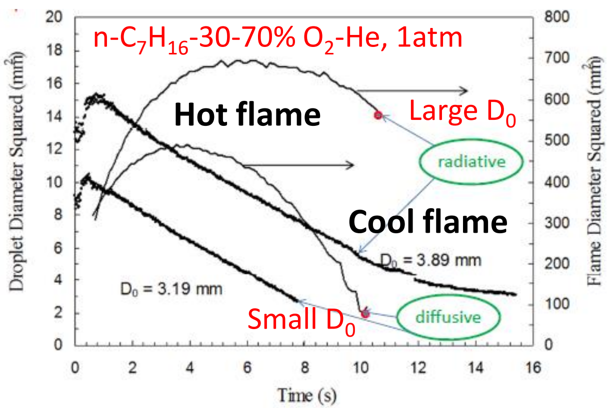
Eric Lin and Y. Ju et al., 2017

Competition between radiation/diffusion heat loss with chemical heat release

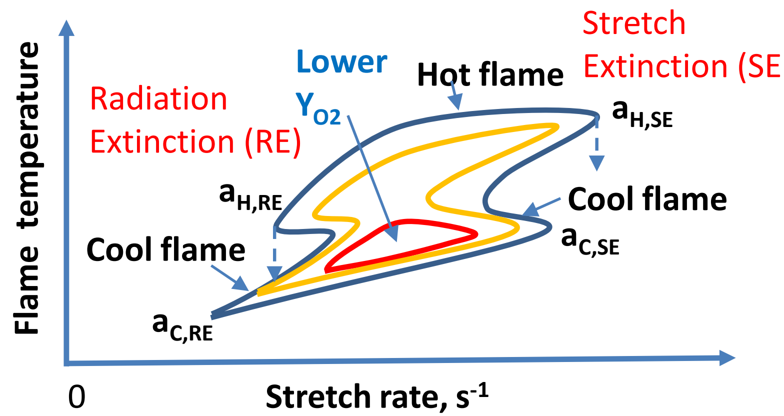






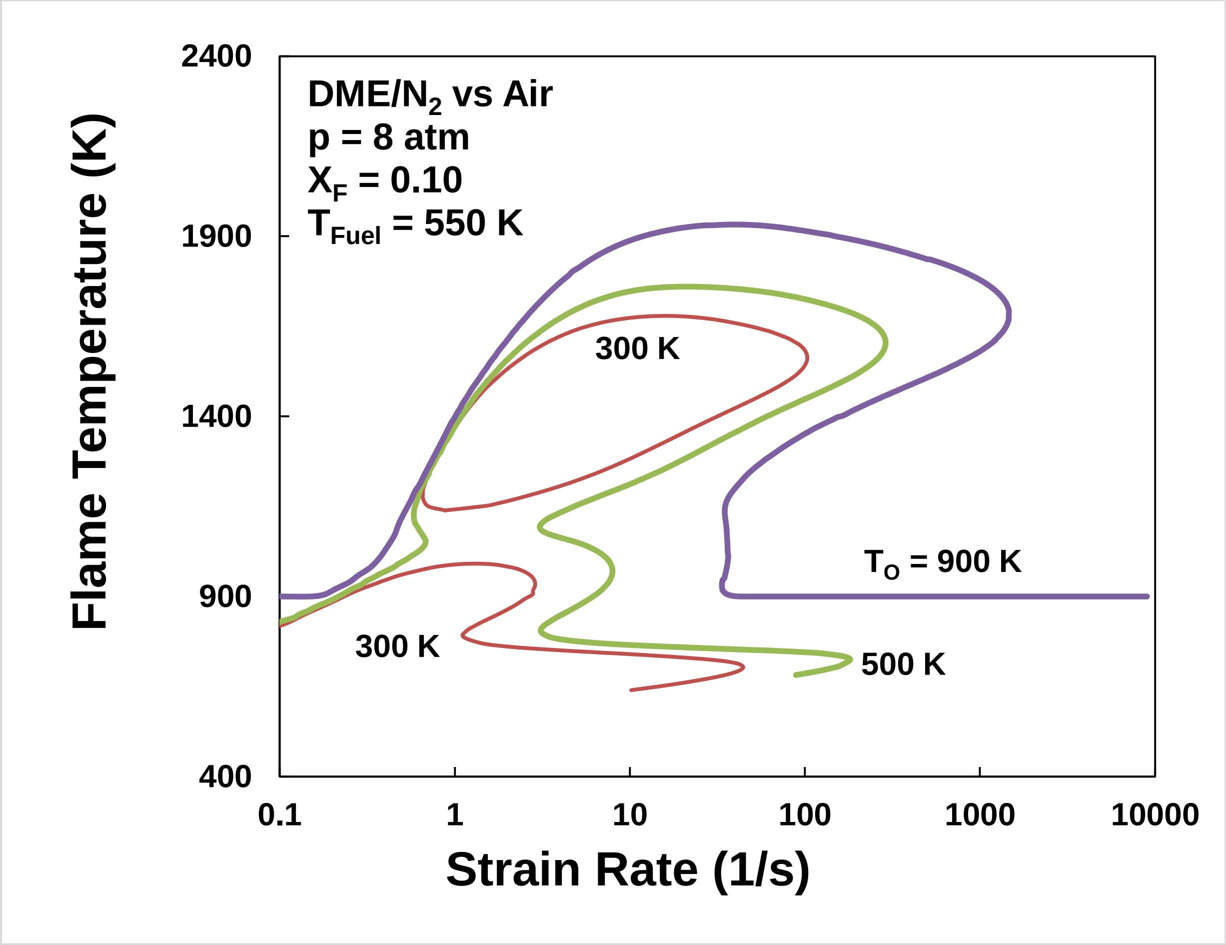


a. Droplet extinction: diffusion vs. radiation (Flex experiment)



