

Effects of Ambient Inert Gas Properties on Cool-Flame Combustion of Normal-Alkane Droplets in Microgravity

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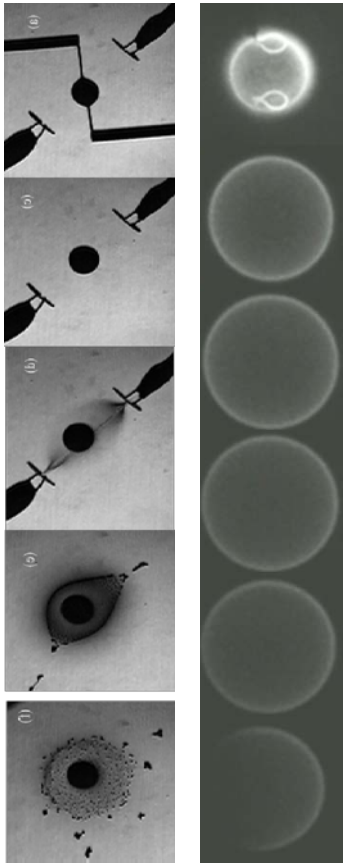
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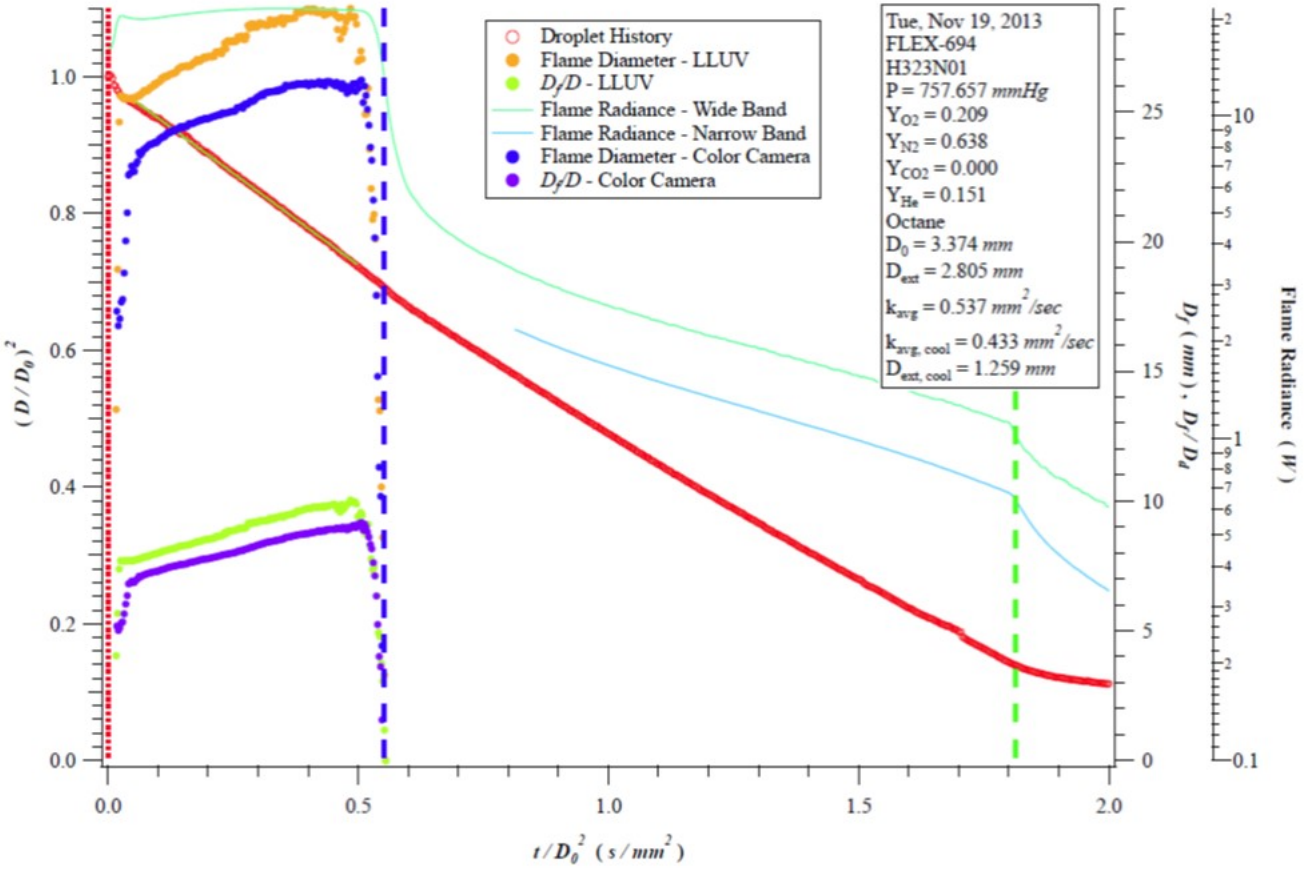
Background & Motivation

