Laminar Flames

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\[ T_i \quad \text{combustion} \quad T_f \]

\[ \text{h.t. combustion} \quad \text{Area} \cdot \lambda \frac{\Delta T}{S} \]

\[= \dot{m} c_p (T_i - T_0) \quad \dot{m} = \rho \text{Vel} \text{ Area} \]

\[ \text{Vel} = S_L \]

\[ \rho S_L c_p (T_i - T_0) = \lambda \frac{\Delta T}{S} \]

\[ S = S_L \cdot \text{Reaction Time} = S_L \cdot \frac{\Delta T}{S} \]

\[ m = \frac{\dot{m}}{S} = \frac{1}{\text{RR}} \]

\[ \gamma = \frac{1}{\text{Reynolds Number}} = \frac{1}{RR} \quad S = S_L / RR \]

\[ \Delta T \quad \text{combustion} \]

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\[ S_l = \frac{\alpha}{S} \left( \frac{T_s - T_i}{T_i - T_o} \right) = \frac{\alpha \cdot RR}{S_l} \left( \frac{T_s - T_i}{T_i - T_o} \right) \]

\[ S_l^2 = \alpha \cdot RR \left( \frac{T_s - T_i}{T_i - T_o} \right)^{\frac{1}{2}} \]

Overall Reaction Order

\[ F + xO \rightarrow yCO_2 + zH_2O \]

\[ -\frac{d[F]}{dt} = y \frac{d[CO_2]}{dt} = A T^{n^*} e^{-E_A/RT} [F]^m [O_2]^n \]

Fit to \( A, n^*, E_A, n, m \)

\( n + m \rightarrow \) overall reaction order

\( n \approx 0.1 \text{ to } 0.2 \)

\( m \approx 1.5 \)

Overall order \( 1.5 - 2 \)

\[ \frac{d[A]}{dt} = -k[A]^n \quad n = \text{rate order} \]
\[
\frac{d[A]}{dt} = -k \frac{(A)^n}{M_A} \\
[A] = \frac{N_A}{V} = \frac{\bar{M}_A N_A}{\bar{M}_A V} = \frac{m_A}{V} \frac{1}{\bar{M}_A} = \frac{p_A \bar{M}_A}{\bar{M}_A} \frac{1}{p_A} \\
\frac{d(p_A)}{dt} = -k^* (p_A)^n \\
\frac{dY_A}{dt} = RR = -k^* p^{-1} Y_A^n \\
p^{n-1} = \frac{p^{n-1}}{(RT)^{n-1}} \\
RR \sim p^{n-1} \\
S_l \sim \alpha^{n/2} R^{n/2} \\
\alpha = \frac{\lambda}{p^0} \\
\frac{1}{p} \sim \frac{1}{p} \\
S_l \sim (\frac{1}{p} p^{n-1})^{n/2} = (p^{n-2})^{n/2} \\
S_l \sim p^{n-2} \\
S = \frac{S_l}{RR} \sim \frac{p^{n-2}}{p^{n-1}} \Rightarrow \frac{n-1}{n+1} = p^{-n/2} \\
S \sim p^{-1} \\
\text{if } n = 2
Zeldovich, Frank-Kamenetski, & Semenov

Assume \( n = 2 \) \( k = A e^{-E_A/RT_f} \) \( \lambda \) \( \rho \) don't change much \( \lambda \approx \frac{\rho}{\rho_c} \)

\[
S_L = \left\{ \frac{2 \lambda_c^2 \rho^3}{\beta_c} \left[ \frac{1}{T_0} \left( \frac{N_{\text{prod}}}{N_{\text{react}}} \right) \left( \frac{1}{E_c} \right) \left( \frac{RT_f^2}{E_A} \right) - \frac{E_A}{(T_f - T_0)^2} \right] \right\}^{1/3}
\]