b. Counterflow l flame extinction: stretch vs. radiation
Top: Experiment cool flame, Bottom: Schematic

Effect of air temperature on diffusion cool flame burning limits

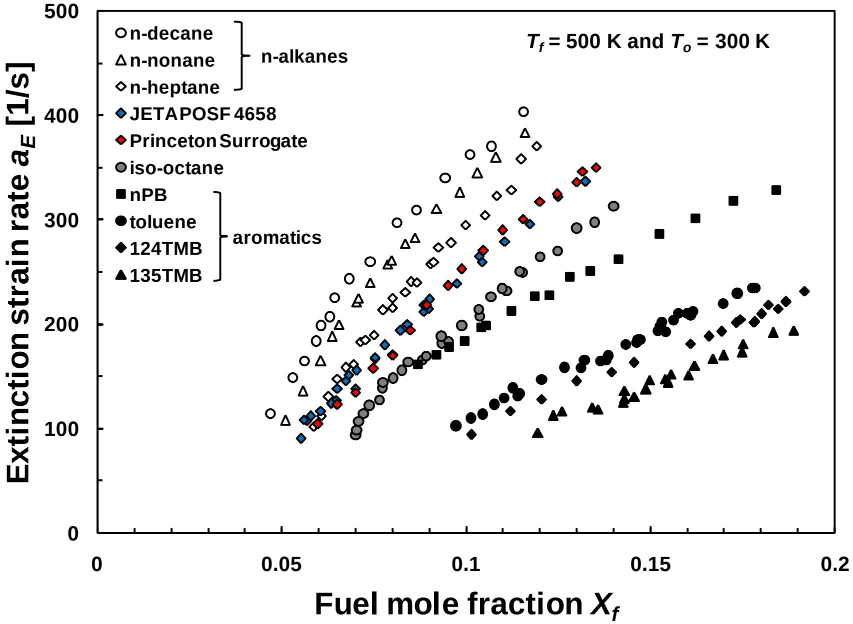


The increase of air temperature dramatically affects the cool flame regimes and burning limits:

