Laminar Diffusion Flame Shapes Under Earth-Gravity and Microgravity Conditions

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• Motivation, Background, and Objectives

• Earth-Gravity (1g) and Microgravity (μg = 10^-6 g) Experimental Setup and Methods
  • Normal Diffusion Flames, NDF
  • Inverse Diffusion Flames, IDF

• Analytical Models
  • Spalding Model
  • Modified Roper Model

• Microgravity Flames
  • Test Conditions
  • Results and Discussion

• Earth-gravity Flames
  • Test Conditions
  • Results and Discussion

• Summary of Results

• Conclusions and Recommendations
Motivation

Fire on board the Mir space station, 1997
  • Microgravity
  • High Oxygen
  • Inverse diffusion flames

• Flame shape is a fundamental parameter used to describe flames

• Fire safety of future manned space missions
Literature

• Burke, S.P., Schumann, T.E.W., (1928)
• Roper, F.G., (1977)
• Spalding, D.B., (1979)
• Baukal, C.E., (1998)
Objectives

• Experimentally observe flame shapes
  • Length
  • Width
  • Contours
  • Luminosity

• To predict analytically the flame shapes of NDF’s and IDF’s under buoyant (earth-gravity) and non-buoyant (microgravity) conditions with varying oxygen content in the oxidizer

• Understand the range of applicability of analytical models and the limitations of the assumptions through comparisons with experimental flame shapes
1g Laboratory Setup
1g Laboratory Setup

NDF Burner

IDF Burner
µg Laboratory
Experimental Methods

- NDF and IDF of C$_2$H$_6$ and CH$_4$ were studied
  - 5.5 mm Dia. ~ Microgravity (quiescent oxidizer/fuel)
  - 11.1 mm Dia. ~ Earth-Gravity (co-flowing oxidizer/fuel)

- Oxygen concentration in the oxidizer: 21% to 100%

- Oxidizer volumetric consumption rate was held constant

- Image acquisition and processing by:
  Panasonic CCD video (Microgravity) and
  Nikon D-100 digital cameras (Earth-gravity)
1. Axial diffusion is neglected

2. $T_f = constant$ in regions where diffusion is dominant, but allowed to vary in the axial direction

3. Axial velocity, $v_z$ is assumed to vary in the axial direction but is a constant at each $z$ location

4. Due to assumption #3, buoyant acceleration and jet deceleration effects can be built into the model

5. Mixture fraction is solved using a similarity transformation, the flame sheet is located where the mixture is stoichiometric
Analytical Models

Spalding Model Assumptions

1. Axial diffusion is neglected

2. Temperature and density are assumed to be constant throughout

3. Axial velocity, $v_z$ follows the Schlichting jet velocity profile

4. Due to assumption #3, buoyant jet acceleration effects cannot be accounted for, hence the model is much more suited for microgravity flames

5. Momentum equation is solved and through similarity the velocity is related to the mixture fraction
Modified Roper Model

\[ \nu_r(r, z) \frac{\partial C(r, z)}{\partial r} + \nu_z(z) \frac{\partial C}{\partial z} - \frac{D}{r} \frac{\partial}{\partial r} \left( \frac{\partial C}{\partial r} \right) = 0 \]  

(1)

\[ C = \frac{(f - f_a)}{(f_o - f_a)} \]  

(2)

- Conservation of a conserved scalar (Cylindrical Cord.)
  - \( r, z, \nu_r, \) and \( \nu_z \) radial and axial coordinates and velocities
  - \( D, \) mass diffusivity

- Conserved scalar approach, concentration utilizing mixture fraction, where
  \[ f = nX_f - X_{O_2} \]

- Mixture Fraction: The mass fraction of material having its origin in the fuel stream
Boundary Conditions for eq. 1

\[
C \rightarrow 0 \quad \text{In the far field}
\]

\[
C(r,0) = 1 \quad r < \frac{d}{2}
\]

\[
C(r,0) = 0 \quad r > \frac{d}{2}
\]

Utilizing the transformations we convert from \( r \) and \( z \) to a new \( \eta \) and \( \theta \) coordinate system

\[
t(z) = \int_0^z \frac{dt}{v_z} \quad \eta(r,z) = \frac{r}{r_D(z)}
\]

\[
\frac{d \ln r_D}{dt} = \frac{v_r}{r} \quad \theta(t) = D \int_0^t \frac{dt}{r_D^2}
\]

\( t \) is the elapsed residence time on the flame axis

\( r_D \) is the characteristic scale of diffusion
Modified Roper Model

\[
\frac{\partial C(\eta, \theta)}{\partial \theta} = \frac{1}{\eta} \frac{\partial}{\partial \eta} \left( \eta \frac{\partial C}{\partial \eta} \right)
\]

(5)

\[
C(\eta, 0) = 1 \quad \eta < 1
\]

(6)

\[C \to 0 \quad \text{In the far field}\]

- After simplification and transformation eq. 1 becomes eq. 5
- Eq. 5 is now subject to the boundary conditions following the previous boundary conditions
- Thus the solution to eq. 5
  Known as the P-Function
  \( I_o \) is the modified Bessel function of the first kind of order zero
Model Solution

\[ r = \frac{\eta \cdot d}{2} \sqrt{\frac{T_f}{T_o}} \]
\[ z = \theta \frac{d^2 \cdot u_z \cdot T_f}{4 \cdot D \cdot T_o} \]

\[ \mu_g \]
\[ T_f(z) = T_f = \text{constant} \]
\[ u_z(z) = u_o = \text{constant} \]

\[ 1_g \]
\[ T_f(z) = T_o + \frac{z}{L_f} (T_f - T_o) \]
\[ u_z(z) = \sqrt{u_o^2 + 2\left(\frac{T_f}{T_o} - 1\right) \cdot g \cdot z} \]
# μg Conditions*