- Quasi-steady cool flames were discovered during normal-alkane fuel droplet combustion onboard ISS in the FLEX experiments.
- Cool flames can extend the flammability of fuels in a microgravity environment, and understanding their burning characteristics is important from spacecraft fire safety point of view.
- Inert gases are used to extinguish fires in microgravity. Currently CO_2 is used in the US module of ISS. Other inert gases such as Helium, Xenon, etc., can also inhibit combustion at sufficient dilution (Limiting oxygen index, LOI).
- In this study we present experimental results (from FLEX/FLEX-2/CFI) for n-alkane fuel-droplet cool-flame burning rates and extinction diameters in Helium or Xenon diluted ambient conditions.
- Unlike hot-flames, cool flames are controlled by chemical kinetics. We employ a simplified, 6-step-chemistry, asymptotic theory developed earlier to correlate the burning rate and extinction diameters of n-alkane fuel droplets.

Cool flame in helium-diluted environment

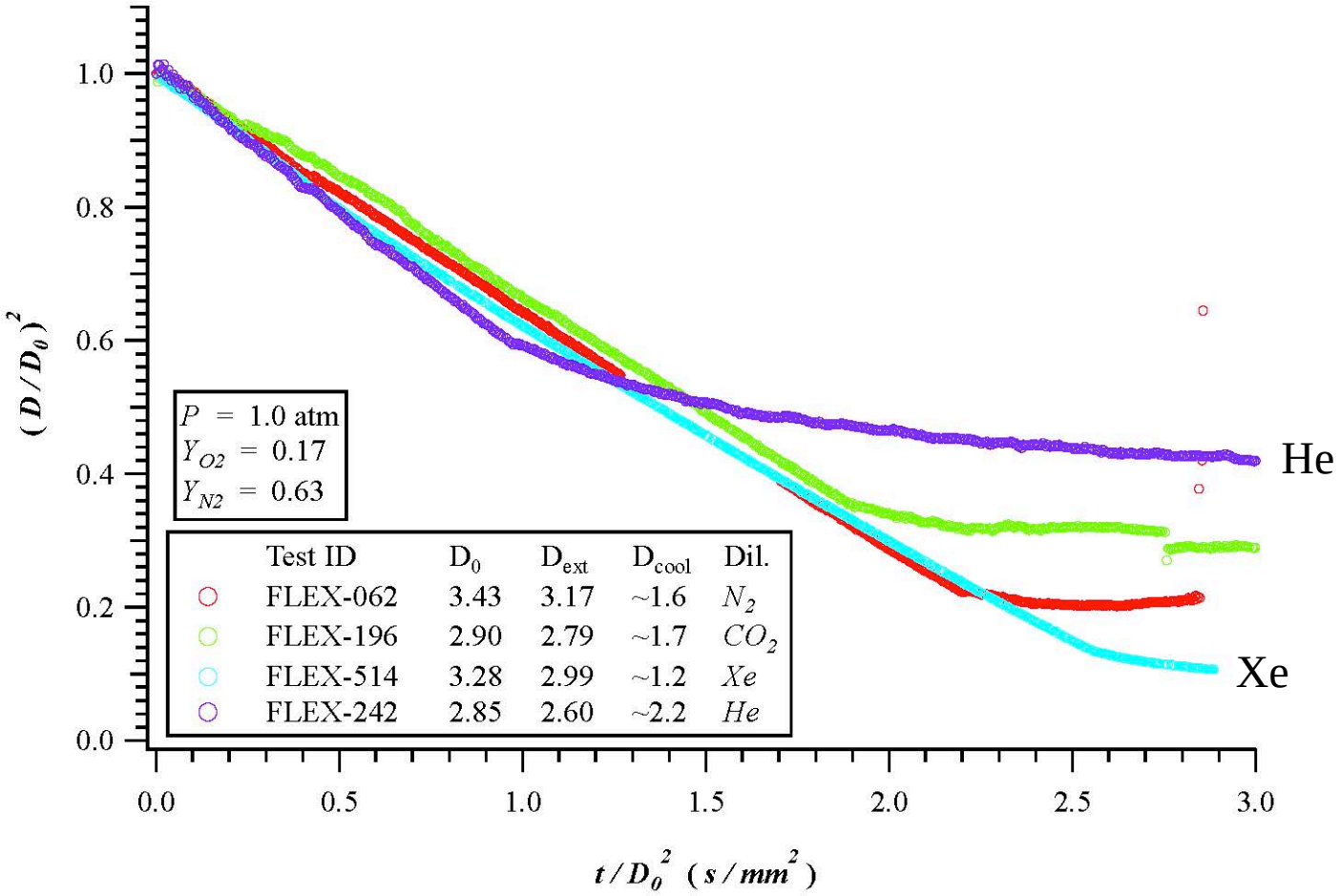
- Video images are analyzed to obtain droplet, and flame diameters.
- Narrow and wide-band radiometers measured radiant emissions from the flame.