Strong \( T_f \) dependence

Hottel flames = faster \( S_L \)

\[
H_2 + \frac{1}{2} O_2 \rightarrow H_2O
\]

\[
H_2 + \frac{1}{2} O_2 + \frac{3.76}{2} N_2 \rightarrow H_2O + \frac{3.76}{2} N_2
\]

\[
N_2 = C_P \sim \frac{3}{2} R + R - \frac{S}{2} R
\]

\[
S_P \Delta T \rightarrow T_f \rightarrow \frac{S}{10} \rightarrow \frac{C_P dT}{10}
\]
\[
\text{trans} \\
\text{Halon Fine extinguishers} \\
L \rightarrow \text{halogen} \quad \text{Br}, \text{Cl}, F = X
\]

\[
\text{H}X + H \rightarrow H_2 + X
\]

\[
X + X + M \rightarrow X_2 + M
\]

\[
X_2 + H \rightarrow XH + X
\]

\[
H + H \rightarrow H_2
\]

\[
\text{HCl, HF}
\]

\[
\varnothing, \varphi_v, \varphi_L, S_L, \eta
\]

quenching distance

\[
\text{\textoplus}\ (\text{\textoplus}) \quad J
\]
Area wall vs. area flame

\[ \frac{\pi d^2}{4} \rightarrow \pi d \delta \]

\( q_{\text{wall}} = A \times \frac{\delta t}{2r} \rightarrow \text{wall} \)

Radical recomb.

\[ \text{HeD} \rightarrow \text{O-H} \]

- M - H - M -

- M M - M
\( \chi_0 \)

\[ \text{3000kL} \]

\[ \text{127 O} \]

\[ \text{02} \]

\[ \text{W.D.M} \]

d_t varies w/P, \( \phi \)

\[ d_t \sim \frac{1}{p} \]

Flashback arrestor

Flow
Flame stabilization

Flow too low
⇒ Flashback

Flow to high
⇒ Blow off

Always a region near well where \( U < S_L \)

Flame cannot propagate
\[ w/i \sim \frac{dT}{2} \text{ of wall} \]

Flow in tube
\[ m_{\text{tube}} = m_{\text{flame surf}} \]

\[ \rho_{\text{tube}} \overline{A}_{\text{tube}} \overline{U}_{\text{tube}} = P_s A_s S_{\text{fixed}} \Rightarrow \text{cone area} \]
\[ u = \pi \left( R^2 - r^2 \right) \]

\[ Q = V = \text{volume flow rate} \]

\[ = \int_0^R 2\pi r \, u \, dr \]

\[ = 2\pi \int_0^R r^2 - r^3 \, dr \]

\[ = 2\pi \left[ \frac{1}{2} R^4 - \frac{1}{4} R^4 \right] \]

\[ = \frac{\pi}{2} R^4 \]

\[ n = \frac{2Q}{\pi R^4} \]

**Velocity gradient at wall**

\[ g = -\frac{\partial u}{\partial r} \bigg|_{r=R} = 2\pi n \bigg|_{r=R} = \frac{2R \cdot 2Q}{\pi R^4} \]

\[ = 4Q \]
\[ \dot{U} = \frac{Q}{A} = \frac{Q}{\pi R^2} \]

\[ g = \frac{4 \dot{U}}{R} \]

Critical condition:
\[ g > \frac{\Delta U}{\Delta r} = \frac{S_L - 0}{d^{1/2}} = \frac{2 S_L}{d} \to \frac{\partial S_L}{\partial t} \]

\[ q_F = \frac{2 S_L}{d} \]

No F.B.
\[ \frac{8 \dot{U}}{d} > \frac{2 S_L}{d} \to \text{to avoid F.B.} \]

\[ \Delta \text{increases} \]

\[ I \quad \phi \]

\[ \text{No B.D.} \quad \text{F.B.} \quad \text{ambient air} \]

\[ \text{ambient air} \]

\[ \text{ambient air} \]
Practical burner design

- no F.I.B. \( g > g_f \)
- no B.O. \( g < g_b \)
- \( D > d_T \) → avoids large burner h.r.l. losses
- \( \bar{u} > 2s_L \) for stability
- \( \bar{u} < 5s_L \) → unburned fuel passes thru tip
- \( Re < 2000 \) not turbulent

\[ \bar{u} = \frac{g_b d}{8} \]
$S_0, n, \phi, \phi_0, \phi_L, d_T$