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<th>% O&lt;sub&gt;2&lt;/sub&gt;</th>
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* Fr<sub>f</sub> = ∞

Ethane Flames conducted at NASA by Dr. Sunderland
Results and Discussion

Microgravity Ethane NDF’s

- Soot obscures comparison, however modified Roper agrees well with luminous flame shape
- Neglecting axial diffusion results in inability of the prediction to move below the burner
Results and Discussion

Microgravity Methane NDF’s
μg Normal Experimental Correlations

Experimental Combustion Laboratory
Indiana University Purdue University Indianapolis

CH₄ Normal Flame Widths

C₂H₆ Normal Flame Lengths

C₂H₆ Normal Flame Widths

CH₄ Normal Flame Lengths

CH₄ Normal Flame Widths
Results and Discussion

Microgravity Ethane IDF’s

- Model predicts the stoichiometric flame lengths fairly accurately
- Widening effect was seen near the burner, linear interpolation has been used at $z = 5\text{mm}$
Results and Discussion

Microgravity Methane IDF’s

Fuel: Methane
Co-Flow: Zero
Burner Dia.: 5.5 mm
Configuration: IDF

30% O₂  50% O₂  100% O₂
µg Inverse Experimental Correlations

Microgravity Ethane & Methane IDF’s

C$_{2}$H$_{6}$ Inverse Flame Lengths

- Sunderland (1999)
- Spalding (1979)
- Roper (1977)

CH$_{4}$ Inverse Flame Lengths

- Sunderland (1999)
- Spalding (1979)
- Roper (1977)
## 1g Conditions

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Results and Discussion

Gravity Ethane NDF’s

- Soot obscures comparison, however modified Roper agrees well with luminous flame shape
Results and Discussion

Gravity Methane NDF’s

Fuel: Methane
Co-Flow Ratio: 3
Burner Dia.: 11.1 mm
Configuration: NDF
@ 2.0 X
1g Normal Experimental Correlations

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C₂H₆ Normal Flame Lengths

- Present Study
- Roper (1977)

C₂H₆ Normal Flame Widths

- Present Study
- Modified Roper

CH₄ Normal Flame Lengths

- Present Study
- Roper (1977)

CH₄ Normal Flame Widths

- Present Study
- Modified Roper
Results and Discussion

Gravity Ethane and Methane IDF’s

- The use of a 430 nm CH Bandpass Filter removes obstructing soot annulus

- Due to highly convective nature of IDF’s, buoyancy is expected to have little effect on IDF’s
1g Inverse Experimental Correlations

Microgravity Ethane & Methane IDF’s

C$_2$H$_6$ Inverse Flame Lengths

CH$_4$ Inverse Flame Lengths

Legend:
- Present Study
- Roper (1977)
Froude number describes the ratio between the inertial momentum and the buoyancy forces

\[ Fr_f = \left( \frac{u_o Y_{F,\text{stoic}}}{L_f g \left( \frac{T_f}{T_\infty} - 1 \right)} \right)^2 \]

- **Region A**
  \( Fr_f < 0.0002 \) \( (u_b/u_o \geq 17.5) \)

- **Region B**
  \( 0.0002 < Fr_f < 0.4 \)
  \( (1.5 \leq u_b/u_o \leq 17.5) \)

- **Region C**
  \( Fr_f > 0.4 \) \( (u_b/u_o \geq 1.5) \)
Results Summary

- Region A: Shows good agreement with Roper
- Region B: Significant scatter
- Region C: Shows good agreement with Roper

![Graph showing Roper Vs. Experimental Data: Present Study and Sunderland Data [2]](image)

- Linear equation: $y = 0.9202x$
- Coefficient of determination: $R^2 = 0.7726$
• NDFs: The experimental flame lengths are luminous flame lengths

• IDFs: The experimental flame lengths are stoichiometric flame lengths (using CH filter)
Conclusions

1. For Microgravity NDFs become longer, wider, and generally sootier in comparison to earth-gravity NDFs. Gravity level had a negligible effect on the IDF due to the large convective velocities.

2. Increasing the oxygen concentration for NDFs and IDFs causes an increase in soot production and luminosity.

3. Comparisons of NDF and IDF shapes using both analytical and experimental techniques have been successfully completed in both earth-gravity and microgravity environments.
   - Earth-gravity: Linear temperature distribution accelerating velocity profile.
   - Microgravity: Constant temperature distribution and a constant velocity profile.

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Conclusions Continued

4. In a flow regime identified by flame Froude numbers lying between 0.0002 and 0.4 (mixed regime), the Modified Roper Model predictions deviated substantially from the experimental flames. In this region convection and buoyancy effects are comparable.

5. The Modified Roper Model performed well for buoyant normal diffusion flames with varying oxidizer concentrations ($Fr_f < 0.0002$) and for some buoyant IDFs ($Fr_f > 0.4$) where convection was dominant. The model also performed well for all non-buoyant ($Fr_f = \infty$) NDFs and IDFs.
Recommendation & Future Work

1. Higher flow rates are needed for larger flames which will be more suitable for comparison with the Roper model. The use of a Critical Flow Orifice (CFO) meter is recommended.

2. Future studies will help establish the exact Froude numbers where flame shape curvature changes.

3. A more complete numerical method which includes detailed chemistry, species diffusion effects, and flame radiation is needed for further study.

4. Flame radiation, species, and flame temperature and soot measurements will aid in identify the stoichiometric flame length and other parameters of importance to fire safety researchers.
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Dr. Hasan Akay (Advisory Committee)

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