Cool flames in different diluents

- Scaled square of the droplet diameter as function of scaled time for n-octane droplets in nitrogen, carbon dioxide, helium, and xenon ambient with oxygen mole fraction at 0.17.

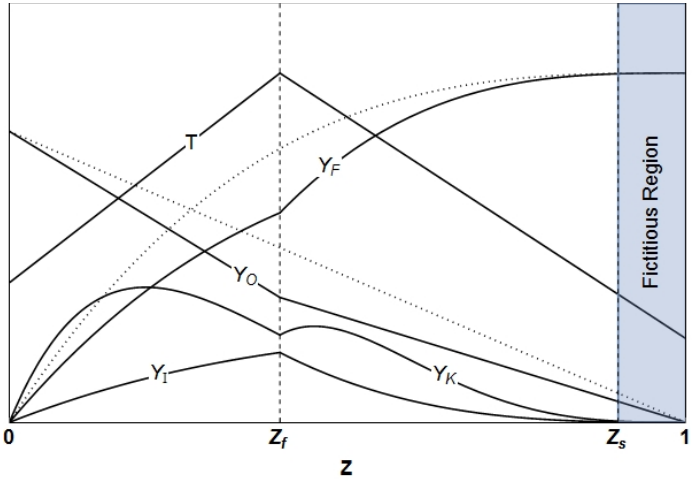


Theory of Quasi-Steady Cool-Flame Combustion Near Extinction*

- Quasi-steady theory using activation energy asymptotics and 6-step simplified chemical kinetic mechanism

Rate parameters				
No.	Reaction	A C7H16 and C8H18	A C10H22 and C12H26	T_a (K)
1	$F + OH \rightarrow R + H_2O$	1×10^{12}	1.5×10^{12}	0
2	$R + O_2 \rightarrow I$	2×10^{12}	3.67×10^{12}	0
3	$I + O_2 \rightarrow K + OH$	3.5×10^{7}	6.42×10^{12}	-8360
4	$K \rightarrow P's + OH$	4×10^{13}	6×10^{7}	19,840
5	$I \rightarrow Q's$	2×10^{12}	3×10^{13}	12,090
6	$R \rightarrow S's$	3.2×10^{13}	4.8×10^{13}	15,110

- Cool flame structure



F – fuel
R – alkyl radical
I – intermediate
K – ketohydroperoxide
P, Q, S – products

* Williams and Nayagam, *Combustion Theory and Modelling*, 23 (4), 2019

Quasi-steady cool-flame theory predictions

- Burning rate constant: $K_c = d(D^2)/dt$

$$K_c = \frac{8\rho_\infty \alpha_{T\infty}}{\rho_l} \ln\left(\frac{2T_f - T_0 - T_\infty}{T_L}\right)$$

- Cool-flame theory assumed constant properties and a property-evaluation procedure is needed to compare against experiments (as with hot-flame QS theories*).

