Institution of Fire Engineers

Rasbash Lecture

40th Anniversary Symposium

Radiation and Incomplete Combustion of Buoyant Turbulent Diffusion Flames

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A 1983 discussion with David Rasbash in led to the recent paper

"Mechanism of Buoyant Turbulent Diffusion Flames"

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Global $V_f \sim \dot{Q}$

- Rayleigh-Taylor Instability drives combustion of flamelets
- τ_{R-T} mixing time independent of fire size
- $\overline{\dot{q}'''} = 1110 \ kW/m^3$ independent of fire size
- Radiant Fraction, χ_R , independent of fire size
- Incompleteness of Combustion, χ_I , independent of fire size

Outline

- Rayleigh-Taylor Instabilities drive $\bar{\dot{q}}'''$ of buoyant turbulent diffusion flames.
- Smoke-Point, ℓ_S, correlates χ_I .
- Diagrammatic and Mathematical models for χ_R and χ_I .
- Comparison of model with experiment for burning in air.
- Correlation of χ_R measurements in general atmospheres.
- Model for flame radiation absorption coefficients in terms of . $\Delta H_C, S$ and ℓ_S
- Recommendations

Definitions:

$$\chi_R = \frac{\dot{Q}_R}{\dot{M}\Delta H_C}; \quad \chi_{conv} = \frac{\dot{Q}_{conv}}{\dot{M}\Delta H_C}; \quad \chi_I = \frac{\dot{Q}_I}{\dot{M}\Delta H_C}$$

Conservation of Energy

$$\dot{M}\Delta H_C = \dot{Q}_R + \dot{Q}_{conv} + \dot{Q}_I$$

$$1 = \chi_R + \chi_{conv} + \chi_I$$

$$\chi_R = 1 - \left(\chi_{conv} + \chi_I\right)$$

Available chemical energy per unit flame mass

$$h_{ch} - h_0 = \Delta H_C / \left(1 + S\right)$$

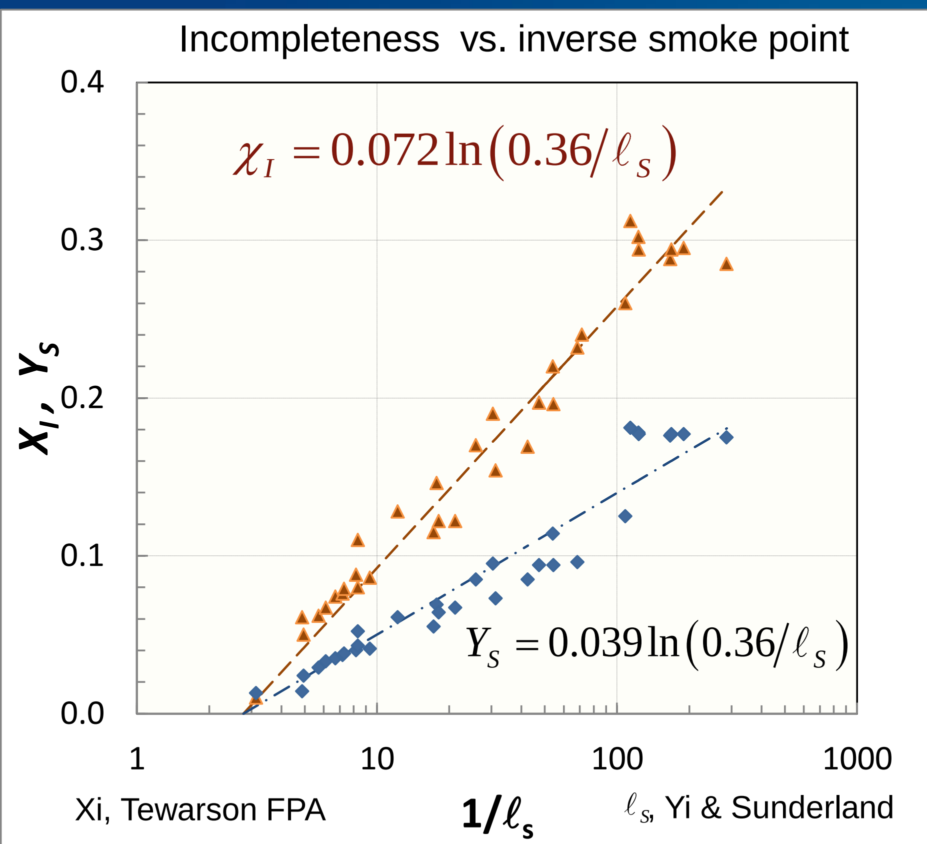
S is the stoichiometric air/fuel mass ratio

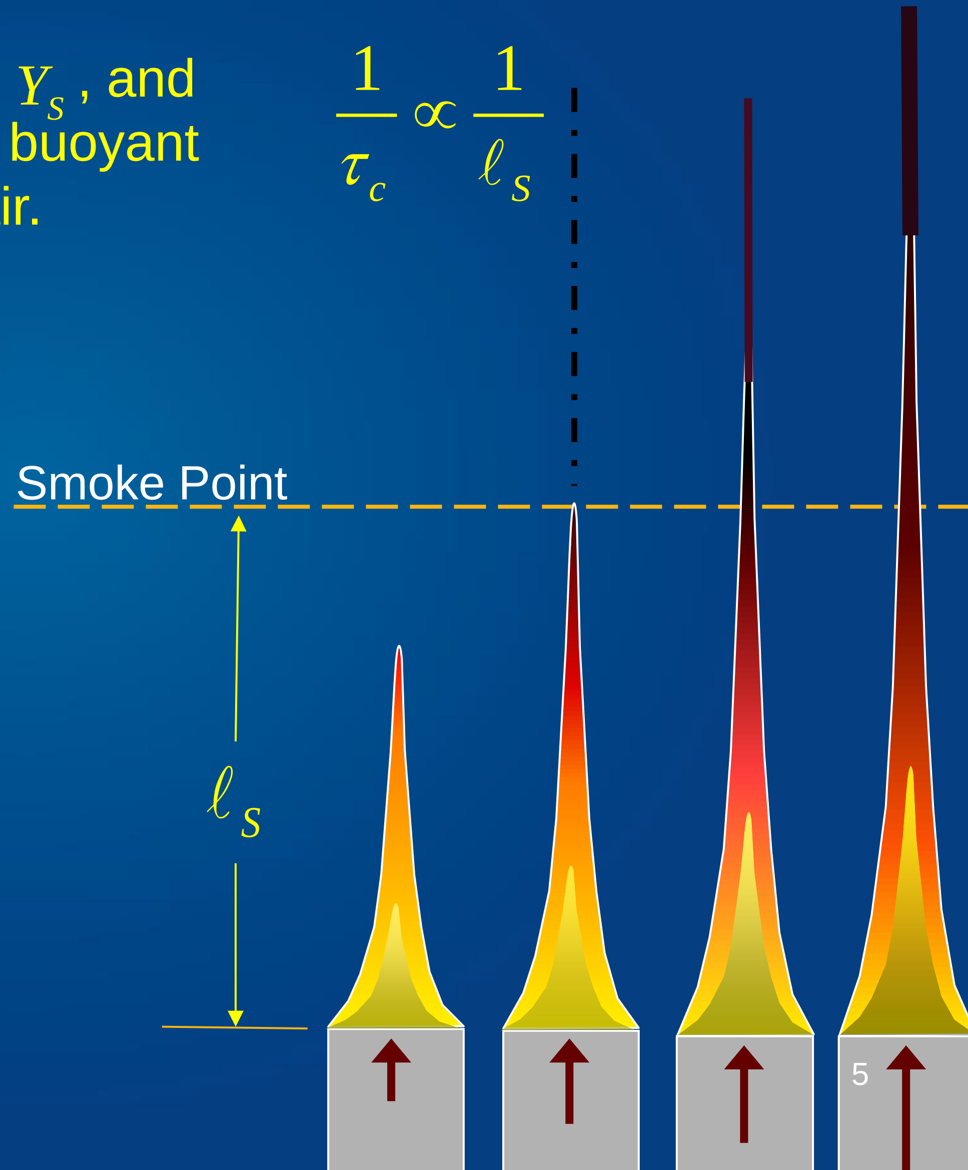
Soot formation rate is inversely proportional to smoke point flame height

Smoke point correlates the soot yield, Y_S , and incompleteness of combustion, χ_I , of buoyant turbulent diffusion flames burning in air.

