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Extinction of Non-Premixed Undiluted-Hydrocarbons vs. Air Counterflow Flames: Comparisons on an “Absolute” Axial-Strain-Rate Scale

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Overview of Presentation

• OJB Extinction Limits Mimic “Idealized” Scramjet Flameholding
• Experimental Approach; and Extinction Data for C_1 to C_4 HCs
• Determination of Gaseous Surrogate HC Fuel for HIFiRE
• Effects of O_2 (and NO) Concentration on HC Extinction
• Results from Convergent-Nozzles and Straight-Tube OJBs; Transformation of Global Strain Rates; and Comparisons.
• Summary Extinction of Non-Premixed, Undiluted-HCs vs. Air; 7 C_1 to C_4 Gaseous HCs, & 11 Vaporized HCs up to n-C_{14}H_{30}. 
Use of OJB Extinction Limits to Mimic “Idealized” Scramjet Flame-Holding Limits, and Define a Simple Gaseous Surrogate Fuel

• HIFiRE Flight 2
  – Hypersonic International Flight Research Experiment. Participants are: NASA Langley; U.S. Air Force AFRL; ATK Alliant Tech Systems; and the Australian Defence Science and Tech Org., DSTO.

  – **Flight Goal:** To demonstrate dual-mode to scramjet performance transition, using a gaseous hydrocarbon surrogate fuel that mimics ignition and flame holding properties of a catalytically-cracked JP-7 “like” kerosene.
Experimental Approach

and

Extinction Data for Non-Premixed $C_1$ to $C_4$ HCs vs. Air
Extinction / Flameholding Performance Gauges

- **Opposed Jet Burner Extinction Limits:**
  - Flame Strength \( [FS = \text{cross-section-average } U_{\text{air}} (MF) \text{ at nozzle exit}] \).
  - FSs measure aerodynamically-strained, non-premixed combustion limits at T’s relevant to flameholding in simple systems.

- **Applied Stress Rate (ASR) Extinction Limits** (after Spalding, Dixon-Lewis)
  - ASRs at extinction represent jet-diameter-normalized FSs for convergent nozzles (plug inflow) and uniform tubes (parabolic).
  - ASR limits define reproducible global scales for fuel–air systems (primarily influenced by chemical kinetics and diffusion).
  - Limits enable a relative assessment of incipient flameholding (flameout) in scramjet (e.g., in subsonic recirculation zone).
  - ASRs allow validation of kinetics & multi-component diffusion.
Focusing Schlieren System to visualize flame structure

Oscillatory-input Opposed Jet Burner (OOJB) System (used for “steady” extinction; latest study of unsteady extinction, AIAA 2009-4879)

Diode laser system is passive in this study

Focusing Schlieren System to visualize flame structure
For FS of undiluted fuel: \( \text{C}_2\text{H}_4 \) is ~ 2.7 times stronger than \( \text{CH}_4 \), but is ~ 12 times weaker than \( \text{H}_2 \).
Liquid-Fuel Vaporizer, and Various-size Horizontal-Tube Opposed Jet Burners (1 atm)
Applied Stress Rate for Tube-OJBs "at 300 K Airside Edge of Flame," for Extinction of $H_2/N_2$—Air CFDFs

![Graph showing applied stress rate](image)

- $U_{air,300}$ / $D_t$, 1000/s
- $X(H_2)$, Mole Fraction in Fuel Jet

Legend:
- 1.8 mm Horiz-SS
- 2.7 H-Ni
- 5.0 H-Py
- 7.0 Vert- & H-Py
- 10.0 H-Py
- All Data (4th deg)
Effect of OJB Tube Diameter on Applied Stress Rate at Extinction, for Various Gaseous Hydrocarbon vs Air CFDFs
Applied Stress Rate at Extinction for Methane + Ethylene Fuel Mix vs Air Counterflow Diffusion Flames, 7.56 mm Tube-OJB, 1 atm

\[ Y = M0 + M1 \cdot x + M2 \cdot x^2 \]

\[
\begin{array}{|c|c|}
\hline
\text{M0} & 79.47 \\
\text{M1} & 79.483 \\
\text{M2} & 55.002 \\
\text{R} & 0.99955 \\
\hline
\end{array}
\]

\( U_{\text{air,300K,1atm}} / D_t, 1/s \)