- Property evaluation prescription – empirically based on data fitting

$$T_{fl} = 730 + 1200(X_{O\infty} - 0.21)$$

$$T_s = \texttt{fuel boiling point}$$

$$T_{ref} = \frac{1}{2}(T_s + T_{fl})$$

$$\rho_\infty \alpha_{T\infty} = k_{eff}/c_{p,eff}$$

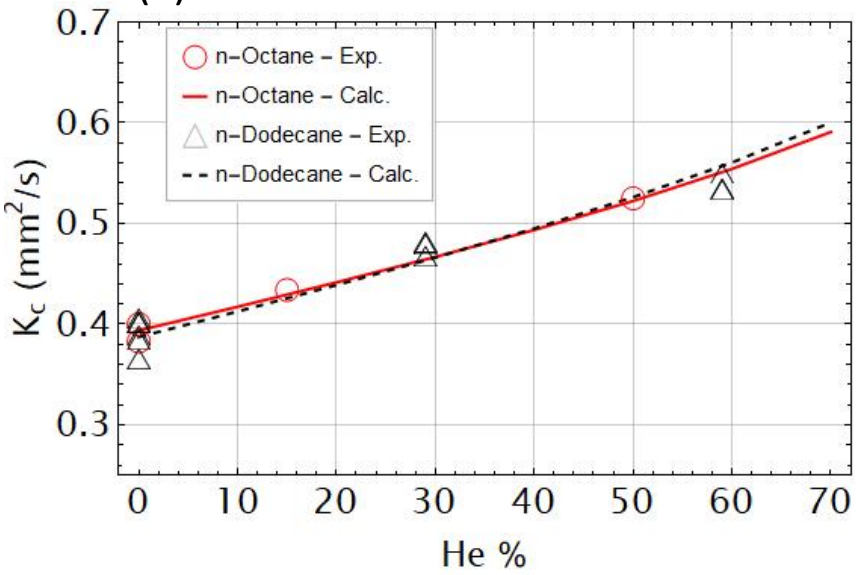
$$k_{eff} = 0.8k_{fuel}(T_{ref}) + 0.2k_{mix}(T_{ref})$$

$$c_{p,eff} = c_{fuel}(T_{ref})$$

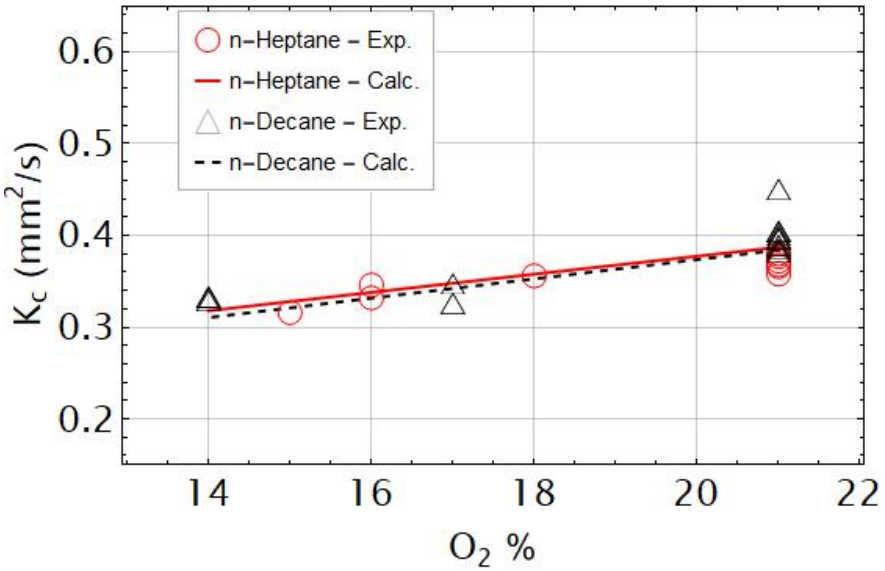
* Law and Williams, *Combustion and Flame*, 19 (3), 1972