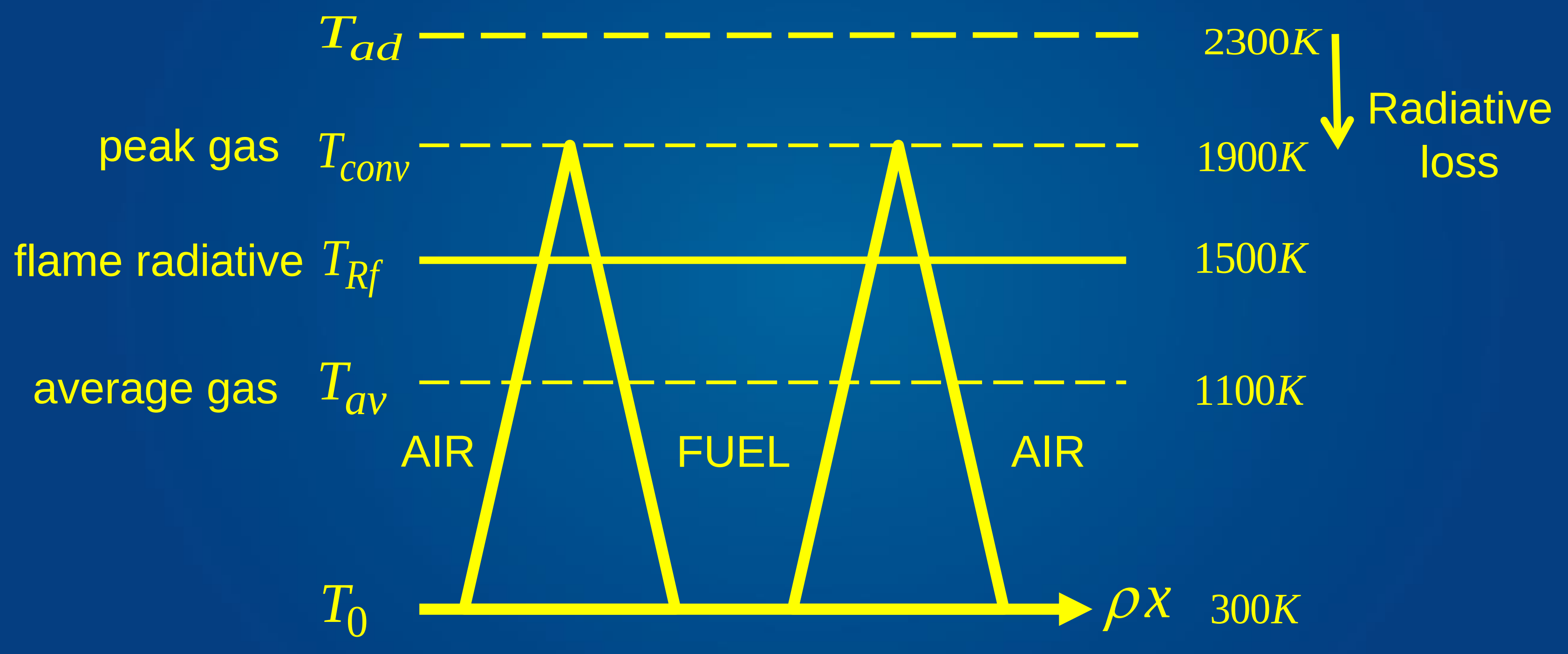
τ_{R-T} is constant

$$\frac{1}{\tau_c} \propto \frac{1}{\ell_S}$$





Coupling between effective flame radiation temperature [$\left(\overline{T_{Rf}^4}\right)^{1/4}$] and peak gas temperature T_{conv}



$$T_{Rf} - T_0 = 3/4\left(T_{conv} - T_0\right)$$

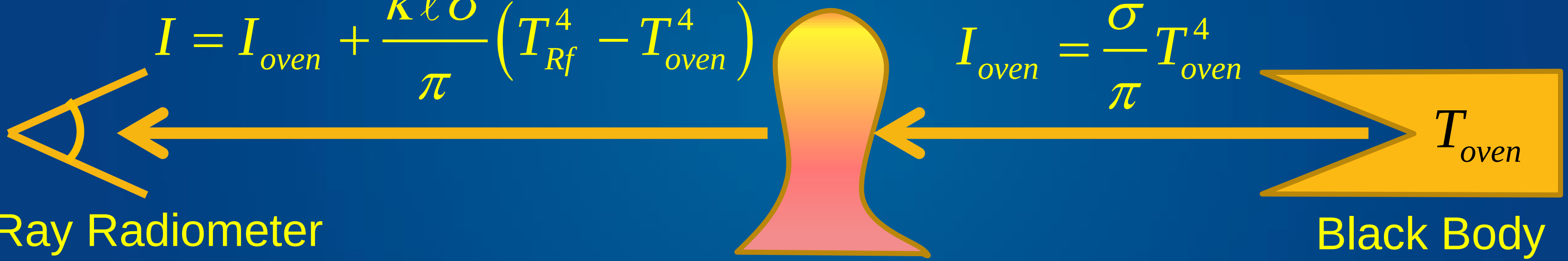
T_{Rf} is sometimes called the Schmidt temperature

Effective Flame Radiation Temperature - T_{Rf}

Schmidt Temperature Measurement

$$I = I_{oven} + \frac{\kappa \ell \sigma}{\pi}\left(T_{Rf}^4 - T_{oven}^4\right)$$

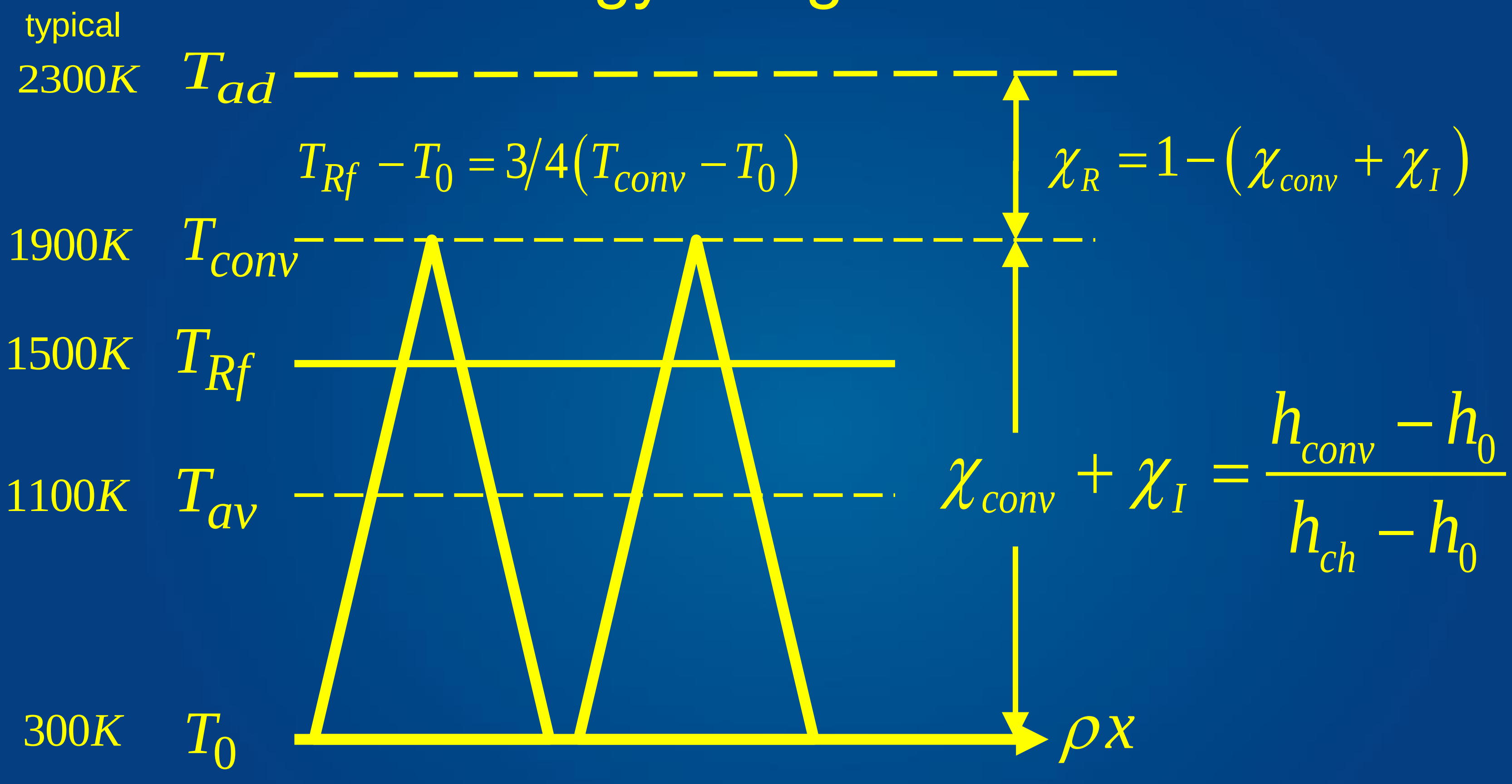
$$I_{oven} = \frac{\sigma}{\pi} T_{oven}^4$$



Flame Absorption equals Flame Emission when the temperature of the block body source, $T_{oven} = T_{Rf}$

$$T_{oven} = T_{Rf} \Rightarrow T_{Schmidt}$$

Energy Diagram



$$\chi_R = 1 - \frac{h_{conv} - h_0}{h_{ch} - h_0} = 1 - \frac{4}{3}\frac{C_P\left(T_{Rf} - T_0\right)}{h_{ch} - h_0}$$