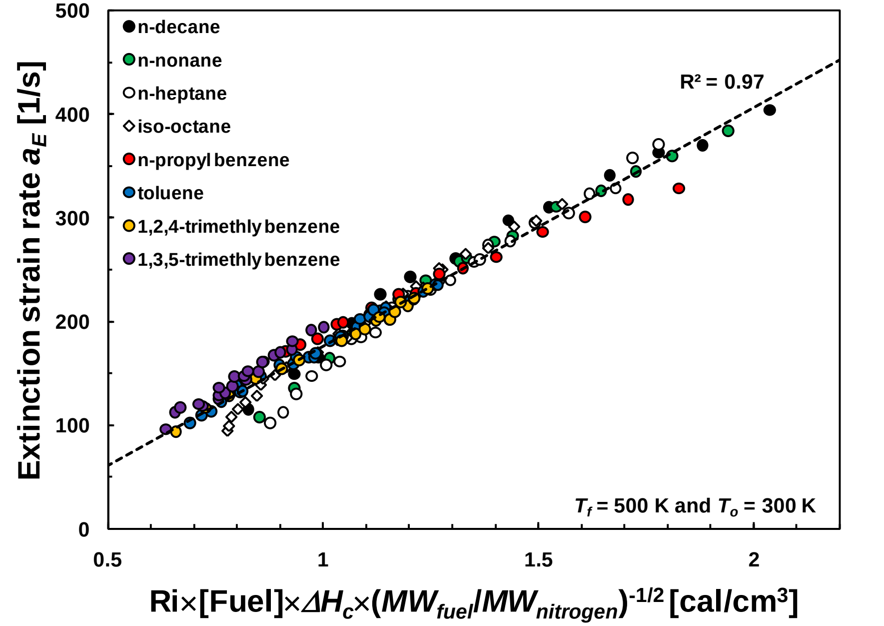
- Cool flame shifts to higher stretch rate
- mild flame branch disappear on high stretch side.
- Radiation extinction limit disappear on low stretch side.