Calculated and measured cool-flame burning rates

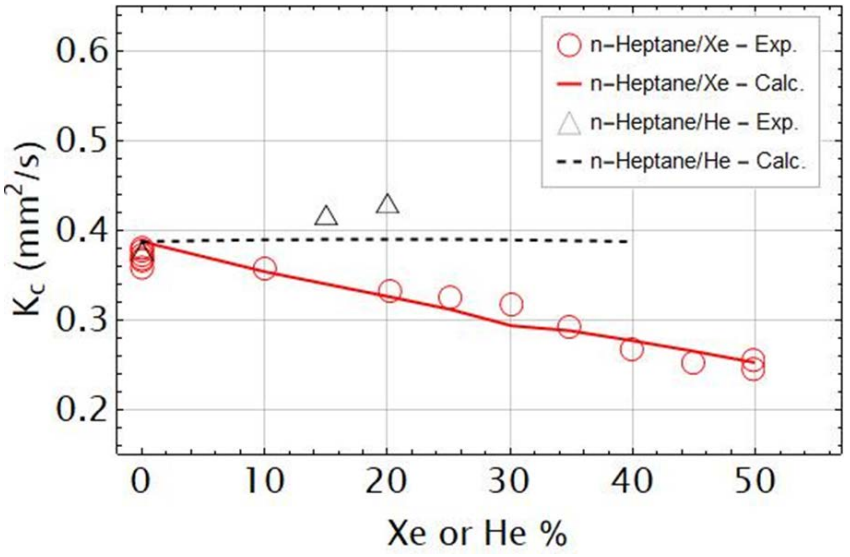
(a)



(b)



(c)



(a) 21% O_2 – He varies –displaces N_2

(b) O_2 varies –rest N_2

(c) Xe or He displaces air

For case (c) with He, the burning becomes highly transient – QS not valid

Quasi-steady cool-flame theory predictions

- Cool-flame extinction diameter D_{ce}: $$D_{ce}^2 = \frac{(\rho_l/\rho_\infty)^2 (K_c^2/\alpha_{T\infty})(T_{fe}/T_\infty)(T_{fe}-T_0)^2}{8(D_{fe}/D)^4 (2T_{fe}-T_0+T_\infty)^2 \chi_{fe}}$$

- Critical dissipation rate, or critical inverse residence time χ_f:

$$\chi_f = \frac{(1-R)(T_f-T_0)T_f^2(Ae^{-T_a/T_f}+Qe^{-T_q/T_f}+He^{-T_h/T_f})}{T_a(2T_f-T_0-T_\infty)^2}[(1+E)^{1/2}-1]$$

$$R = \left(1-\frac{T_f-T_\infty}{2T_f-T_0-T_\infty}\right)^L$$

- Critical dissipation rate involves evaluation of Lewis number L (via R-parameter). An effective L is evaluated at the flame where extinction chemistry occurs:

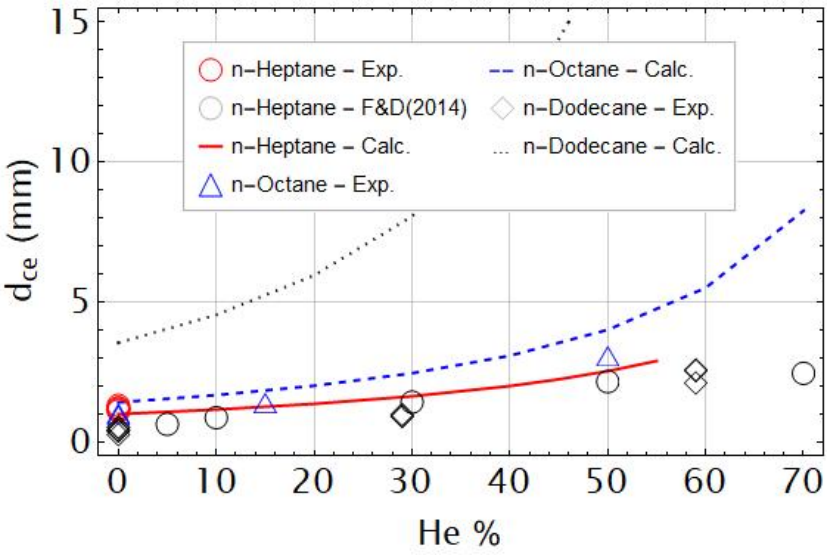
$$L = \frac{k}{\rho c_p D_{f,mix}}$$

$$D_{fmix} = \frac{1}{X_{N2}/D_{fN2} + X_{CO_2}/D_{fCO_2} + X_{He}/D_{fHe} + X_{Xe}/D_{fXe} + X_{O2}/D_{fN2}}$$