Governing Equation

$$\chi_R = 1 - \frac{h_{conv} - h_0}{h_{ch} - h_0} = 1 - \frac{4}{3}\frac{C_P\left(T_{Rf} - T_0\right)}{h_{ch} - h_0}$$

Non-Dimensional Transformation

$$T_{\text{Ref}} = 1500K; \quad h_{\text{Ref}} = \frac{4}{3} C_P T_{\text{Ref}} = 2.79\, kJ/g; \quad \zeta = \frac{T_{Rf}}{T_{\text{Ref}}}; \quad \zeta_0 = \frac{T_0}{T_{\text{Ref}}};$$

$$\zeta_{ch} - \zeta_0 = \frac{h_{ch} - h_0}{h_{\text{Ref}}} = \frac{\Delta H_C}{h_{\text{Ref}}\left(1 + S\right)};$$

$$\chi_R = 1 - \frac{4/3 C_P\left(T_{Rf} - T_0\right)}{h_{ch} - h_0} = 1 - \frac{4/3 C_P T_{\text{Ref}}\left(\zeta - \zeta_0\right)}{h_{\text{Ref}}\left(\zeta_{ch} - \zeta_0\right)} = 1 - \frac{\zeta - \zeta_0}{\zeta_{ch} - \zeta_0}$$

mathematical equation relating χ_R & ζ

$$\chi_R = \frac{\zeta_{ch} - \zeta}{\zeta_{ch} - \zeta_0}$$

Radiant Fraction

$$\dot{Q}_R = A_f \sigma \left(T_{Rf}^4 - T_0^4\right)\left[1 - \exp\left(-\kappa \ell_m\right)\right]$$

$$\dot{Q} = \overline{\dot{q}'''} V_f = \left(1110\, kW/m^3\right) V_f$$

$$\chi_R = \frac{\dot{Q}_R}{\dot{Q}} = \frac{A_f \sigma}{\overline{\dot{q}'''} V_f}\left(T_{Rf}^4 - T_0^4\right)\left(1 - \exp\left(-\kappa \ell_m\right)\right)$$

Mean Beam Length $\ell_m = \frac{3.6 V_f}{A_f} \Rightarrow \frac{A_f}{V_f} = \frac{3.6}{\ell_m}$

$$\chi_R = \frac{3.6\kappa\sigma}{\overline{\dot{q}'''}}\left(T_{Rf}^4 - T_0^4\right)\left[\frac{1 - \exp\left(-\kappa \ell_m\right)}{\kappa \ell_m}\right] \xrightarrow[\kappa \ell_m \to 0]{} \frac{3.6\kappa\sigma}{\overline{\dot{q}'''}}\left(T_{Rf}^4 - T_0^4\right)$$

Flame radiation comes from both soot and gases

Physical Governing Equation

$$\chi_R = 1 - \frac{h_{conv} - h_0}{h_{ch} - h_0} = 1 - \frac{4}{3}\frac{C_P\left(T_{Rf} - T_0\right)}{h_{ch} - h_0} = \frac{3.6\kappa\sigma}{\overline{\dot{q}'''}}\left(T_{Rf}^4 - T_0^4\right)$$

Non-Dimensional Transformation

$$T_{\text{Ref}} = 1500K; \quad h_{\text{Ref}} = \frac{4}{3}C_P T_{\text{Ref}} = 2.79\,kJ/g; \quad \zeta = \frac{T_{Rf}}{T_{\text{Ref}}}; \quad \zeta_0 = \frac{T_0}{T_{\text{Ref}}};$$

$$\zeta_{ch} - \zeta_0 = \frac{h_{ch} - h_0}{h_{\text{Ref}}} = \frac{\Delta H_C}{h_{\text{Ref}}\left(1 + S\right)}; \quad U = \frac{3.6\sigma T_{\text{Ref}}^4 \kappa}{\overline{\dot{q}'''}}\left[\frac{1 - \exp\left(-\kappa \ell_m\right)}{\kappa \ell_m}\right]$$

$$\chi_R = 1 - \frac{4/3 C_P\left(T_{Rf} - T_0\right)}{h_{ch} - h_0} = 1 - \frac{4/3 C_P T_{\text{Ref}}\left(\zeta - \zeta_0\right)}{h_{\text{Ref}}\left(\zeta_{ch} - \zeta_0\right)} = 1 - \frac{\zeta - \zeta_0}{\zeta_{ch} - \zeta_0} = U\left(\zeta^4 - \zeta_0^4\right)$$

Mathematical Equation to be solved

$$\chi_R = \frac{\zeta_{ch} - \zeta}{\zeta_{ch} - \zeta_0} = U\left(\zeta^4 - \zeta_0^4\right)$$

Mathematical Model 5

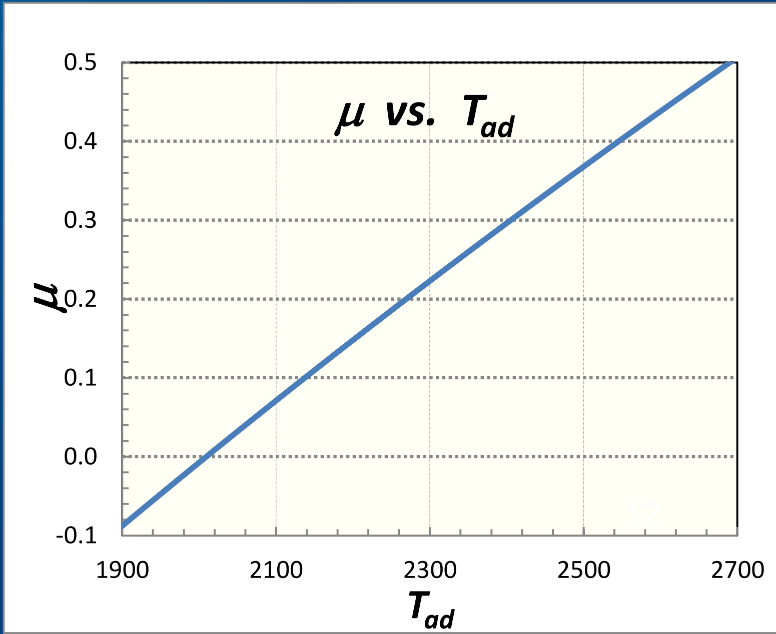
$$\chi_{Ra} = \frac{\zeta_{ch} - \zeta}{\zeta_{ch} - \zeta_0} = \underbrace{\frac{\zeta_{ch} - 1}{\zeta_{ch} - \zeta_0}}_{\mu} + \underbrace{\frac{1 - \zeta}{\zeta_{ch} - \zeta_0}}_{\chi_{Ia}} = \mu_a + \chi_{Ia} \quad \text{in air}$$

What is μ ?

$$\chi_{Ia} = Max\left(0, \chi_{Ra} - \mu_a\right)$$

$$\mu = \frac{\zeta_{ch} - 1}{\zeta_{ch} - \zeta_0} = 1 - \frac{\left(1 - \zeta_0\right)}{\zeta_{ch} - \zeta_0} = 1 - \frac{0.8 h_{\text{Ref}}}{\Delta H_C / \left(1 + S\right)}$$

1. μ is a function of $\Delta H_C, S, T_0$ and h_{Ref}
2. approximately linear function of T_{ad}
3. empirically, χ_R is a linear function of μ
4. also, $\chi_I = 0$ if $\chi_R \le \mu$ or $\zeta \ge 1$



THREE CASES:

