

ME 96
Flame Temperature Measurement Experiment

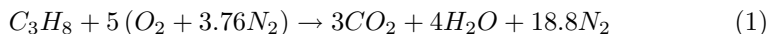
Revised: March 2003

1 Introduction

In this experiment, the line-reversal technique will be used to measure the temperature of a premixed propane-air flame. Line-reversal is a spectroscopic technique used commonly to measure flame temperature. Since it is non-intrusive, the method can be used for very high temperature measurements (> 3000 K) where thermocouples are difficult or impossible to use. In addition, thermocouples will be used to measure the flame temperature at several locations. These measurements must be corrected for radiation losses.

The burner used in this experiment is a premixed, laminar flow slot burner. Fuel and air enter a plenum where they thoroughly mix, and then the fuel/air mixture exits through a narrow slot where it is ignited. A small tube connected to an aspirator allows a fine water mist to be introduced into the gas, which is used to introduce sodium into the flame.

The fuel for these experiments is propane, C_3H_8 plus a small amount of other hydrocarbons. The stoichiometric combustion of propane in air may be represented by

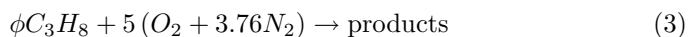


For a *stoichiometric* reaction such as shown here, there is just enough air (represented by $O_2 + 3.76N_2$) for complete conversion of the fuel to CO_2 and H_2O . For this case, the *molal* fuel to air ratio is $(F/A)_{\text{stoich}} = 1/23.8 = 0.042$ and *mass*-based ratio is 0.064.

In general, the flame may be run at a fuel to air ratio different than the stoichiometric value. In this case, the equivalence ratio ϕ (molal or mass basis) is defined as

$$\phi = \frac{(F/A)}{(F/A)_{\text{stoich}}} \quad (2)$$

The combustion reaction for a general, non-stoichiometric flame can be represented as



If $\phi < 1$, this is *lean* combustion, and the products are those in Equation (1) plus O_2 . On the other hand, if $\phi > 1$, then we call this *rich* combustion, and the products contain unburnt fuel, CO and H_2 , in addition to those molecules in Equation (1). These statements assume that there is no dissociation of the products.

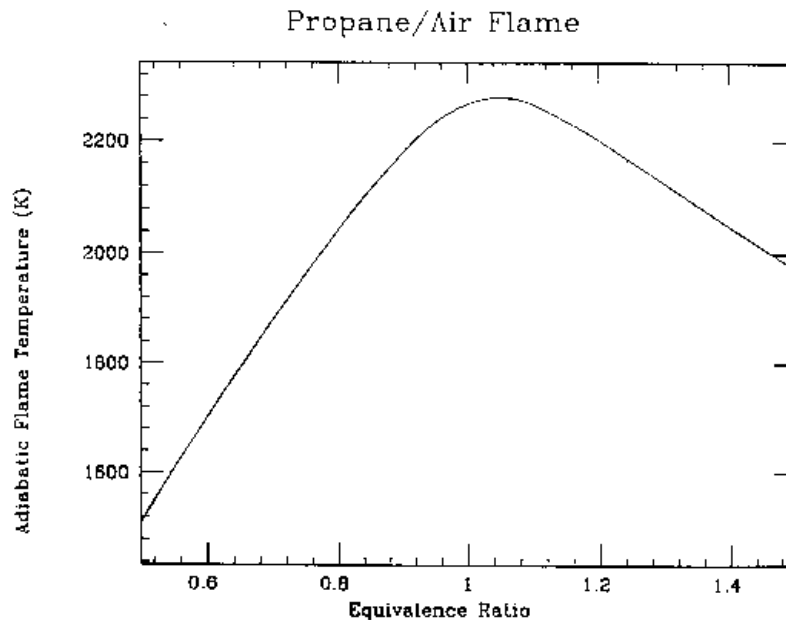


Figure 1: The adiabatic flame temperature for propane burning in air.

1.1 Adiabatic Flame Temperature

When the combustion reaction occurs, heat is liberated. Some of the heat increases the temperature of the products, and some is radiated or conducted or convected away to the surrounding air or to the burner body. For the special case where no heat losses occur (an adiabatic flame), the entire heat of reaction goes into raising the temperature of the products. In this case, the temperature attained by the products is known as *the adiabatic flame temperature*, T_{ad} , and can be calculated from considerations of thermochemistry and chemical equilibrium among the products.

The adiabatic flame temperature for propane burning in air is shown in Figure 1 as a function of ϕ . The calculation of the adiabatic flame temperature allows for dissociation of the products; hence CO, NO, OH may also be present in the product gases. Note that the maximum temperature occurs slightly on the rich side of stoichiometric.

1.2 The Line-Reversal Technique

To measure the flame temperature using the line-reversal technique, light from a lamp (usually a tungsten strip lamp) is focused into the flame with a lens, and the transmitted radiation is collected by a second lens and focused onto the entrance slit of a spectrometer. The light detected by the spectrometer also contains a component due to thermal *emission* from the flame. If the flame is

approximated as isothermal, then the light intensity seen by the spectrometer is the sum of the intensity transmitted through the flame plus the intensity emitted by the flame [1],

$$I_\lambda(L) = I_{\lambda b}(T_\ell) e^{-k_\lambda L} + I_{\lambda b}(T_f) (1 - e^{-k_\lambda L}) \quad (4)$$

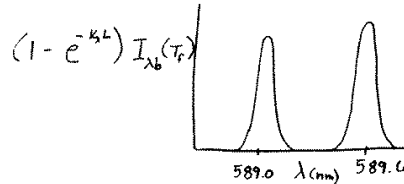
where L is the optical pathlength through the flame, and k_λ is the absorption coefficient (cm^{-1}) of the flame. The quantity $I_{\lambda b}(T)$ is the intensity emitted by a black-body at absolute temperature T , given by

$$I_{\lambda b}(T) = \frac{2C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} \quad (5)$$

