Pressure Effects on Structure and Temperature Field of Laminar Diffusion Flames

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Introduction

• A considerable amount of literature has been published on Laminar Diffusion Flame (LDF) at atmospheric pressure.

• Most practical combustion devices operate at elevated pressures to increase thermodynamic efficiency and decrease size.

• Current understanding of the influence of pressure on thermo-physical properties of sooty flames is still weak.

• Accurate and reliable measurements of soot temperature and concentration in the diffusion flames by nonintrusive means are highly desirable to achieve in-depth understanding of combustion and pollutant formation processes.

• The present study focuses on the influence of elevated pressures up to 10 bar, on soot temperature distribution of ethylene-air laminar co-flow diffusion flame.
Diffusion Flames

Flame in which the oxidizer combines with the Fuel by diffusion

Typical examples of Diffusion flames:

1. **Candle**: A classic example of a diffusion flame

2. **Furnace**: operate under nonpremixed conditions for safety reasons.

3. **Diesel Engines**: a liquid fuel spray is injected into the combustion chamber.

4. **Gas Turbines**: nonpremixed combustion occurs in the swirl-stabilized combustion zone.

5. **Fire**: If the fuel is a solid or liquid, it will first be gasified by radiative heat flux from the fire before mixing with the surrounding air.
Two-Color Pyrometry Method

- The two-color technique relies on the measurement of the emission intensity from incandescent soot particles in the flame based on the Planck radiation law.
- This method measures temperature based on the signal ratios at two different wavelengths.

\[ T = C_2 \cdot \left( \frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \left[ \ln \left( \frac{I_{\lambda_2}}{I_{\lambda_1}} \right) + \ln \left( \frac{S_{\lambda_1}}{S_{\lambda_2}} \right) + \ln \left( \frac{\lambda_2}{\lambda_1} \right)^6 \right] \]

- \( \lambda \); The wavelength of the radiation (\( \mu \text{m} \)),
- \( T \); absolute temperature (K)
- \( C_1 \) and \( C_2 \); The first and second Planck constants
- \( I_{\lambda} \); Monochromatic radiation intensity
- \( S_{\lambda_1} / S_{\lambda_2} \); Instrument factor (from calibration)
Choice of the Filters

The filter wavelengths should be in a region:

- To avoid the radiation from gas molecules (e.g.; CO$_2$ and H$_2$O) and intermediate free radicals (e.g.; OH*, CH*, C$_2$* and CN*).
- Where the camera sensors are expected to have a reasonable sensitivity and signal-to-noise ratio
- To prevent the camera from image saturation
- Compromising the factors addressed above rise to choose the two wavelengths in NIR at following wavelengths:

$$I_1 = 780 \text{ nm} \quad \text{and} \quad I_2 = 1064 \text{ nm}$$

with a central wavelength tolerance of $\pm 2 \text{ nm}$. 
An ordinary digital camera can see the Near Infra-red (NIR) region!
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Schematic of experimental setup

High Pressure Chamber

Digital Camera (Canon EOS-30D)

Narrow Band Filter

Optical Windows

Sooty Flame

Infratherm Pyrometer (INFRATHERM IS 5/F) with ±1% accuracy
Co-flow High Pressure Burner Facility

- Working Pressures: 1~20 bar
- Height * internal diameter: 600 mm * 120 mm
- No of windows: 4
- Viewing diameter of windows: 45 mm
- Window Glass Types:
  1) Two from fused quartz (for transmission of Visible and NIR Spectrum)
  2) Two from float-zone silicone (for transmission of beyond NIR spectrum- for a different study based on THz time domain spectroscopy)
Calibration of Instrument factor (with tungsten ribbon lamp)

\[ S = 1.5R^{-1.7} \]
At atmospheric pressure, the base of the flame had a bulbous appearance.

As the pressure is increased:
- Axial flame diameters decreased at all heights.
- The flame height shows an initial stretches by pressure then decreased by more pressure.
- From 2 bar and above non-completely oxidized soot particles escapes from the flame tip leading to a sooting flame (Due to dramatic increase in soot formation and the flame temperature drop by pressure).
Narrow band (780 nm) images of ethylene (0.15 L/min)-air (15 L/min) flame, at different pressures.
Monochromic (780 nm) intensity distribution of ethylene flame at P=10 bar
2-D monochromic (780 nm) intensity distribution at different heights of ethylene (0.15 L/min)-air (15 L/min) diffusion flame (P = 10 bar)
2-D monochromic (1064 nm) intensity distribution at different heights of ethylene (0.15 L/min)-air (15 L/min) diffusion flame (P= 10 bar)
Two-color intensity distribution along the flame centerline at P=1 bar & P=10 bar

- The intensity at the centerline increases by distance from the fuel nozzle tip and then it starts to decrease when the position increases further downstream of the flame.
Two-color temperature profile as a function of intensity ratio (R), considering an average for instrument factor (S)

- The temperature is higher at lower amounts of “R” and visa versa, by increase in “R” the soot temperature tends to be decreased.
Soot temperature along the flame centerline as a function of flame height at different pressures

- The two-color temperature results in the NIR region are shown to be consistent with the pyrometry results.
- The overall temperatures decreases with increasing pressure.
The average temperature drop of about 177 K is recorded along the flame centerline for a pressure increase from atmospheric to 2 bar and also from 2 to 4 bar. However, at higher pressures the rate of temperature drop decreases to 1/3 of the previous temperature drop.
Conclusions:

✓ Applying two-color pyrometry method in the NIR region, utilizing a commercial digital camera, is capable of measurement of 2-D soot temperatures with a simple and relatively high accuracy approach.

✓ The maximum recorded error of the method was found to be about 8%.

✓ The overall temperature decreases with increasing pressure.

✓ The rate of temperature drop is greater for a pressure increase at lower pressures in comparison with higher pressures.

✓ The axial flame height increases initially and then starts decreasing (according to the narrow band images).

✓ The cross-sectional area of the flame shows an average inverse dependence on pressure at all heights.
Thank you for your attention