Effects of Buoyancy and Forcing on Transitioning and Turbulent Lifted Flames

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Outline

• Numerical Method
  – Boundary conditions

• Simulation results
  – Parametric study

• Conclusions
Motivation

- Microgravity Research
  - Eliminate buoyancy → fundamental combustion problem
  - Experiments
    * Expensive
    * Limited parameter space
  - DNS - gravity is easily removed

- Lifted Flame Stabilization
  - Theory historically difficult
  - Achieve better understanding by isolating buoyancy effects

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Round Fuel Jet

Figure 1: Computational Domain
Numerical Method

- Compressible Navier-Stokes with Low Mach Number Approximation (McMurtry et al.)
- Predictor-Corrector scheme (Najm et al.) handles large density ratios
- Cylindrical, staggered mesh
- One step, reversible, Arrhenius-type reaction
Lateral Boundary

- Open to allow entrainment
  - Closed boundary causes recirculation (Boersma et al.)
- No viscous traction (e.g. Gresho)
  - Lateral flow is irrotational

Figure 2: Lateral Surface Element
Outlet Boundary

\[
\frac{\partial \rho u}{\partial t} + u_{\text{max}} \frac{\partial \rho u}{\partial x} = 0 \tag{1}
\]

- Convection velocity
  - \( u_{\text{ave}} \) - insufficient outflow near jet
  - \( u_{\text{max}} \) - represents region of interest

- Mass conservation
  - Evenly distributed correction \( \equiv \) uniform pressure gradient
Free-Slip Collar

Corrective pressure gradient

Computational domain

Inconsistency

No viscous traction

Figure 3: Corner Region

- Corrective pressure gradient inconsistent with no traction

- Collar decouples outlet and lateral boundary conditions

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Simulations

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
<th>Value(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds</td>
<td>$Re = \frac{\rho_0 u_0 d}{\mu}$</td>
<td>1000</td>
</tr>
<tr>
<td>Froude</td>
<td>$Fr = \frac{u_0}{\sqrt{gd}}$</td>
<td>3.33-∞</td>
</tr>
<tr>
<td>Damköhler</td>
<td>$Da = \frac{Ad}{u_0}$</td>
<td>600-900</td>
</tr>
</tbody>
</table>

Table 1. Nondimensional Parameters

- Sixteen axisymmetric simulations
  - Varied $Fr$ and $Da$
Results

Figure 4: Density contours, $Da = 800$

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Buoyancy Effects

• Buoyancy produces instability

• Disturbance source
  – Low level forcing from round-off
  – High frequency, small fluctuations in outlet pressure

• Slightly buoyant and non-buoyant flames differ significantly (Bahadori et al.)
  – Perturbations in nature $>>$ low level forcing in simulations
  – 3D instabilities
Liftoff Height vs. $Fr^{-1}$

- Liftoff height increases as Froude number decreases

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Liftoff Height vs. $Da$

- Liftoff height increases as Damköhler number decreases

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Conclusions

- Numerical Method
  - Lateral no-viscous-traction
  - Convective outflow with $u_{max}$
  - Free-slip collar
    * Decouples inconsistent b.c.’s
    * Improves numerical stability

- Simulations Results
  - Buoyant flames sensitive to low level disturbances
  - $H$ increases for both decreasing $Fr$ and decreasing $Da$