1. Complete oxidation of soot: $\chi_I = 0$

   $T_{Rf} \geq 1500K \Rightarrow$ all soot is eventually oxidized

   Unusual for fuels burning in air

2. Partial oxidation and release of soot : $0 \leq \chi_I \leq 0.2$

   $1200K \leq T_{Rf}` < 1500K$ with $T_{conv} \geq 1500K$

   all fuel pyrolyzes in flame

   Typical of aliphatic hydrocarbons

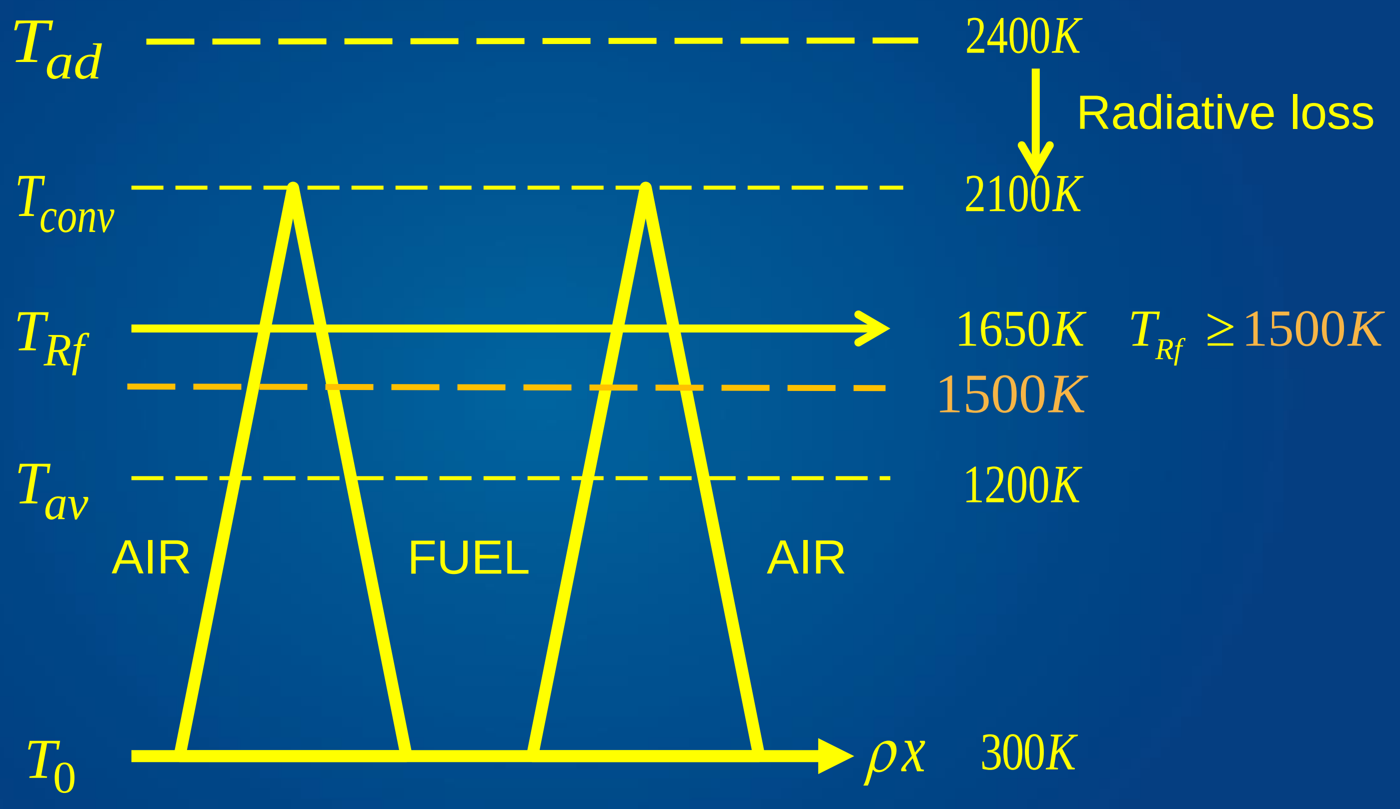
3. Copious soot formation: $\chi_I > 0.2$

   some fuel decomposes at low temperatures and bypasses flame

   $T_{Rf}` < 1200K$ and $T_{conv} \leq 1500K$

   Typical of aromatic hydrocarbons

CASE 1. Complete oxidation of soot $\chi_I = 0$ and $\zeta = \frac{T_{Rf}}{1500K} \geq 1$

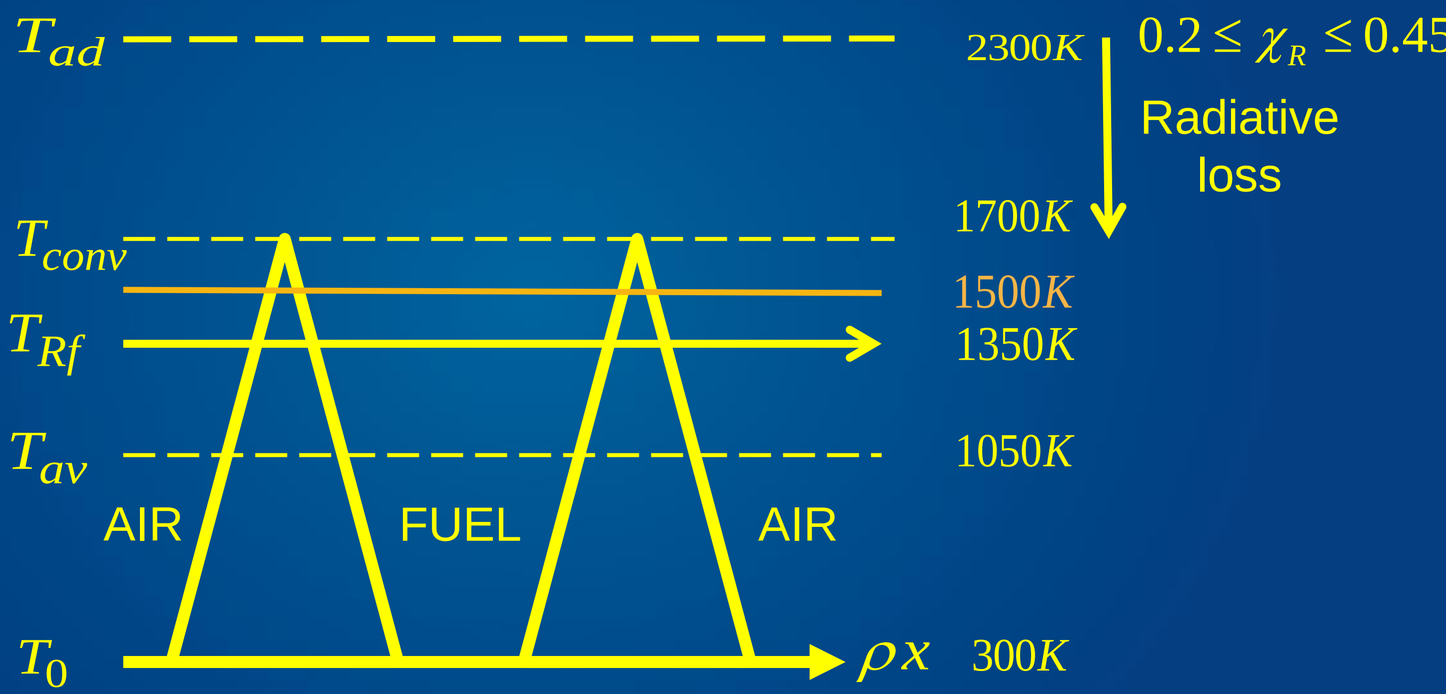


Unusual case

Examples: CH_4 or C_2H_6 burning in O_2 enhanced air

CASE 2. Partial oxidation and release of soot $1200K \leq T_{Rf}` < 1500K$

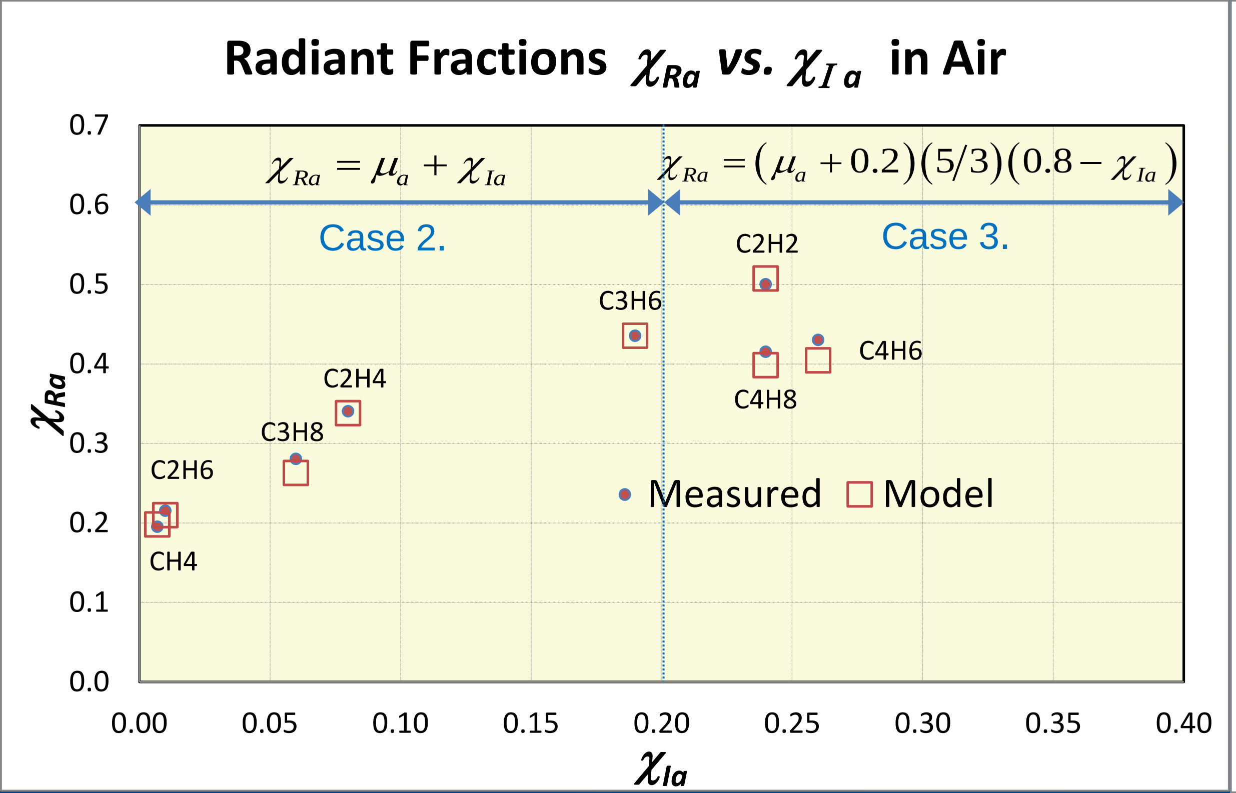
$0 < \chi_I \leq 0.2$ and $0.8 \leq \zeta < 1$ $T_{conv} \geq 1500K$