3. The role of cool flames in rating low temperature fuel reactivity and model validation

Diffusion Flame Extinction Limit: n-Alkanes, iso-Alkanes, Aromatics

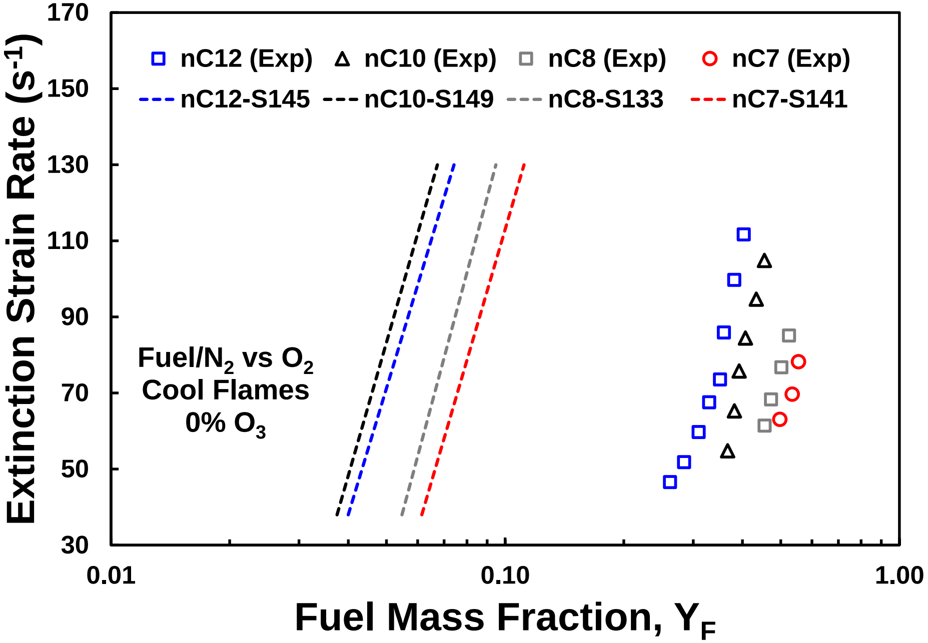


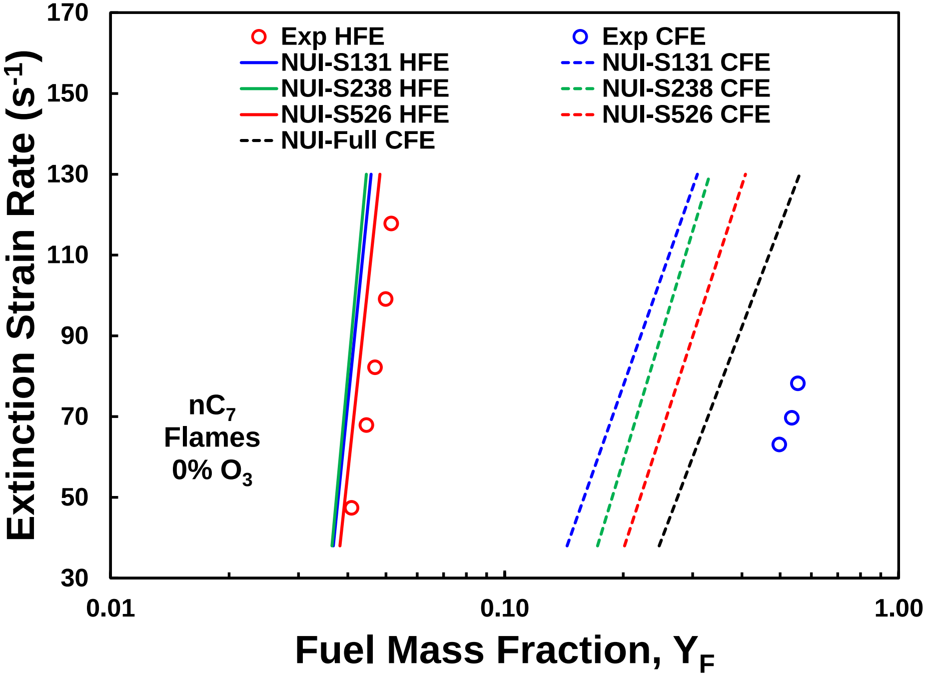
Co-relation with radical index and enthalpy weighted transport



Won, Sang Hee, et al. "A radical index for the determination of the chemical kinetic contribution to diffusion flame extinction of large hydrocarbon fuels." *Combustion and Flame* 159.2 (2012): 541-551.

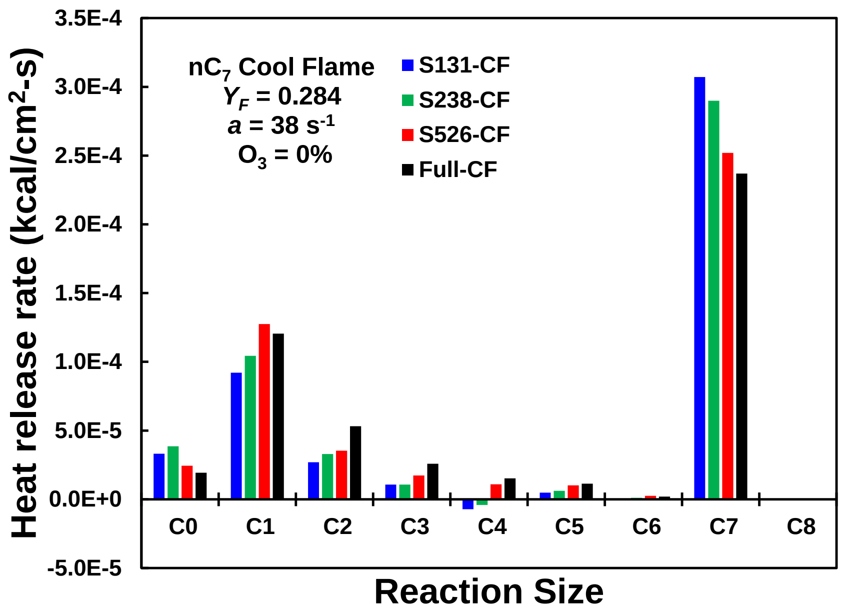
Will a model, which captures low temperature ignition well, be able to predict extinction limits of cool flames?





