Diffusion Flame Images

Video images of ethane jet diffusion flames in quiescent air in 1g and µg. Burner tube inside diameter= 2.87 mm; mean fuel jet velocity=7.5 cm/sec.


Computed Images (from 1 to 200 msec) in terms of temperature field (contours) of a propagating edge diffusion flame in an ethane jet in quasi-quiescent air in 0g. Burner tube diameter= 3 mm; mean fuel jet velocity=6.86 cm/sec.
Flame Images

Spherical Flame Surrounding a Droplet In Microgravity
Burner Configurations

(a) Still air
Ceramic Flow Straightener
Still air

(b) Rich Mixture
Air

Still air
Stainless Steel Burner

(Dimensions are in mm)

Briones and Aggarwal, Physics of Fluid, Vol. 18, 2006
Nonpremixed and Partially Premixed (Double) Flames

Flames Established in a Counterflow Burner

Image of syngas (50%H$_2$-50%CO)/air nonpremixed flame established at p=1 atm, strain rate $a_s = 65 \text{s}^{-1}$.

N-Heptane PPFS showing the double flame structure characteristic of non-premixed and premixed reaction zones. The fuel enters at the bottom and the oxidizer at the top.
Nonpremixed n-Heptane/Air Counterflow Flame

- Good agreement between the predicted and measured flame structures.
Hydrogen-Air Nonpremixed Counterflow Flame
Laminar Nonpremixed (Diffusion) Flames

References: Turns (Chapter 9), Kuo

- Introduction
- Nonreacting Laminar Jet
- Laminar Jet Flame
- Flame Lengths for Circular (Axisymmetric) and Slot burners
- Counterflow flames
- Partially Premixed Flames
Laminar Nonpremixed Flames

Introduction

• Fuel and oxidizer are unmixed before they are transported to the reaction zone (flame).

• Nonpremixed flames are the most common in practical systems. Examples:
  • Burning of liquid fuel droplets (gas turbine, diesel, and rocket engine combustors)
  • Candle flame, match, cigarette lighter
  • Pool fires
  • Burning of solids and liquid-fueled combustors contain significant regions of nonpremixed combustion
  • Most fires involve nonpremixed combustion

• Most residential gas appliances such as furnaces (gas heaters) and cooking ranges involve laminar nonpremixed or partially premixed flames.

• A laminar jet flame represents a fundamental flame, and has been extensively investigated.
Topics and Approaches

- **Important Characteristics**
  - Flame height and shape
  - Flame Structure
  - Emissions

- Scale Analysis
- Constant Density Solution: **Equations 9.8-9.13**
- Solution Based on Flame Sheet Approximation: **Equations 9.23-9.29**.
- Solution Based on the Conserved Scalar Approach, Mixture fraction (f): **Equations 9.23, 9.24, 9.30-9.34**
- Numerical Solution and State Relationships
- Non-Dimensional Equations: **Equations 9.36-9.40**
- Laminar jet flame height: various solutions

Turns: Chapter 9
Laminar Nonpremixed Flames

Significant insight and qualitative information can be gained through scale analysis and constant-density jet analysis.

**Scale Analysis**

The flame height can be estimated by equating the convection time and diffusion time, i.e.

\[
\frac{L_f}{V_e} = \frac{R^2}{D} \quad \Rightarrow \quad L_f \propto \frac{V_e R^2}{D}
\]

- Flame height is proportional to the volume flow rate of fuel and the diffusivity. This result can also be obtained using a scale analysis of the species conservation equation.
- Interestingly, this result has been shown to be valid for both laminar and turbulent diffusion flames. For laminar flames, \(D\) is the molecular diffusion. For turbulent flames, \(D\) is given by the product of a turbulent length scale and a turbulent velocity scale, which are, respectively, proportional to \(R\) and \(V_e\), since the global features such as mixing are determined by large eddies. Then

\[
L_f \propto R
\]
Nonpremixed Flames

Diffusion Flame Regimes.

http://arrow.utias.utoronto.ca/~ogulder/ClassNotes8.pdf
Laminar Nonpremixed Flames