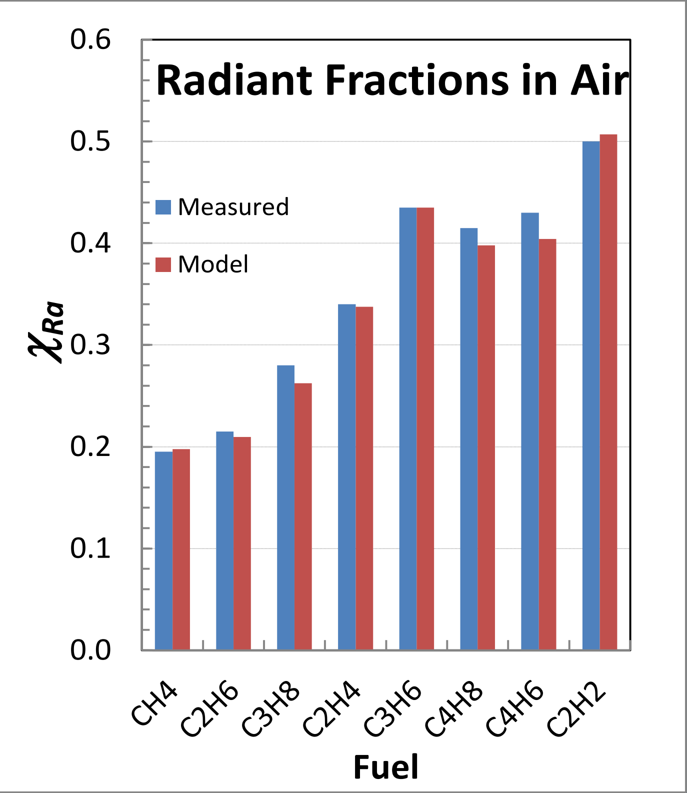


All fuel decomposes in flame

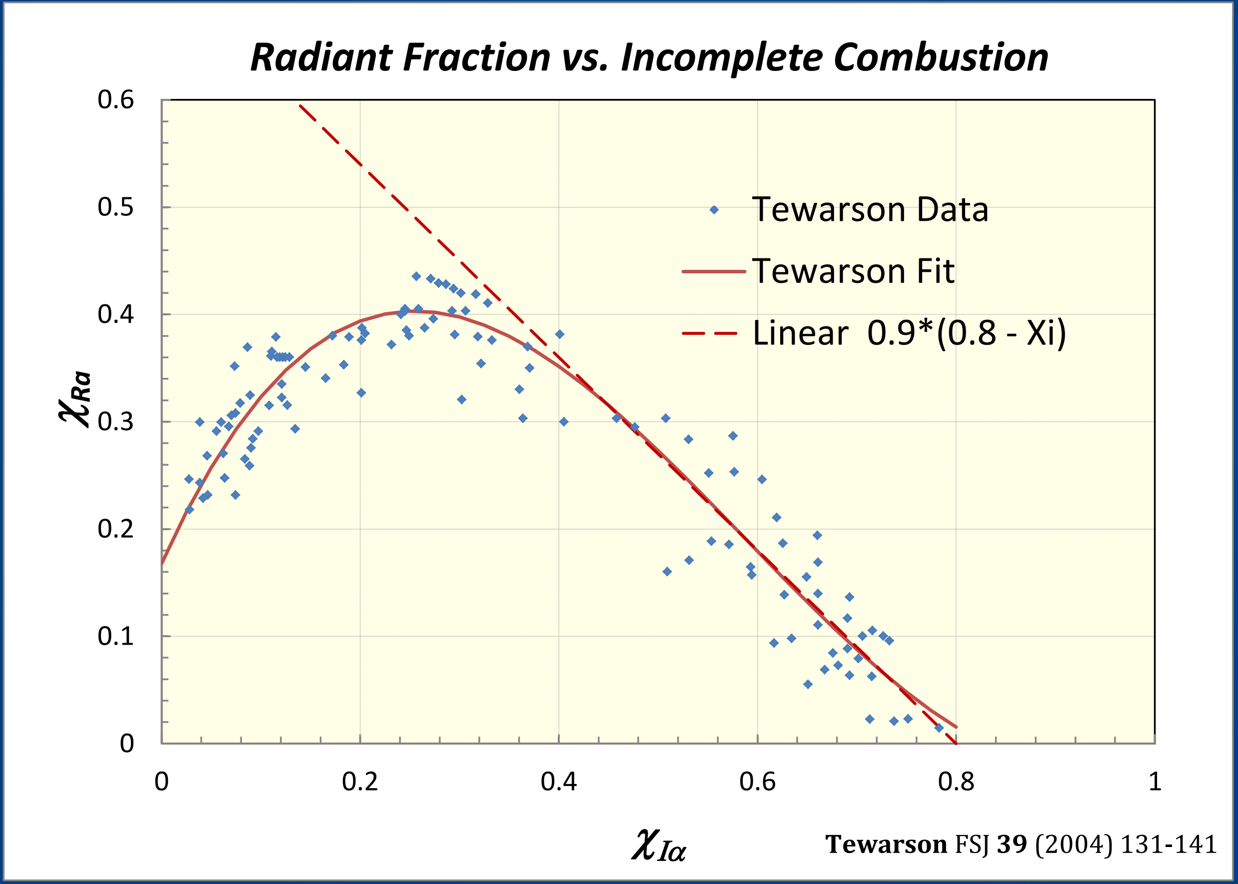
Typical of aliphatic hydrocarbons

Comparison with Experiment





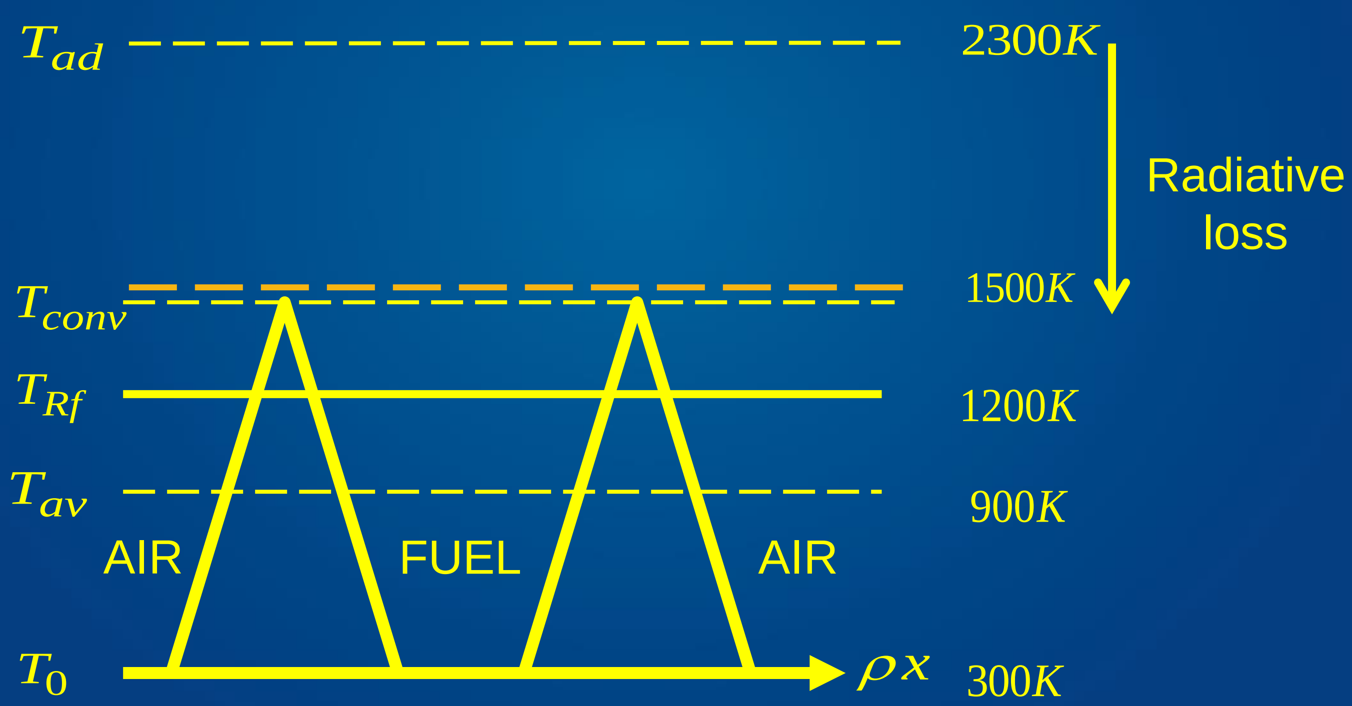
CASE 3. Extremely sooty flames
Tewarson FPA measurements



CASE 3. Copious soot formation with some fuel decomposing at low temperatures and bypassing flame

$T_{Rf}` < 1200K$ and $T_{conv} \leq 1500K$ $0.2 < \chi_I$ and $\zeta \leq 0.8$

Also, T_{conv} being less than $\leq 1500K$ results in some flame extinguishment.