- The answer is no! we need to capture the low temperature heat release rate correctly.

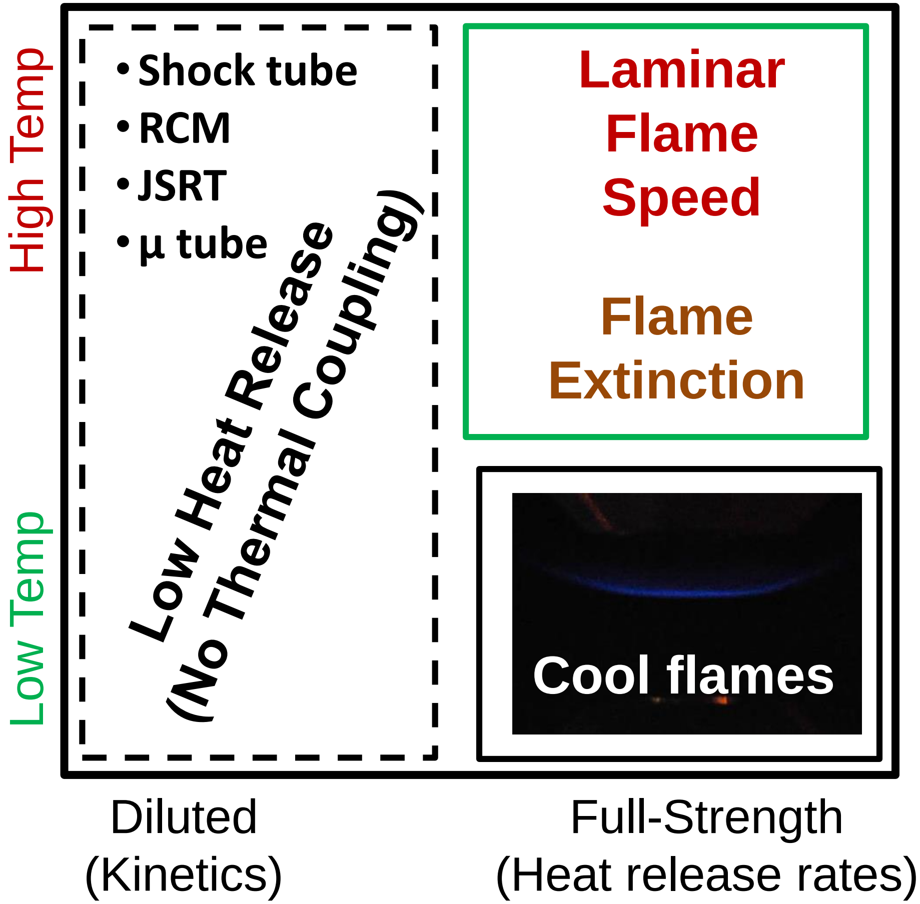
- Cool flames can play an important role in model validation for heat release rate.



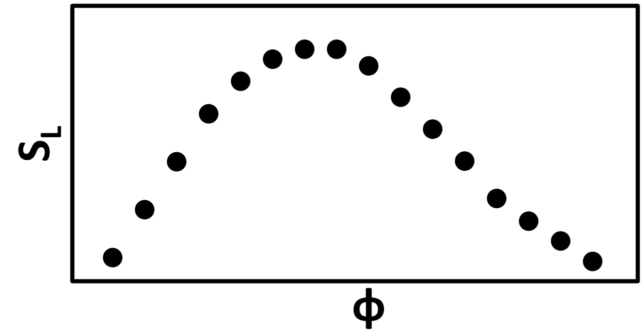
Reuter, C.B., Lee, M., Won, S.H. and Ju, Y., 2017. *Combustion and Flame*, *179*, pp.23-32.