\( X(C_2H_4), \text{Mole Fraction Ethylene in Fuel Mix} \)
Applied Stress Rate at Extinction for Ethane + Ethylene Fuel Mix vs Air Counterflow Diffusion Flames, 7.56 mm Tube-OJB, 1 atm

\[ Y = M_0 + M_1 x + M_2 x^2 \]

<table>
<thead>
<tr>
<th></th>
<th>M0</th>
<th>M1</th>
<th>M2</th>
<th>R</th>
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<td>120.1</td>
<td>60.426</td>
<td>33.85</td>
<td>0.99921</td>
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\[ x_{(C_2H_4)} \text{, Mole Fraction Ethylene in Fuel Mix} \]
Applied Stress Rate at Extinction for Methane + Ethane Fuel Mix vs Air Counterflow Diffusion Flames,
7.56 mm Tube-OJB, 1 atm

\[ U_{\text{air,300K,1atm}} / D_t, \text{ 1/s} \]

\[ y = 80.543 + 40.357x \quad R^2 = 0.99687 \]

\[ X(C_2H_6), \text{ Mole Fraction Ethane in Fuel Mix} \]
Applied Stress Rate at Extinction for Methane + Propylene Fuel Mix vs Air Counterflow Diffusion Flames, 7.56 mm Tube-OJB, 1 atm

\[
y = 79.218 + 28.014x \quad R = 0.99522
\]
Definition of HIFiRE Gaseous Surrogate Fuel

- Gaseous Binary Surrogate that Mimics Cracked JP-7 “like” Fuel
  
  - Determine binary-mixture Flame Strength (FS) for a Counter Flow Diffusion Flame (CFDF), that equals FS for a ternary baseline surrogate mixture proposed by Colket & Spadaccini (JPP, 2001).
  
  - Ternary baseline surrogate (above) was based on extensive shock tube ignition (and cracking) data for methane, ethylene, and \( n \)-heptane (30/60/10 mole %), that mimics a cracked (reformed) JP-7 “like” fuel.
  
  - Gaseous 64/36 ethylene / methane surrogate mixture was derived from detailed OJB data (documented in AIAA 2007-5664; JANNAF-847, May, 2008; and JANNAF-752, Dec. 2009).
Applied Stress Rate at Extinction for 600 ± K Methane + n-Heptane Fuel Mix vs Air Counterflow Diffusion Flames, 7.56 mm Tube-OJB, 1 atm

\[ y = 84.135 + 16.085x \quad R^2 = 0.86079 \]
Applied Stress Rate at Extinction of Gaseous n-Heptane + Ethylene Fuel Mix vs Air Counter Flow Diffusion Flames, 7.56 mm Tube-OJB, 1 atm

$Y = M_0 + M_1 x + M_2 x^2$

<p>| | |</p>
<table>
<thead>
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<tbody>
<tr>
<td>$M_0$</td>
<td>100.38</td>
</tr>
<tr>
<td>$M_1$</td>
<td>38.775</td>
</tr>
<tr>
<td>$M_2$</td>
<td>87.96</td>
</tr>
<tr>
<td>$R$</td>
<td>0.99417</td>
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</table>

1 hr & 0.1 hr at ~ 600 K;

<--- 300 K
Applied Stress Rate at Extinction of 600 K Methane + Ethylene +10.8 mole % gaseous n-Heptane Fuel vs Air Counter Flow Diffusion Flames, 7.56 mm Tube-OJB, 1 atm

Baseline Simulant, based on Shock Tube Ignition Studies by Colket & Spadaccini (JPP, 2001), for Endothermically Cracked JP-like Fuel

\[ Y = M_0 + M_1x + M_2x^2 \]

- \( M_0 = 88.147 \)
- \( M_1 = 98.156 \)
- \( M_2 = 35.365 \)
- \( R = 0.99957 \)
Applied Stress Rate at Extinction for 600 K Methane + Ethylene Fuel Mixtures vs Air Counterflow Diffusion Flames, 7.56 mm Tube-OJB, 1 atm

![Graph showing the relationship between applied stress rate and ethylene mole fraction in fuel mixtures. The graph includes data points for pure JP-7 and a mixture with 64 mole% ethylene and 36% methane surrogate. The equation Y = M0 + M1x + M2x^2 is given, with coefficients M0 = 80.125, M1 = 83.453, M2 = 65.034, and R = 0.99961. The graph notes that this composition mimics OJB Flame Strength (ASR) of a Colket & Spadaccini "simulated reformed fuel" composition, based on their 2001 Shock Tube Ignition & previous fuel cracking studies.]
Effects of O₂ (and NO) Concentration on Extinction Limits - for “Idealized” HIFiRE Flameholding

★ Motivation:
★ Test air contamination, from production of nitric oxide with consumption of O₂ in Arc-Jet-Heater Facility, occurs in tests of HIFiRE scramjet combustors.