Aromatic hydrocarbons typically burn according to Case 3.

CASE 3. Copious soot formation with some fuel decomposing at low temperatures and bypassing the flame

Let $\chi_{IB} = \chi_I - 0.2$ be the fuel bypassing the flame.

$\chi_R + \chi_{conv} + 0.2 + \chi_{IB} = 1$ or

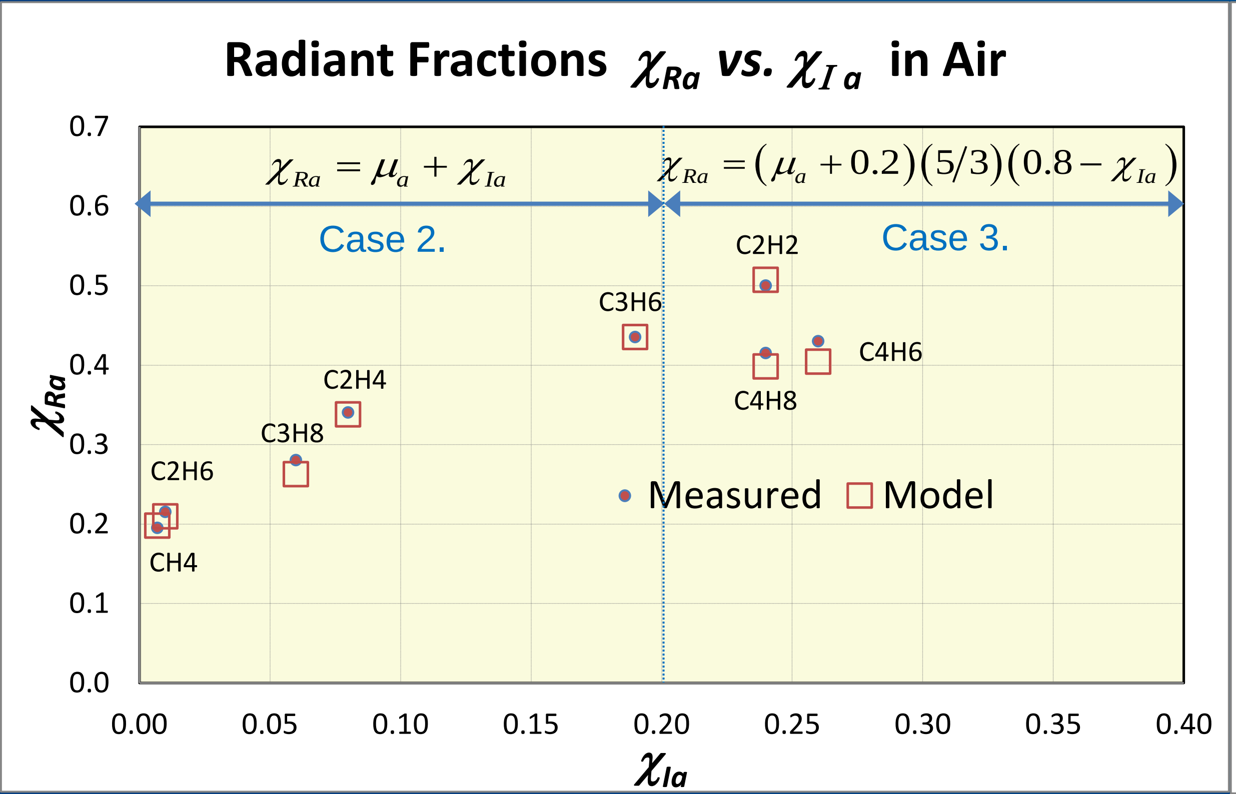
$$\frac{\chi_R}{1-\chi_{IB}} + \frac{\chi_{conv}}{1-\chi_{IB}} + \frac{0.2}{1-\chi_{IB}} = 1$$

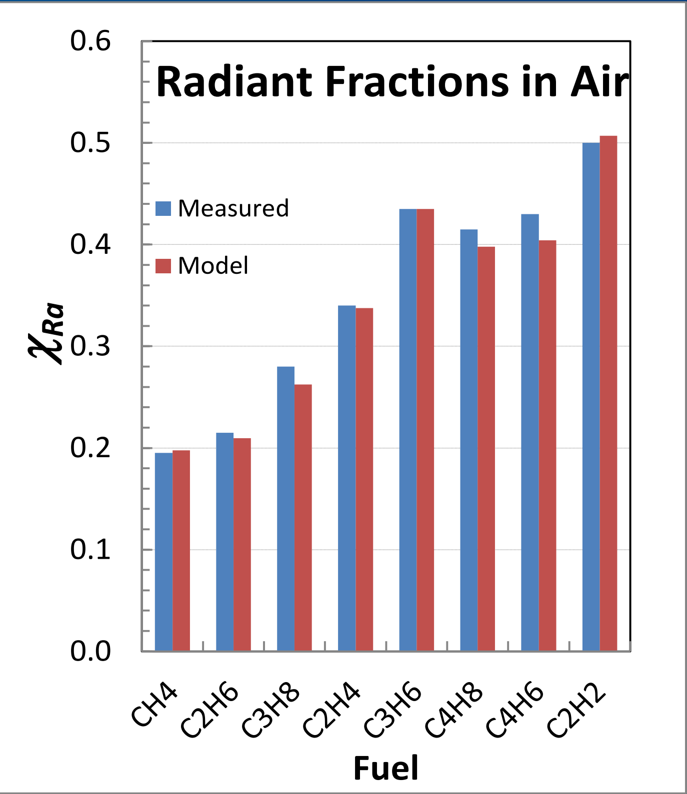
$$\zeta_{ch} - \zeta_0 = \frac{\Delta H_C \left(1-\chi_{IB}\right)}{\left(1+S\left(1-\chi_{IB}\right)\right)h_R} \cong \frac{\Delta H_C}{\left(1+S\right)h_R}$$ assuming $S \gg 1$.

$$\frac{\chi_R}{1-\chi_{IB}} = \underbrace{\frac{\zeta_{ch}-\zeta}{\zeta_{ch}-\zeta_0}}_{\chi_R} = \underbrace{\frac{\zeta_{ch}-1}{\zeta_{ch}-\zeta_0}}_{\mu} + \underbrace{\frac{1-\zeta}{\zeta_{ch}-\zeta_0}}_{0.2} = \mu + 0.2$$

$$\chi_R = \left(\mu+0.2\right)\left(1-\chi_{IB}\right) = \left(\mu+0.2\right)\left(1.2-\chi_I\right) \simeq \left(\mu+0.2\right)\frac{5}{3}\left(0.8-\chi_I\right)$$