Cool Flames as Mechanism Validation Experiments

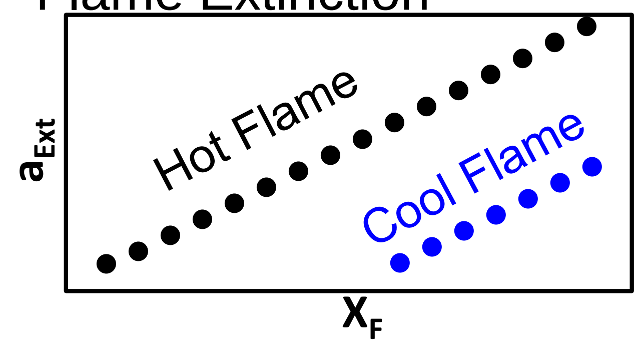
Validation in systems with chemistry-transport-heat release coupling:



- Laminar Flame Speed



- Flame Extinction

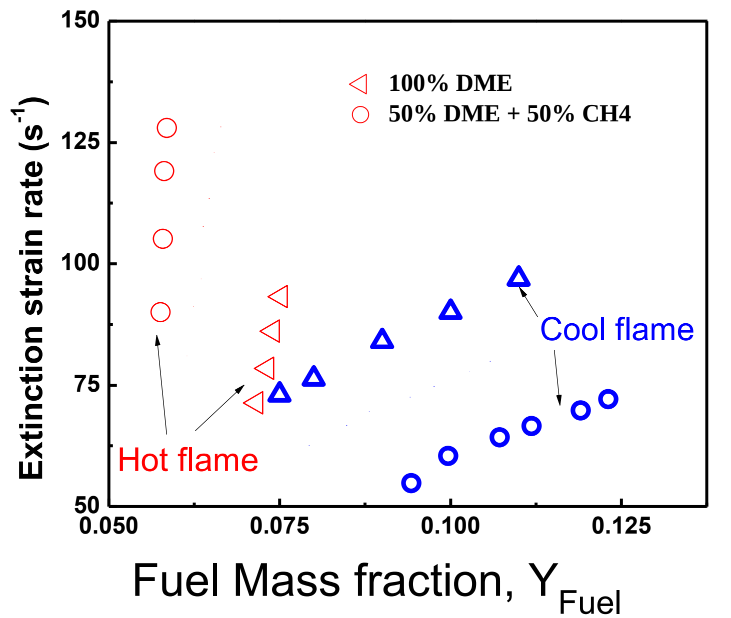


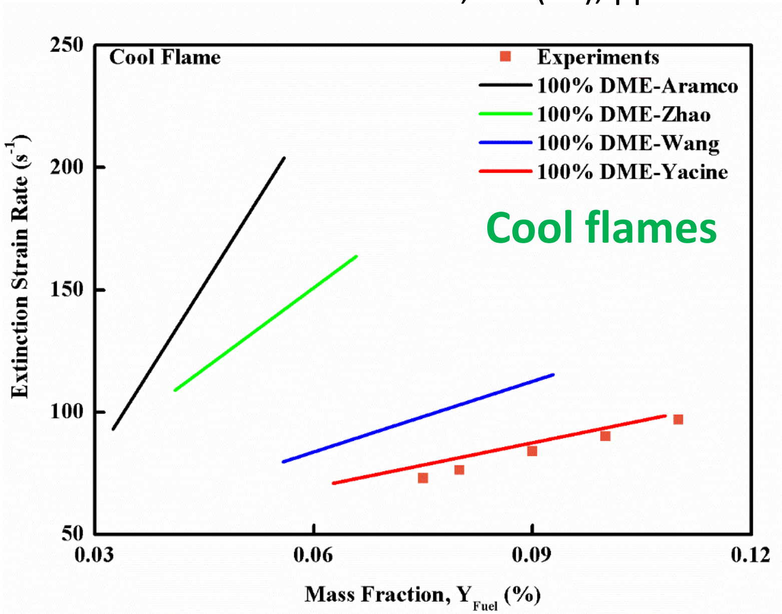
No validation of heat release rate at low temperatures!