★ Flight testing of the HIFiRE vehicle may experience an offset in robust flameholding, mode transition, and/or flameout, due to the “final” switch from facility contaminated air to clean air.

★ Development of advanced HC-fueled scramjets will require greatly improved chemical kinetics for accurate simulations of flameholding during flight in clean and facility-contaminated air.

★ Related Work:
★ Compared with our earlier OJB extinction results (JANNAF-847, May, 2008), 1-D simulations (UVa) of ethylene vs. air flame extinction were high by ~ 45 %, based on USC (2007) kinetics.
Effects of \( \text{N}_2^* \) Dilution of Air on Extinction of HC vs. Air CFDFs, using 9.3 mm Tube-OJB System at 1 atm

\[
\text{Applied Stress Rate (ASR)} = \frac{U_{\text{air}}}{D_t}, \text{ 1/s}
\]
Effects of $N_2$ Dilution of Air on Extinction of HC vs. Air CFDFs, using 9.3 mm Tube-OJB Systems at 1 atm; and Comparison with Relative Maximum Flame Velocity [NACA Rpt. 1300, (1959)]
Effects of Mole % $\text{O}_2$ in Air on Extinction of HC vs. Air CFDFs, using 9.3 mm (and 7.56 mm for $\text{C}_2\text{H}_6$) Tube-OJB System at 1 atm

**Applied Stress Rate (ASR) = $U_{\text{air}}/D_t$**

- **$\text{C}_2\text{H}_4$**
- **84/36 Mixes (2)**
- **$\text{C}_2\text{H}_6$ (7.56 mm)**
- **$\text{C}_2\text{H}_6$ (9.3 mm)**
- **$\text{C}_3\text{H}_6$**
- **$\text{C}_3\text{H}_8$**
- **$\text{C}_4\text{H}_{10}$**
- **$\text{CH}_4$**

![Graph](image-url)
Sensitivity of ASR at Extinction due to Decreased $O_2$ in Air, for Various HCs vs. $N_2^*$—Contaminated Air, using 9.3 mm Tube-OJB System at 1 atm.
Effects of NO Dilution of Air on Extinction of HCs vs. Air CFDFs, using 9.3 mm Tube-OJB System at 1 atm

Applied Stress Rate (ASR) = $U_{\text{air}}/D_t$

- C2H4
- 64/36 Mixes (2)
- CH4

64% Ethylene / 36% Methane Premixed Surrogates
(7/2 & 9/17 Rec’d bottles)

ASR at Extinction, 1/s @300K, 1 atm

Mole % NO Diluent in Air + NO Mixture

0 2 4 6 8 10
Effects of $N_2^*$ Dilution of Air on Extinction of HC vs. Air CFDFs, using 9.3 mm Tube-OJB System at 1 atm

![Graph showing the relationship between Applied Stress Rate (ASR) and Mole % $N_2^*$ Diluent in Air + $N_2^*$ Mixture. The graph includes various lines representing different HC and air dilution mixtures.](image)
Fractional Effects on ASR at Extinction, for HC vs. Arc-Jet-Contaminated Air with 3 mole % NO: For NO Enhancement, Oxygen Depletion, and Net Effects on ASR, based on 9.3 mm Tube OJB at 1 atm.
Fractional Effects on ASR at Extinction, for Ethylene and 64/36 C$_2$H$_4$/CH$_4$ Surrogate Fuels vs. Arc-Jet-Contaminated Air: For "NO Enhancement", "Oxygen Depletion" and "Net" Effects, from 9.3 mm Tube OJB at 1 atm.
Re: Air Contamination Effects on “Ideal” Flameholding

🌟 Very significant “oxygen-deficiency” weakening effects on flame extinction for all seven HCs tested. **Effects are ~ 2.5 times that for H₂.**

🌟 “Nitric oxide (NO) enhancement” effects on flame extinction are small (to ~ 4 %) for methane, ethylene, the “64/36” mix, and probably most simple gaseous HCs.