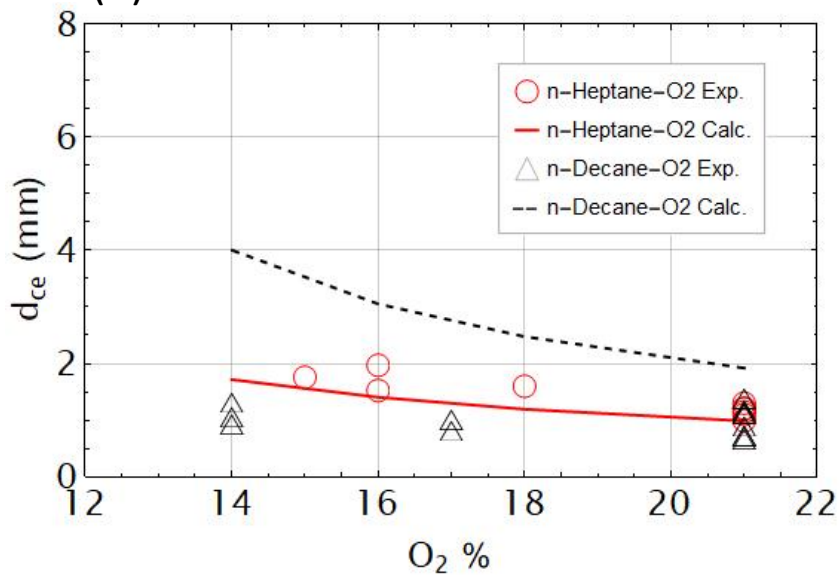
D_{ij}- binary diffusion coefficient, c_p – mixture c_p, and ρ - mixture density

Calculated and measured cool flame extinction diameters

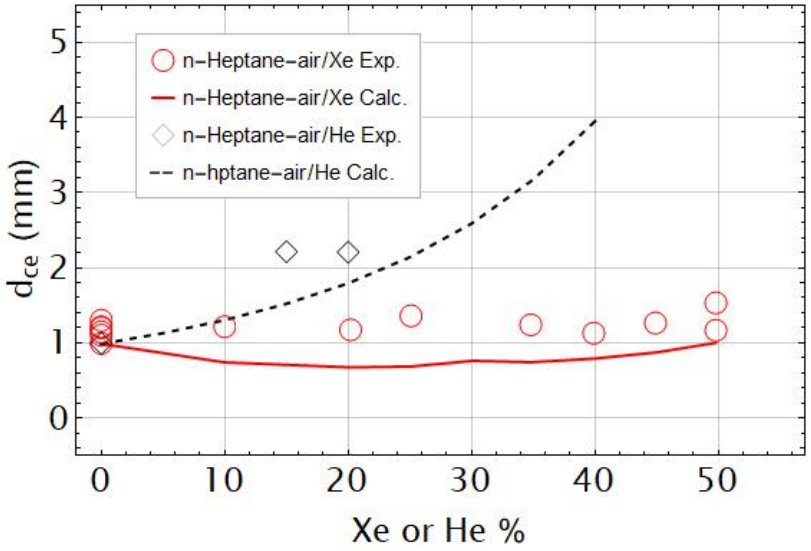
(a)



(b)



(c)



(a) 21% O_2 – He varies –displaces N_2

(b) O_2 varies –rest N_2

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Agreements for heptane and octane seem reasonable, but dodecane extinction diameters are over predicted appreciably, despite the lumped parameters.

Summary & Conclusions

- Inert diluents affect the cool-flame-supported n-alkane droplet combustion substantially, through heat-transfer and diffusion processes, and not by influencing chemical-kinetic rates.
- A simplified, quasi-steady theory can be used to predict the burning rates and to a large extent extinction diameters when thermodynamic and transport properties are selected appropriately. A recipe for such selection is presented here.
- Extinction-diameter correlations suggest that the currently available chemical-kinetic descriptions are adequate for lower normal alkanes, while further study is needed for higher alkanes.
- Xenon decreases burning rates substantially, but can sustain cool flames at much lower oxygen concentrations compared to helium.