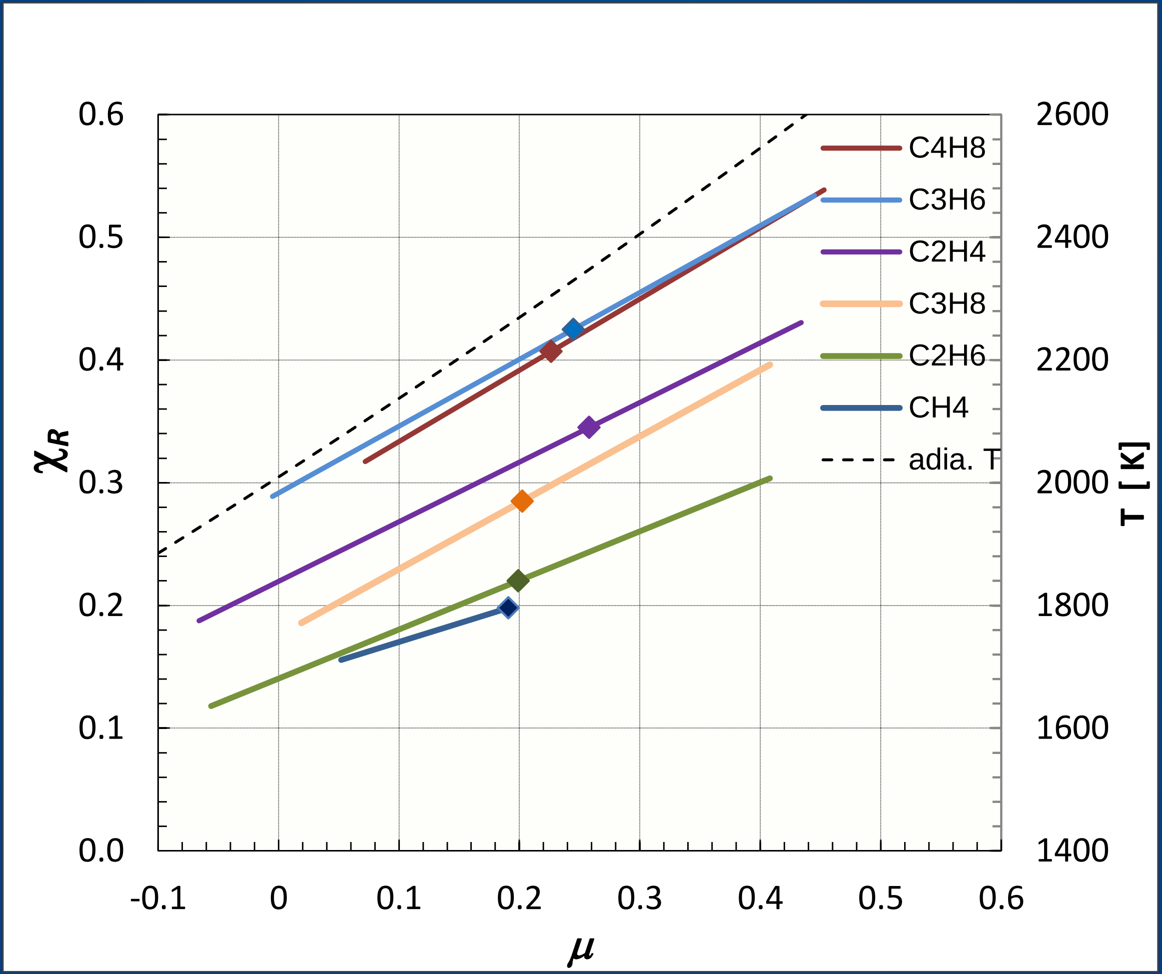
Comparison with Experiment





General Correlations of Radiant Fractions

$$\chi_{Rj} = \chi_{Raj} + \delta_{1j}\left(\mu - \mu_{aj}\right) + \delta_{2j}\left(\sqrt{S} - \sqrt{S_{aj}}\right) \text{ for each fuel "j"}$$



Linear correlations provide a amazingly good fit.

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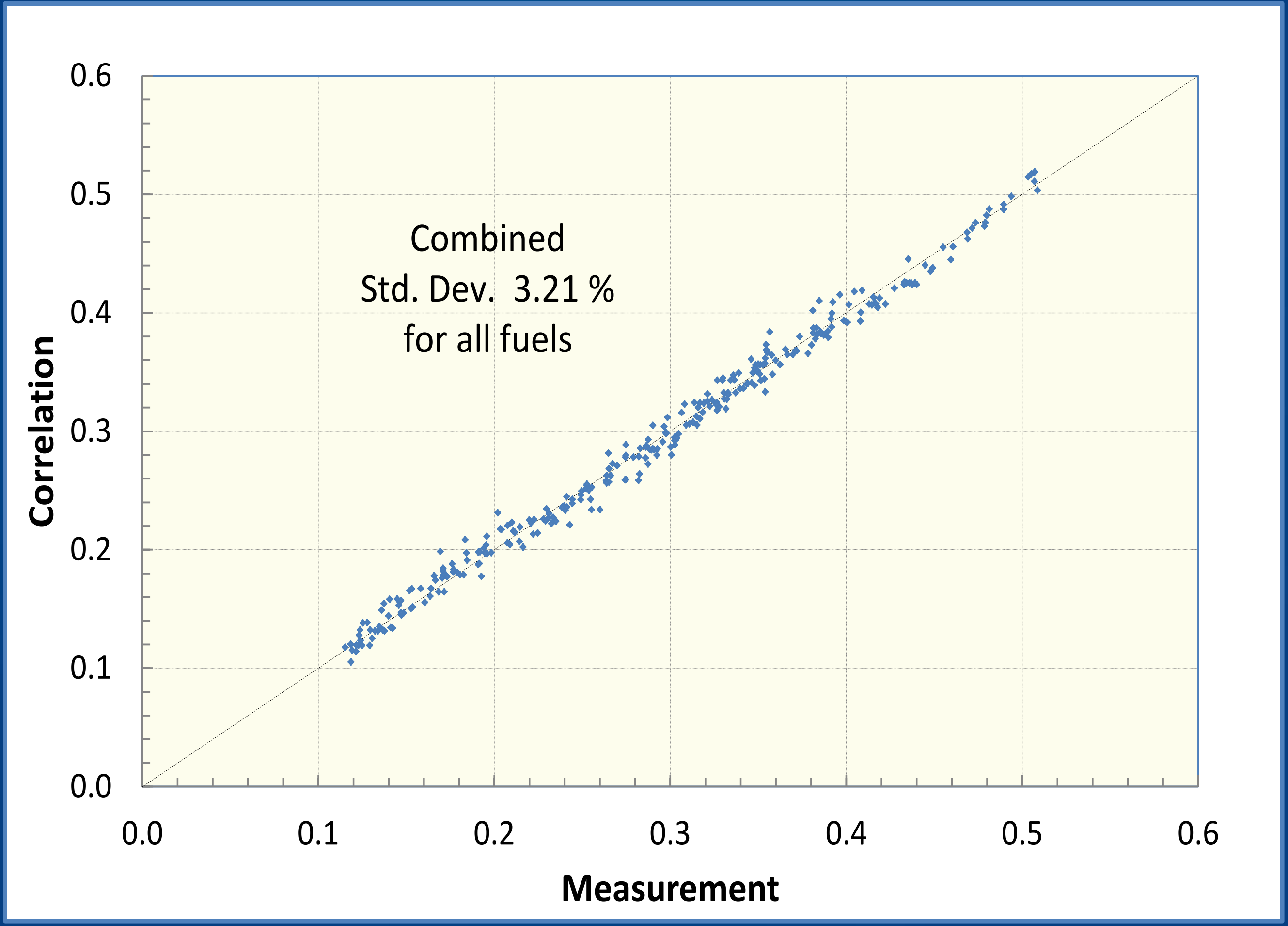
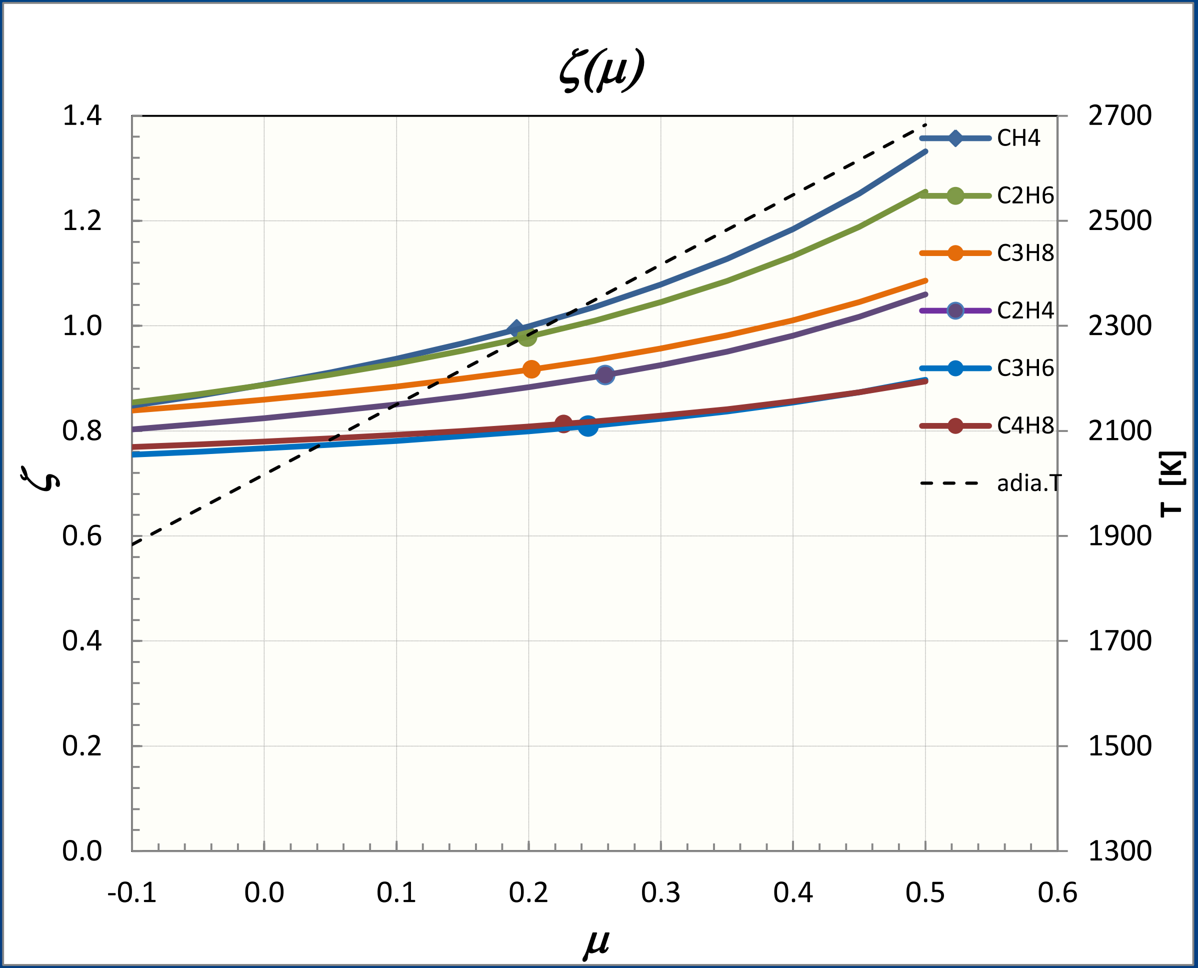