🌟 Because “oxygen-deficiency” weakening effects grow large (*and* ~ 2.5 times that for H₂), renewed scrutiny is needed for tests that alter local O₂ (e.g., vitiated air with O₂ make-up, and arc-heaters that consume O₂ to produce NO).

🌟 The deduced 26 % reduction in FS for the “64/36” surrogate fuel vs. Arc-Jet-contaminated air with 3 % NO suggests that “clean air” flameholding processes *may be strengthened* during flight.
(1) Extinction Limits for 7 Gaseous HCs, from Convergent-Nozzle and Uniform-Tube OJBs;

(2) Transformation of Global Strain Rates to “Absolute” Input Axial Strain Rate Scales;

(3) Comparisons with Published Results.
Extinction-Limit "Idealized Flameholding Scale," from 7.2 mm Convergent Nozzle- and 7.5 mm Straight Tube-OJBs, for gaseous HCs vs Air CFDFs, using Best Linear Fit WITH INTERCEPT

\[ \frac{U_{\text{air}, 300K, 1 \text{atm}}}{D_{n or t}} = \text{Applied Stress} \]

Rate, or normalized Flame Strength, for nozzle (n) or tube (t) inflows

\[ y = -37.124 + 2.5331x \quad R = 0.99531 \]
Extinction-Limit "Idealized Flameholding Scale," from 7.2 mm Convergent Nozzle- and 7.5 mm Straight Tube-OJBs, for gaseous HCs vs Air CFDFs, using Linear Fit WITH ZERO INTERCEPT

\[
\frac{U_{\text{air,300K,1atm}}}{D_{\text{n or t}}} = \text{Applied Stress}
\]
Rate, or normalized Flame Strength, for nozzle (n) or tube (t) inflows

\[
\begin{align*}
C_2H_4 & \quad \circ \\
64\% C_2H_4 + 36\% CH_4 & \quad \circ \\
C_2H_6 & \quad \circ \\
C_3H_8 & \quad \circ \\
C_3H_6 & \quad \circ \\
C_4H_{10} & \quad \circ \\
CH_4 & \quad \circ \\
(5 \text{ mm n & t}) & \quad \circ \\
\end{align*}
\]

\[
y = 2.2331x \quad \text{(with zero intercept)}
\]
Comparison of Rolon's LDA-Measured Strain Rates for Variable Separation of 25 mm Contoured Nozzles, Air vs Air. Rolon et. al, Exp. in Fluids, 11, 313-324 (1991)

Fig. 2
2-D Numerical Strain Rate Ratios for Cold Opposed Jet Air Flows, using 3 mm OJB's, 6 mm spacing, and both Plug and Parabolic Inflow Profiles

[2-D Results from Dissertation by Kyu C. Hwang, Old Dominion University, May 2003]

NOTE: For each of the 2-D cases, AND the 1-D Potential Flow Input Model, Radial SR @ SP = 0.5 Axial SR, Airside

2.53 = Ratio of Parabolic/Plug SR ratios, for (1) Axial Inputs on Airside, AND (2) Radial SRs at Stag Pt

~ 1.15

Rolon et. al (1991)
LDA-measured SRs, 25 mm Contoured Nozzles, L/D 1.1 - 1.4

Parabolic Inflows (tubes)
[Radial @ SP and 0.5 Axial]

Plug Inflows (conv. nozzles)
[Radial @ SP and 0.5 Axial]
Comparison of Experimental and Numerical Strain-Induced Extinction Limits for Fuel vs Air Counterflow Diffusion Flames at 1 atm, Using Best Estimates of Airside Axial Strain Rate

Outdated May 2008 Comparison

-\( \frac{du}{dx} \), Airside Axial Strain Rate, 1/s

**Numerical, Park & Fisher (2007)**

**Numerical, Zambon & Chelliah Comb. Flame (2007)** (solid circle)
71 species, 469 Rxns

-\( \frac{du}{dx} \approx 2.3 \times \frac{U_{air,300}}{D_{noz}} \)

**Pellett et al, Exp. 7.2 mm Nozzle-OJB**

\( U_{air} \)