Constant Density Solution

This analysis considers a steady, laminar jet flame, established by a gaseous fuel jet (of radius R) issuing into either quiescent ambient (oxidizer). Major assumptions are:

- Axial diffusion of momentum, species, and thermal energy is negligible compared to radial diffusion.
- Pressure is uniform (isobaric flames): Total momentum flow rate is constant.
- Species diffusion is represented by the Fick’s law, with equal diffusivities for all species.
- Schmidt number (Sc=ν/D) is unity.
- Governing equations (continuity, x-momentum for Vx, and fuel species equation for Yf, (Eqns. 9.3-9.7) are solved analytically using a similarity variable.
- See the solution in Turns book; Eqns. 9.8-9.19 Consequently, Vx(x,r), Vr(x,r), and Yf(x,r) are known.
- From this solution, and using the flame sheet approximation, the flame contour (or shape) and flame height can be computed.
Mixing of a Fuel Jet in Still Air

Distribution of axial velocity and fuel mass fraction in the jet

Figure 9.1 Nonreacting, laminar fuel jet issuing into an infinite reservoir of quiescent air.
Laminar Nonpremixed Flames

Constant Density Solution

From these solutions (Equations 9.8-9.13), one can obtain the jet spreading rate, spreading angle, as well as expressions for the axial velocity and fuel mass fraction along the jet axis.

\[ \frac{V_{x,o}}{V_e} = \frac{Y_{F,o}}{Y_{Fe}} = 0.375 \text{Re}_j \left( \frac{x}{R} \right)^{-1} \]

Then the value of \( x \) corresponding to \( Y_{F,o} = Y_{Fs} \) gives the flame height as

\[ L_F = \frac{0.375V_e R^2}{D Y_{F,S}} = \frac{0.375Q_F}{\pi D Y_{F,S}} \]

Effects of \( V_e, R, Q_F, D, \) and \( Y_{F,S} \) on the flame length can be discussed using this equation.
Laminar Nonpremixed Flames

Analysis Based on the Flame Sheet Approximation

This analysis considers a steady, laminar jet flame, established by a gaseous fuel jet (of radius $R$) issuing into either quiescent ambient (oxidizer) or a coflowing jet. Major assumptions are:

- Axial diffusion of momentum, species, and thermal energy is negligible compared to radial diffusion.
- Three species are considered: fuel, oxidizer, and product. Note, however, the conserved scalar approach can be extended to many species.
- Infinitely fast chemistry (large Damkohler limit) or flame-sheet approximation: The flame is represented by a surface. Fuel and oxidizer are transported to the flame surface in stoichiometric proportions.
- Radiation heat transport is negligible.
- Species diffusion is represented by the Fick’s law, with equal diffusivities for all species.
- Lewis number ($Le=\lambda/(\rho cpD)$) is unity.
- Pressure is uniform (isobaric flames).
Laminar Nonpremixed Flames

Analysis Based on the Flame Sheet Approximation

Flame surface: Locus of points corresponding to stoichiometric conditions
Laminar Jet Flame Length: Various Solutions

1. Constant Density Solution

\[ L_F = \frac{0.375 V_e R^2}{D Y_{F,S}} = \frac{0.375 Q_F}{\pi D Y_{F,S}} \]


3. Roper’ s Correlations (Circular Port):

\[ L_{F,\text{theory}} = \frac{Q_F (T_\infty / T_F)}{4\pi D_\infty . \ln(1 + 1/S)} (T_\infty / T_f) \]

\[ L_{F,\text{exp}} = \frac{1330 Q_F (T_\infty / T_F)}{\ln(1 + 1/S)} \]

S=molar stoichiometric oxidizer-fuel ratio=4.76.(x+y/4), and \( T_F \) and \( T_f \) are the fuel and flame temperatures, respectively.

4. Roper’ s Correlations for Square Port and Slot Burners: Equations 9.61-9.64
Effect of Nozzle Geometry

Methane-Air Diffusion Flames

![Figure 9.9](image)

Predicted flame lengths for circular and slot burners having equal port areas.

