Temperature Field Measurements of Small, Nonpremixed Flames using Abel Inversion of Holographic Interferograms

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Motivation

- Desire: a relatively simple 2-D measurement to characterize flames (perhaps useful for control)
- Existing methods
  - velocity (e.g., PIV)
  - species (e.g., PLIF; RHI)
  - heat release (e.g., chemiluminescence)
  - temperature (e.g., shadow methods)
Capillary Flame

- 2 mm dia. capillary
- methane
- high voltage
- ground
- flame
- wire mesh
1-D Balance of Body Forces

- **Body force due to buoyancy**
  \[ F = (\rho - \rho_0)g \approx \rho_0 g \]
  - \( \rho \) is the density of hot gas
  - \( \rho_0 \) is the density of ambient
  - \( g \) is the acceleration due to gravity

- **Force balance with ion wind**
  \[ \int g(\rho - \rho_0)dx = \int \rho_0 g \left( \frac{T_0}{T} - 1 \right) dx = \int \frac{j}{K} dx \]
  - \( K \) is mobility of the charge carrier
  - \( j \) is the current density
Flame in an Applied Field

Applied Potential (Volts)

0 1000 2000 2500 3000 4000 5000

Luminosity

CH chemiluminescence
Shadowgraph

0 Volts  |  2312 Volts  |  5000 Volts

Note: Increased flowrate to enhance shadow
Vertical CARS Temperature Profiles

Distance below capillary (cm)

Temperature (K)

- No Field
- 319 V/cm
- 485 V/cm
Vertical CARS Temperature Profiles

Distance below capillary (cm)

Temperature (K)

- 319 V/cm
- Diffusion profile
- $T(r) = c_1/r + c_2$
Holographic Interferometry

Apparatus

a. AR+ laser; b. periscope; c. mirror; d. shutter; e. beam splitter; f. spatial filter; g. lens; h. objective; i. flame; j. iris; k. holographic plate
Double Exposure Holographic Interferometry Images

No field  Near balance  Excess field
Abel Transform and Inversion

\[ p(x) = 2 \int_x^\infty \frac{F(r)r}{(r^2 - x^2)^{1/2}} dr \]

transform

\[ F(r) = \frac{1}{\pi} \int_x^\infty \frac{p'(x)}{(x^2 - r^2)^{1/2}} dx \]

inversion

\[ \text{F(R)} \]

\[ \text{p(x)} \]

\[ \text{Original} \]

\[ \text{Reconstructed} \]
\[ \Delta \phi = \phi_0 - \phi = \int_0^L n_0(x) dx - \int_0^L n(x) dx \]

\[ \phi(x) = \frac{1}{\lambda} \int_L^0 n(x, z) dL \]

\[ n(r) = \lambda \int_r^R \frac{\phi'(x)}{(x^2 - r^2)^{1/2}} dx \]

\[ T = \frac{(n_0 - 1) \cdot T_0}{(n - 1)} \]
CARS vs. Interferometric Thermometry

![Graph showing comparison between balanced and natural conditions in CARS vs. Interferometric Thermometry. The graph plots temperature (T) in Kelvin (K) against radius in millimeters (mm). The data points and lines indicate the temperature distribution under balanced and natural conditions.]
Droplet Stream Flame Apparatus
Droplet Stream Flame

burning, monodisperse, methanol droplet stream

OH Transmission Image
5 Shot average:
- flame on, on resonance
- tuned to line center
- $\lambda = 310.123$ nm
- non-linear sensor
Holographic Interferogram

Temperature Interferogram
- 2 shots
- off resonance
- flame on
- flame off

don't stream
Droplet Stream Inversion

(a) FS

(b) φ

(c) δ\times10^4

(d) T

Radius (mm)
Droplet Stream Temperature Profile via CARS

From Zhu et al., 1991
Temperature Field

Droplet stream geometry

Temperature contours for a methanol droplet stream flame
Summary and Future

- Nonresonant holographic interferometry
  - electric field controlled flame
    » good agreement based on single profile
    » extend to full field analysis
  - droplet stream flame
    » symmetry challenges in instantaneous results
    » extend to long time average

- Resonant holographic interferometry
  - droplet stream flame
    » short pathlength a challenge
    » images taken, reconstruction in process
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Electric Field Control of Flames

- Study effects of electric field magnitude and direction on flame behavior
- Generate micro-buoyant combustion environment
- Compare temperature profiles of flame under electric field control with a purely diffusive thermal field
- Compare force generated on flame via electric field with the buoyant force

\[ Vel = 6.6 \text{ cm/s} \]
\[ Re = \frac{\text{inertia} / \text{viscous}}{} = 4.5 \]
\[ Gr_L = \frac{\text{buoyancy} / \text{viscous}}{} = 2e4 \]
\[ Gr_L/Re^2 = \frac{\text{gravity} / \text{inertia}}{} 
\geq 1 \implies \text{forced convection neglected} \]
\[ Pr = \frac{\text{momentum} / \text{thermal}}{} = 0.7 \]
\[ Ra = Gr \cdot Pr = 1.5e4 \]
\[ Nu = \text{surf ace temp grad} = 7 \]