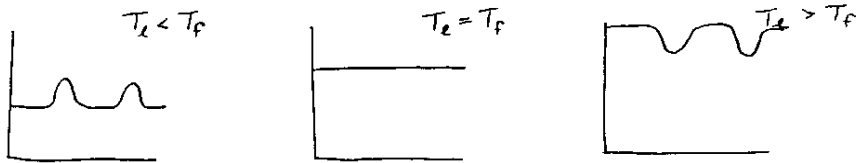
where $C_1 = 5.9544 \times 10^{-16} \text{ W}\cdot\text{m}^2$ and $C_2 = 14,388 \text{ }\mu\text{m}\cdot\text{K}$. The quantity T_1 in Equation (4) is the *brightness temperature* of the lamp, defined so that the intensity emitted by the lamp at temperature T is $I_{\lambda b}(T_\ell)$. Since the lamp is not a perfect blackbody, in general $T_\ell < T$. T_f in Equation (4) is the flame temperature we are interested in determining.

To have a large enough absorption coefficient at convenient wavelengths, we add sodium to the flame by aspirating a salt solution into the fuel/air mixture. The sodium produces an orange glow, due to two emission lines, at $\lambda = 589.0 \text{ nm}$, and $\lambda = 589.6 \text{ nm}$, respectively.

If we scan the spectrometer over this wavelength region with the lamp off, we see two emission lines:



Since over this narrow wavelength range the blackbody function may be taken as essentially constant, as we turn up the lamp current, we see the following:



At the point $T_\ell = T_f$, the emission by the flame exactly balances the absorption of lamp light, and the signal measured by the spectrometer is *constant*. This is also clear from Equation (4), which for the case $T_f = T_\ell$ gives $I_\lambda(L) = I_{\lambda b}(T_\ell)$. This point is known as the reversal point.

We may determine the flame temperature T_f by varying T_ℓ until the reversal point is reached. The value of T_ℓ at which this occurs must then be equal to

the flame temperature T_f . Note that this technique does not require knowing the value of k_λ , and thus we don't need to know the exact salt concentration, etc. This is a very useful feature of this technique [1].

2 Experimental Procedure

2.1 Lamp Calibration

You must first calibrate the lamp by measuring T_ℓ as a function of lamp current. This calibration is done using the optical pyrometer, which allows direct optical measurement of the brightness temperature by matching its emission to that of an internal heated filament. The power to the pyrometer filament is adjusted until it “disappears” against the image of the lamp.

2.2 Stoichiometric Ratio

Measure the volumetric flow rate of fuel and air. These measurements must be corrected because the standard calibration tables are only for air with no back pressure. The correction factors are found with the calibration tables. A ratio of the volumetric flow rate of fuel to air is equal to the molal fuel-air ratio.

2.3 Flame Temperature Using Line Reversal Technique

Choose a set of air and fuel flow rates (start close to stoichiometric) and light the flame. Take several spectral scans over the sodium lines, starting with zero lamp current, and increasing the current until beyond the reversal point. Determine the reversal for the flame. How does it compare to the adiabatic flame temperature?

Repeat this procedure for a range of equivalence ratios. You should find that the flame temperature depends on ϕ in a way similar to that for the adiabatic flame temperature.

2.4 Flame Temperature Using a Platinum-Rhodium Thermocouple

For the stoichiometric mixture, insert the thermocouple into the flame and measure the temperature at several positions across the width of the flame and at several different heights. There are two thermocouples with different wire diameters. Make a few measurements with both thermocouples. The thermocouple measurements must be corrected for radiation losses, see Appendix A.

3 Results

The laboratory report should include the following material:

1. Calibration of lamp.
2. Using the results based on the line-reversal technique, plot the flame temperature versus equivalence ratio.
3. Using the attached notes, correct your temperature measurements obtained with the thermocouple for radiation losses. What effect does the bead diameter have on the measurements?
4. From the thermocouple measurements, plot the temperature distribution as a function of position within the flame for different heights above the burner.
5. Present the results of the flame speed measurements and if possible compare to measured values. See reference [2].

4 Discussion

The discussion should include the following points.

1. What factors might result in the flame temperature being different from T_{ad} ?
2. For a stoichiometric mixture, calculate the adiabatic flame temperature assuming that the reaction proceeds as given in Equation (1). Why is this temperature different than given in Figure 1?
3. How does the equivalence ratio influence the temperature distribution? Does your graph of the flame temperature as a function of ϕ compare well. Why or why not? How do the thermocouple measurements compare with that obtained by the line reversal method? Which measurements are more accurate?
4. How does the structure of the flame change with stoichiometry?

5 References

1. A. G. Gaydon and W. G. Wolfhard, *Flames*, Chapter X, "Flame Temperature I. Measurement by the Spectrum-line Reversal Method", 3rd edition, Chapman & Hall, London, 1970.
2. K. K. Kuo, *Principles of Combustion*, John Wiley & Sons, New York, 1986.

Prelab

1. Construct 2 tables of fuel and air flow values. For the first table, assume 1 SLPM of air flow and pressures of 0 to 40 psig and list the resulting fuel flow for mixture fractions of 0.5 to 5. For the second table, assume 0.05 SLPM of propane and tabulate air flow as a function mixture fraction and air pressure.
2. Explain the operating principle for a platinum thermocouple.
3. Explain black-body radiation and how that might apply to the thermocouple.
4. The lab write-up shows that for $T_l > T_f$ the graph (page 3) looks like a flat line with two dips. Are the dips in the same place as the peaks? Why are they the same or shifted? Why do they occur?