Methane-Air Diffusion Flames
Effects of Various Parameters on Flame Length

1. Effect of fuel flow rate \((Q_F)\): \(L_F \propto Q_F\)

2. Effect of Nozzle Shape: Circular, square, slot:
   \(L_F\) decreases as the nozzle aspect ratio increases

3. Effect of Stoichiometry \((S)\):
   As \(S\) increases, \(L_F\) increases.

   \[ S = \frac{x + y/4}{X_{O_2}} \]

   \(L_F \propto \frac{1}{\ln(1 + 1/S)}\)

Effect of fuel

<table>
<thead>
<tr>
<th>Fuel</th>
<th>(x + y/4)</th>
<th>(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH4</td>
<td>2</td>
<td>9.5</td>
</tr>
<tr>
<td>C2H4</td>
<td>3</td>
<td>14.3</td>
</tr>
<tr>
<td>C3H8</td>
<td>5</td>
<td>23.8</td>
</tr>
<tr>
<td>C7H16</td>
<td>11</td>
<td>52.4</td>
</tr>
</tbody>
</table>

Figure 9.10 Dependence of flame length on fuel stoichiometry. Flame lengths for various fuels are shown relative to methane.
Laminar Jet Flame Length: Effects of Various Parameters

4. Effect of Primary Aeration (Partial Premixing):
Addition of air to the fuel jet decreases the flame length. Amount of air added is expressed as a percentage of the stoichiometric requirement. Then S is modified as

\[ S = \frac{1 - (\psi / S_{\text{pure}})}{1 / S_{\text{pure}} + (\psi / S_{\text{pure}})} \]
and

\[ S_{\text{prim}} = \psi / S_{\text{pure}} \]

\[ S_{\text{pure}} = \frac{x + y/4}{X_{O_2}} \]

\[ L_F \propto \frac{1}{\ln(1 + 1/S)} \]

<table>
<thead>
<tr>
<th>( \psi_{\text{prim}} )</th>
<th>S</th>
<th>Lf/Lf0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>2.1</td>
<td>0.26</td>
</tr>
<tr>
<td>0.4</td>
<td>1.2</td>
<td>0.16</td>
</tr>
<tr>
<td>0.5</td>
<td>0.8</td>
<td>0.13</td>
</tr>
</tbody>
</table>

As \( \psi_{\text{prim}} \) increases, S decreases, and \( L_F \) decreases.

Note: As \( \psi_{\text{prim}} \) exceeds 0.5, the flame contains two reaction zones, i.e., partially premixed flame.
Laminar Jet Flame Length: Effects of Various Parameters

5. Effect of oxygen concentration in air

\[ S = \frac{x + y/4}{X_{O_2}} \]

As oxygen mole fraction in air decreases, \( S \) increases and thus \( L_F \) increases.

6. Effect of diluent addition to the fuel stream

\[ S = \frac{x + y/4}{1 - \frac{X_{dil}}{X_{O_2}}} \]

As \( X_{dil} \) is increased, \( S \) decreases, which decreases \( L_F \).
Effect of Primary Aeration (Partial Premixing)

Figure 9.11  Effect of primary aeration on laminar jet flame lengths. For primary aeration greater than the rich limit, premixed burning (and flashback) is possible.

Effect of O₂ Content in Air

Figure 9.12  Effect of oxygen content in the oxidizing stream on flame length.
Partially Premixed (Double) Flames

Methane-air

\( \phi = 1.24 \)
\( V_{in} = 30 \text{cm/s} \)
\( V_{out} = 30 \text{cm/s} \)

\( \phi = 1.43 \)
\( V_{in} = 30 \text{cm/s} \)
\( V_{out} = 30 \text{cm/s} \)

\( \phi = 1.7 \)
\( V_{in} = 37 \text{cm/s} \)
\( V_{out} = 30 \text{cm/s} \)

\( \phi = 2.1 \)
\( V_{in} = 38 \text{cm/s} \)
\( V_{out} = 30 \text{cm/s} \)