**Tube-OJB Airside Axial Strain Rate = 5.1 \times \frac{U_{air}}{D_{tube}}, 1/s **
Effects of N\textsubscript{2} \textsuperscript{*} Dilution of Air on Extinction of HC vs. Air CFDFs, using 9.3 mm Tube-OJB System at 1 atm

\[
\text{Applied Stress Rate (ASR)} = \frac{U_{\text{air}}}{D_t}, \text{1/s}
\]

ASR at Extinction, 1/s @300K, 1atm

Mole \% N\textsubscript{2} \textsuperscript{*} Diluent in Air + N\textsubscript{2} \textsuperscript{*} Mixture
Effect of OJB Tube Diameter on Applied Stress Rate at Extinction, for Various Gaseous Hydrocarbon vs Air CFDFs

Updated with new 9.3 mm data

$U_{air,300} / D_t$, ASR, 1/s

$D_t$, OJB Tube Diameter, mm
Extinction-Limit "Idealized Flameholding Scale," from 7.2 mm Convergent Nozzle- and 7.5 mm Straight Tube-OJBs, for gaseous HCs vs Air CFDFs, using Best Linear Fit WITH INTERCEPT

\[ \frac{U_{\text{air},300K,1\text{atm}}}{D_n \text{ or } t} = \text{Applied Stress} \]

Rate, or normalized Flame Strength, for nozzle (n) or tube (t) inflows

\[ y = -37.124 + 2.5331x \quad R = 0.99531 \]
Transformation of Extinction ASR’s from Tube-OJB to Best Estimates of Airside Axial Strain Rate for Convergent Nozzle-OJB

(1) Use of 2.3 factor (= 2 * 1.15) corrects nozzle-based $\text{ASR}_n$ data, and

(2) Use of best empirical LS fit of $\text{ASR}_n$ vs. $\text{ASR}_t$ for extensive extinction data on 7 gaseous HCs,

$$\text{ASR}_n = -37.12 + 2.533 \times \text{ASR}_t,$$

allows the use of $2.3(-37.12 + 2.533 \times \text{ASR}_t)$ to represent Tube-OJB $\text{ASR}_t$ data on an equivalent $2.3 \times \text{ASR}_n$ scale.
Comparison of Experimental and Numerical Strain-Induced Extinction Limits for Fuel vs. Air Counterflow Diffusion Flames at 1 atm, Using Best Estimates of (local) Airside Axial Strain Rate

Exp. data using 7.2 mm Nozzle-OJB and also:
7.56 mm Tube-OJB, open circles, and
9.3 mm Tube-OJB, solid circles

Open squares: Numerical, H. Chelliah, 9-10: with BL Corr. for L/D=1.8, based on USC Mechanism of H. Wang et al. (2009); 111 species, 784 x 2 Rxns

Chelliah, 9/10: PIV-based with L/D=0.9-1.8, & est. w/o part’s; using 8 mm nozzle-OJB

Nozzle-based Airside Axial Strain Rate, 1/s

(-du/dx = 2.3 * U_{air,300}/D_{noz} (= 0.72 cm))
Conclusions Re: Extinction Limits for C$_2$H$_4$ and Simple HCs

* The new ASR extinction limits for 7 gaseous HCs agree exceptionally well with the author’s previous (2008) results derived from a slightly smaller Tube-OJB.

* (1) New independent global extinction, and refined PIV axial Strain Rate measurements at UVa for C$_2$H$_4$ and CH$_4$ OJB flames; and (2) Refined numerical simulations at UVa for C$_2$H$_4$ and CH$_4$ extinctions, using a revised 2009 chemical kinetics model (USC), agree quite closely with present experimental results on a deduced “absolute” axial SR scale (both are ~ 12 % higher for C$_2$H$_4$).