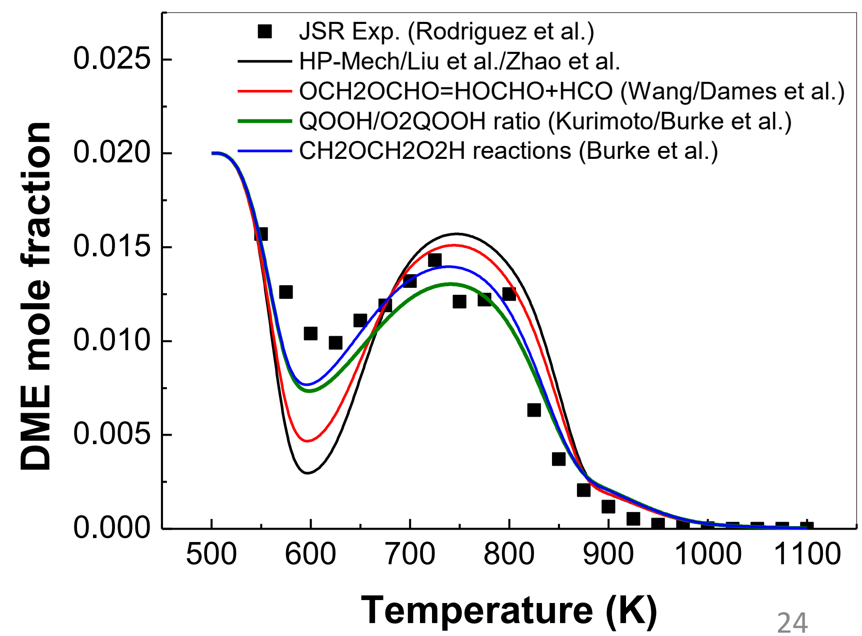
"Experimental blind spot" – can be addressed in cool flame measurements

CH4/DME Cool flames and mechanism validation

1. Zhao, Zhenwei, Marcos Chaos, Andrei Kazakov, and Frederick L. Dryer, *IJCK,* 40, no. 1 (2008): 1-18.
2. Kurimoto, N., Brumfield, B., Yang, X., Wada, T., Diévart, P., Wysocki, G. and Ju, Y., 2015. *Proc. Combust. Inst.*, *35*, p.457.
3. Wang, Z., Zhang, X., Xing, L., Zhang, L., Herrmann, F., Moshammer, K., Qi, F. and Kohse-Höinghaus, K., 2015. Combust. Flame, 162(4), p.1113.
4. Burke, U., Somers, K.P., O'Toole, P., Zinner, C.M., Marquet, N., Bourque, G., Petersen, E.L., Metcalfe, W.K., Serinyel, Z. and Curran, H.J., 2015. *Combustion and Flame*, *162*(2), pp.315-330.
5. Dames, E.E., Rosen, A.S., Weber, B.W., Gao, C.W., Sung, C.J. and Green, W.H., 2016. *Combustion and Flame*, *168*, pp.310-330.
6. Liu, D., Santner, J., Togbé, C., Felsmann, D., Koppmann, J., Lackner, A., Yang, X., Shen, X., Ju, Y. and Kohse-Höinghaus, K., 2013. sures. *Combustion and Flame*, *160*(12), pp.2654-2668.







Conclusion

- **Cool flames lead to many new flame regimes, dynamics, and insights in combustion research and engine development.**

- **Cool flames extend the burning limits and add new physics and time/length scales in combustion dynamics.**

- **Cool Flames provide a new platform in validation of low temperature chemistry.**

- **Experiments of high pressure/turbulent cool flames, and ignition assisted cool flames are interesting and challenging.**