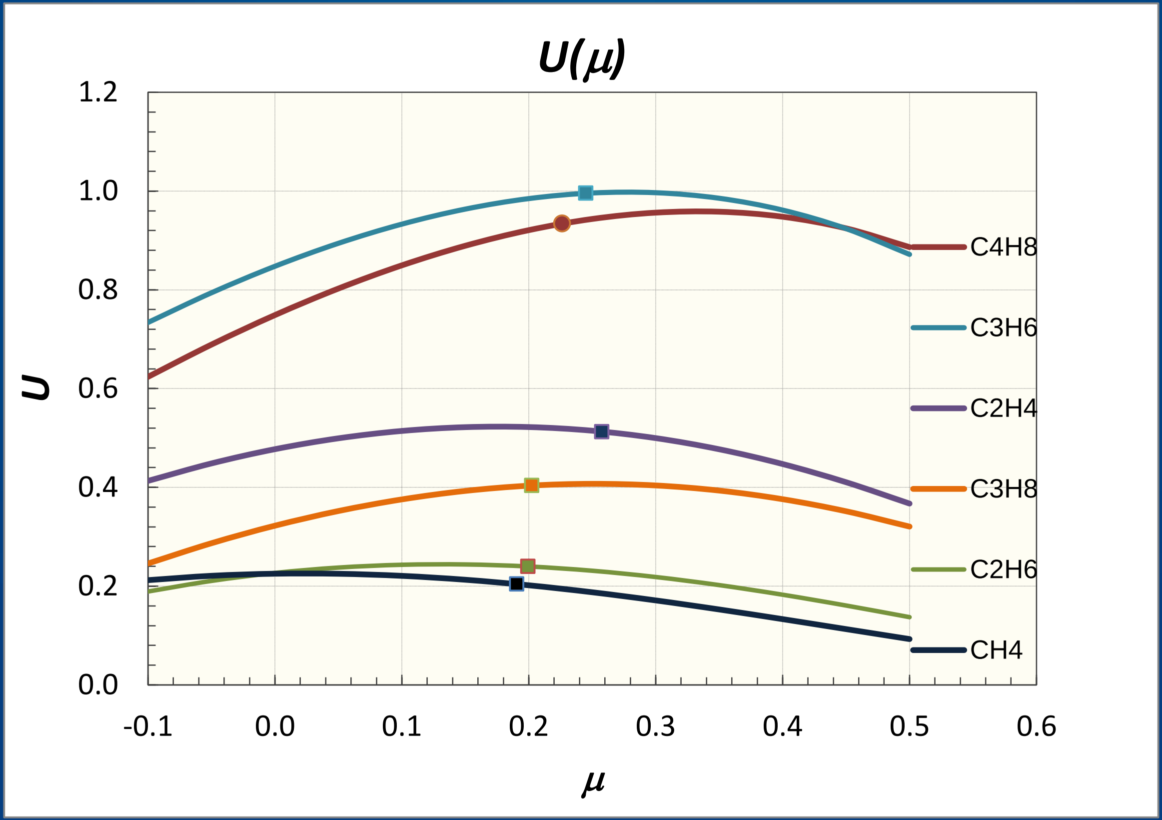
Solving for effective flame radiative temperature

$$\zeta = T_{Rf} / 1500K \qquad \zeta(\chi_R, \mu)$$

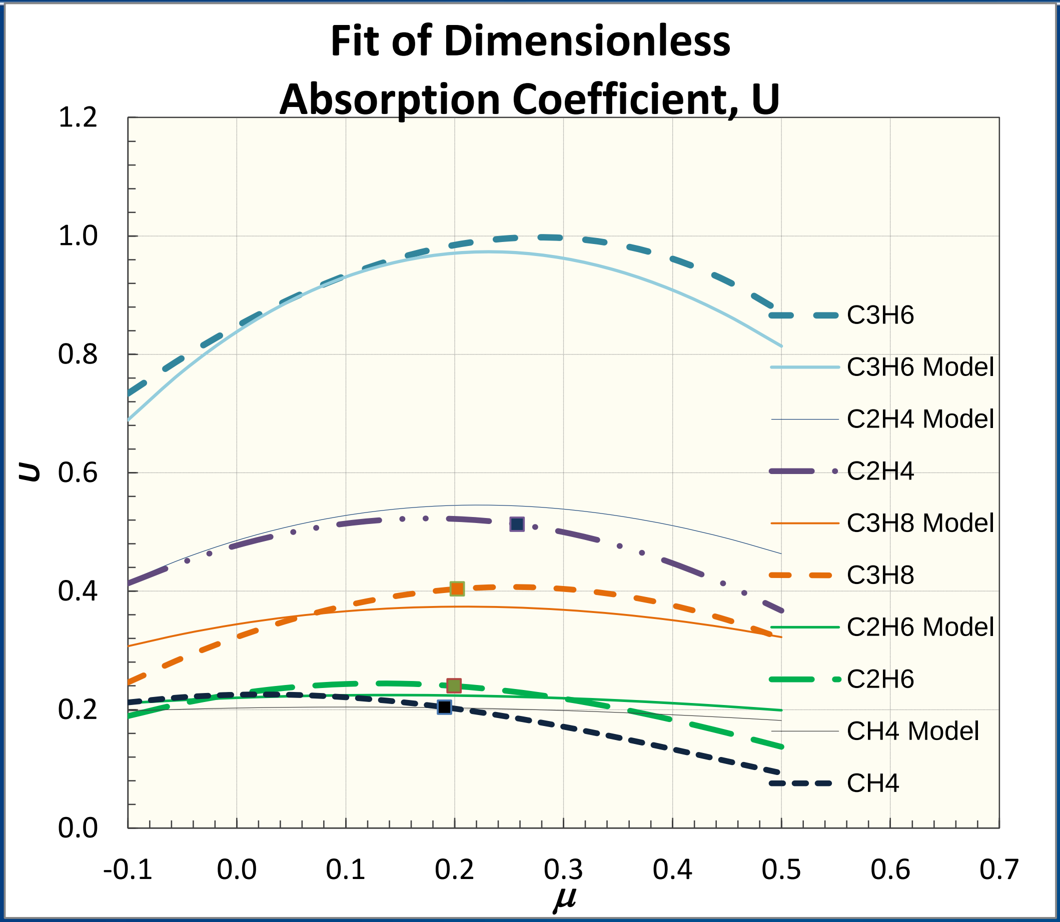


Dimensionless Absorption Coefficient $U = \dfrac{3.6\sigma T_{\text{Ref}}^4 \kappa}{\bar{\dot{q}}'''}$

From the radiation equation $\chi_R = \dfrac{\zeta_{ch} - \zeta}{\zeta_{ch} - \zeta_0} = U\left(\zeta^4 - \zeta_0^4\right)$



$$U\left(\Delta H_C, S, \ell_S\right)$$



$$U = \frac{3.6\sigma T_{\mathrm{Ref}}^4 \kappa}{\bar{\dot{q}}'''}$$

$$U \cong 0.15\left(\frac{2200}{T_{ad}}\right)^{1/2} + \left[0.037 + 0.33\ln\left(\frac{0.36}{\ell_{Sa}}\right)\right]\left[\sqrt{S} - \sqrt{15}\right]P(x); \quad x = \mu - 0.24$$

$$P(x) = \frac{(x-\mu_L)(x-\mu_H)}{\mu_H^2 \mu_L^2}\left((x+\mu_H)(x+\mu_L) - x^2\right); \quad \mu_L = -0.55; \quad \mu_H = 0.65$$

Conclusions

- Rayleigh-Taylor Instabilities drive the combustion of buoyant turbulent diffusion flames.
- Smoke-Point, ℓ_S, correlates χ_I .
- Diagrammatic and Mathematical models for χ_R and χ_I .
- Excellent comparison with experiment for burning in air.
- Correlation of χ_R measurements in general atmospheres.
- Predictions of flame radiation absorption coefficients in terms of $\Delta H_C, S$ and ℓ_S .

Recommendations

1. Apply existing model to predict:
   - pool fire burning rates
   - wall fire radiant heat transfer rates
2. Measure χ_I in general atmospheres using the FPA
3. Model soot mantle surrounding very large pool fires
4. Measure & model effect of wind on pool fires burning rates