* The present agreement helps justify development of a reduced kinetics model (with ~ 30 species) that will permit detailed numerical simulations of flameholding in HIFiRE-like scramjet combustor designs.
Extinction of Non-Premixed, Undiluted Vaporized-HCs vs Air;

and

Consolidation of Results from 7 Simple Gaseous HCs

with Results from 11 Vaporized HCs, up to Tetradecane.
Extinction of N$_2$-diluted n-Heptane and n-Dodecane, and JP-7 vs Air CFDF's, using 7.5 mm Tube-OJB with Batch Vaporizer, and Comparison with Gap-Corrected UCSD Matrix Burner Data

![Graph showing extinction of N$_2$-diluted hydrocarbons and JP-7 versus air CFDF's with batch vaporizer. The graph plots the applied stress rate, $U_{air,200}/D_t$, against the mole fraction of hydrocarbons, X(HC), in N$_2$-diluted fuel. The x-axis represents X(HC) from 0 to 1, and the y-axis represents the applied stress rate from 0 to 120. The graph includes data points for n-Heptane, C$_7$H$_{16}$, n-Dodecane, C$_{12}$H$_{26}$, and JP-7, with solid circles and squares representing gap-corrected data from Seiser et al. and Hummer et al., respectively.](image-url)
ASR at Extinction for Vaporized n-Heptane + n-Dodecane Mixtures vs Air Counterflow DFs, using "Minimally Heated" Vaporizer System to feed 7.56 mm Tube-OJB, 1 atm

\[ y = 98.586 - 0.12065x \quad R = 0.97957 \]
OJB-Extinction-Limit "Idealized Flameholding Scale" from Convergent-Nozzle- and Tube-OJBs, for: JP-10, n-Dodecane, JP-7, n-Heptane; and Methane, Butane, Propane, Propylene, Ethane, 36% CH\textsubscript{4}/64% C\textsubscript{2}H\textsubscript{4}, Ethylene, and H\textsubscript{2} vs Air CFDFs

\[
\frac{U_{\text{air,300K atm}}}{D_{\text{n or t}}} = \text{Applied Stress}
\]
Rate, or normalized Flame Strength, for nozzle (n) or tube (t) inflows

\[
y = -56.551 + 2.7284x \quad R = 0.99976
\]

\# means Measured w/Tube-OJB; and plotted on LS fit of gaseous fuel, Nozzle-OJB vs Tube-OJB data

- Gaseous fuels (w/ noz & tube)
- \# vap n-Heptane (highest), & 50/50, 0/100 n-Dodecane
- \# vap 100% JP-7
- \# vap 100% JP-10
OJB-Extinction-Limit "Idealized Flameholding Scale" from Convergent-Nozzle- and Tube-OJBs, for: JP-10, n-Dodecane, JP-7, n-Heptane; and Methane, Butane, Propane, Propylene, Ethane, 36% CH\textsubscript{4}/64% C\textsubscript{2}H\textsubscript{4}, Ethylene, and H\textsubscript{2} vs Air CFDFs

![Graph](image-url)

- **U\textsubscript{air,300K,1 atm} / D\text{ n or t} = Applied Stress**
- Rate, or normalized Flame Strength, for nozzle (n) or tube (t) inflows

- **36% CH\textsubscript{4} + 64% C\textsubscript{2}H\textsubscript{4}**
- **# measured w/Tube-OJB; and plotted on LS fit of gaseous fuel, Nozzle-OJB vs Tube-OJB data**

- **Gaseous fuels (w/ noz & tube)**
  - ◇ vap n-Heptane (highest), & 50/50, 0/100 n-Dodecane
  - ● vap 100% JP-7
  - □ vap 100% JP-10

- **Regression Equation:**
  - \( y = -56.551 + 2.7284x \)
  - \( R^2 = 0.9997 \)

- **ASR at Extinction, U\textsubscript{air,300 K} / D\text{ tube}, 1/s**
Applied Stress Rate (Extinction) for Gaseous & Vaporized-Liquid Hydrocarbons vs Air, using "Minimally-Heated" 10.6 L System to Feed 7.56 mm tube-OJB @ 1 atm

![Graph showing carbon number vs ASR for various hydrocarbons](image_url)
Best Estimate of Airside Axial Strain Rate for Extinction of Gaseous & Vaporized-Liquid Hydrocarbons vs. Air, using "Minimally-Heated" 10.6 L System to Feed 7.56 mm Tube-OJB @ 1 atm

\[ y = 603.35 - 13.413x \quad R = 0.860 \]
Conclusions Re: Extinction of Gaseous and Vaporized HCs

Consistent scaling of ASRₙ and ASRₜ results has been obtained.

The ASRₜ results appear basically consistent with expected trends as a function of molecular structure.

The present ASRₜ extinction results on gaseous and vaporized HCs are now transformed as best empirical estimates of the (cool) airside axial strain rate at extinction for the (non-premixed) HC vs. air flames.