Propane-air

\( \phi = 1.5 \)
\( V_{in} = 30 \text{cm/s} \)
\( V_{out} = 30 \text{cm/s} \)

\( \phi = 1.7 \)
\( V_{in} = 30 \text{cm/s} \)
\( V_{out} = 30 \text{cm/s} \)

\( \phi = 1.9 \)
\( V_{in} = 30 \text{cm/s} \)
\( V_{out} = 30 \text{cm/s} \)

\( \phi = 2.1 \)
\( V_{in} = 48 \text{cm/s} \)
\( V_{out} = 30 \text{cm/s} \)
**Governing Equations**

\[
\frac{\partial (\rho \Phi)}{\partial t} + \frac{\partial (\rho v \Phi)}{\partial r} + \frac{\partial (\rho u \Phi)}{\partial z} = \frac{\partial}{\partial r} \left( \Gamma^r \frac{\partial \Phi}{\partial r} \right) + \frac{\partial}{\partial z} \left( \Gamma^z \frac{\partial \Phi}{\partial z} \right) - \frac{\rho v \Phi}{r} + \frac{\Gamma^\Phi}{r} \frac{\partial \Phi}{\partial r} + S^\Phi
\]

<table>
<thead>
<tr>
<th>Equations</th>
<th>(\Phi)</th>
<th>(\Gamma^\Phi)</th>
<th>(S^\Phi)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Continuity</strong></td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
| **Axial momentum** | \(u\)  | \(\mu\)       | \[-\frac{\partial P}{\partial z} + (\rho_0 - \rho)g + \frac{\partial}{\partial z} \left( \mu \frac{\partial u}{\partial z} \right) + \frac{\partial}{\partial r} \left( \mu \frac{\partial v}{\partial z} \right) + \frac{\mu \partial v}{r \partial z} \]
| | \[\frac{1}{3} \left( \frac{\partial}{\partial r} \left( \mu \frac{\partial u}{\partial r} \right) + \frac{\partial}{\partial r} \left( \mu \frac{\partial v}{\partial r} \right) \right) + \frac{\partial}{\partial r} \left( \mu \frac{v}{r} \right) \]
| | \[\frac{2}{3} \left( \frac{\partial}{\partial r} \left( \mu \frac{v}{r} \right) \right) \]|
| **Radial momentum** | \(v\)  | \(\mu\)       | \[-\frac{\partial P}{\partial r} + \frac{\partial}{\partial r} \left( \mu \frac{\partial u}{\partial r} \right) + \frac{\partial}{\partial r} \left( \mu \frac{\partial v}{\partial r} \right) + \frac{\mu \partial v}{r \partial r} - 2\mu \frac{v}{r^2} \]
| | \[\frac{1}{3} \left( \frac{\partial}{\partial r} \left( \mu \frac{\partial u}{\partial r} \right) + \frac{\partial}{\partial r} \left( \mu \frac{\partial v}{\partial r} \right) \right) + \frac{\partial}{\partial r} \left( \mu \frac{v}{r} \right) \]
| | \[\frac{2}{3} \left( \frac{\partial}{\partial r} \left( \mu \frac{v}{r} \right) \right) \]|
| **Species Continuity** | \(Y_k\) | \(\rho D_{i-mix}\) | \(\dot{\omega}_i\) |
| **Energy** | \(H\)   | \(\lambda/c_p\) | \[\nabla \left[ \frac{\lambda}{c_p} \sum_i \left\{ (Le^{-1} - 1)H_i \nabla Y_i \right\} \right] - \sum_i \left\{ h^n_{i,j} \dot{\omega}_i \right\} + q_{rad} \] |
Boundary Conditions

- Calculations are initiated with uniform flow conditions everywhere.
- Neumann conditions are applied to pressure.
Non-premixed Flame Structure: Effect of Fuel-Stream CO$_2$ Dilution on Flame Liftoff

Briones and Aggarwal, Physics Fluids Vol. 18 (2006)
Ignition and Triple Flame Propagation

TIME=0 ms

0% H₂

50% H₂

Fuel ↑↑ Air
10 cm/s  30 cm/s