Combustion and Flame 161 (2014) 1678–1686

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Plasma sheath behavior and ionic wind effect in electric field modified flames

Kunning Gabriel Xu

Mechanical & Aerospace Engineering Department, The University of Alabama in Huntsville, 301 Sparkman Dr., Huntsville, AL 35899, USA

ARTICLE INFO

Article history:
Received 3 July 2013
Received in revised form 17 October 2013
Accepted 6 December 2013
Available online 29 December 2013

Keywords:
Electric field modified flames
Plasma combustion
Ionic wind
Plasma sheath

ABSTRACT

Plasma sheath theory is applied to understand the plasma behavior in electric field modified flames. This paper presents a set of 1D plasma sheath equations with approximated analytical solutions to calculate the sheath thickness for given applied voltages and plasma properties. The results show that the anode sheath is ten of microns thick, less than 1 V, and largely independent of the applied voltage. The cathode sheath grows with the applied voltage to centimeters thick. The limited extent of the anode and cathode sheaths, which limits the reach of the electric field, in part explains the different flame behaviors reported in the literature. The ionic wind body force is also calculated based on ion energy losses due to collisions. The sheath analysis provides a possible explanation for reported flame behavior under a DC field modified such as saturation current and diode-like behavior.

1. Introduction

The ability of an electric field to modify flame behavior is well known. It was first reported by Chattock in 1899 [1]. Since then, a wide range of research has shown electric field induced changes in both premixed [2–9], and diffusion [10–12] flames. Some of the experimentally observed flame changes include increased flame speed [3,5,8,13,14], decreased lean blow-off equivalence ratio [5–7], decreased emissions and soot formation [10,15–17], and simulated gravity in diffusion flames [11]. Based on these results, the development of flame control methods using electric fields is promising. However, the basic interaction mechanism and physics is still unclear. In fact, the results tend to disagree on the magnitude and type of response.

Take for example, the laminar flame speed, the most widely reported measurement. Blair and Shen [4] and Bowser and Weinberg [18] showed very small changes <4% in flame speed using a flat flame with axial field. Comparatively, van den Boom et al. [3] showed an 8% increase in flame speed with a similar flat flame geometry, and Jaggers and Von Engel [14] showed a 100% increase in flame speed in a tube flame with transverse fields. Similar differences in field influenced flame speed changes have been reported for conical flames [5–8]. The reason for the differences is unknown, but may be related to experiment geometry or measurement technique. It has also been noticed that flame modifications only occur with a grounded burner such that ions are attracted upstream. The opposite configuration, a high voltage burner that repels ions, causes little to no change in the flame behavior. No physical explanation for this behavior has been found by the author.

There are also different theories for the cause of the observed flame behavior. An often referenced paper by Lawton and Weinberg [9] attributed the flame response to the ionic wind effect, a body force on ions due to the electric field. They analytically determined the maximum velocity, force, and static pressure a field can exert on the flame based on a maximum ion current density. Their results have been used by many researchers to support the ionic wind effect.

With all the research into this field, the exact mechanism and physics responsible for the flame modification is still unclear. The current literature discusses two causes for the flame response to an electric field: an electro-hydrodynamic effect (the ionic wind), or a change in flame kinetics from ion–electron recombination. Both of these theories have a commonality in the assumption of full electric field penetration into the bulk of the flame between the electrodes. Some early numerical simulations make this assumption as well by using a constant electric field [19]. This assumption neglects an important aspect of plasma, namely the plasma sheath and the non-uniform potential distribution and electric field. Some recent work has begun to discuss a non-uniform electric field. Goodings et al. modeled the floating potential distribution in a flame and discussed the presence of a sheath [20,21], Marcum and Ganguly measured the floating potential in a 15 kV field modified flame with a floating probe [13], van den Boom et al. briefly discusses the presence of the non-uniform field [3], and Belhi et al. numerically simulated the potential distribution in a diffusion flame under a 0.625 kV field [22]. These papers

E-mail address: gabe.xu@uah.edu

0010-2180/$ - see front matter
http://dx.doi.org/10.1016/j.combustflame.2013.12.008

showed that the potential distribution is very non-uniform and is important to understand the electric field effect on the flame.

The goal of the present study is to investigate the impact and behavior of the plasma in electric field modified flames from a plasma physics perspective. An analytical model for the growth of the plasma sheath as a function of the potential is presented for the case of an ideal stoichiometric 1D premixed methane/air flat flame at 2210 K. The sheath thickness and the impacts on the electric field and ionic wind force are discussed. This work is a first step to examine the fundamental plasma behaviors and the interaction mechanisms in electric field modified flames.

2. Flame plasma sheath model

2.1. Flame plasma properties

Two primary properties of interest in plasma physics are plasma density and temperature. This can further be dividing into electron and ion specific densities and temperatures. For hydrocarbon flames, the ion number density has been both measured and computed to peak around $1 \times 10^{10}\ \text{cm}^{-3}$ [23,24]. This is many orders of magnitude smaller than the neutral density, which at 1 atm and 2210 K is $3.3 \times 10^{18}\ \text{cm}^{-3}$. Nonetheless the flame plasma density is sufficiently high for noticeable effects under external fields. In hydrocarbon flames, the dominant positive species are H_3O^+ and CHO^+. The dominant negative species are electrons, followed far behind by O_2^- and CHO_2^-. These charged species are produced through chemical ionization in the reaction zone [9]. As with most other works in this field, we will consider H_3O^+ as the sole positive charge carrier and electrons as the sole negative charger carrier. The use of only H_3O^+ to account for ion species is due to its abundance downstream in the burnt gas as shown by Goodings et al. [23] and Prager et al. [24]. Most of the other positive ions disappear quickly outside the reaction region.

The average electron temperature of flame plasma can be taken equal to the flame temperature, assuming thermal equilibrium. For a stoichiometric ($\phi = 1$) methane–air flame, the adiabatic flame temperature is 2210 K, which equates to 0.19 eV [25]. The assumption of thermal equilibrium is valid as long as the collision frequency between electrons and neutrals is high. From kinetic theory, the collision frequency of a fast electron colliding with slow neutrals is $\nu_{en} = n_n \sigma_{en} \bar{v}_e$, where n_n is the neutral density, σ_{en} is the electron–neutral collision cross-section, $\overline{v_e} = \sqrt{8kT_e/\pi m_e}$ is the average electron thermal velocity, k is Boltzmann's constant, T_e is the electron temperature, and m_e is the electron mass. For the $\phi = 1$ flame considered here, taking the electron momentum transfer cross-section for N_2 ($\sigma_{en}(T_e = 0.19) = 7.9 \times 10^{-16}\ \text{cm}^2$) [26] to represent the neutral flame species overall, the collision frequency is $\nu_{en} = 7.8 \times 10^{10}$ coll/s.

In the absence of an external field, the quasi-neutral assumption holds for flame plasmas, $n_i \approx n_e$. Along with the thermal equilibrium assumption, this means ions have the same energy as electrons and neutrals. The plasma density however is not uniform throughout space. As has been experimentally [27] and computationally [24] shown, the plasma density is a maximum in the reaction zone where ionization occurs and decreases both upstream and downstream. This drop in density can be attributed primarily to neutralization [9]. Charge loss can only occur through ion and electron collisions with surfaces, or each other. The charge particles have too low of an energy to cause collisional ionization of neutrals, and charge-exchange collisions with neutrals do not decrease the total charge. Neglecting surface neutralization, ion–electron recombination must be the dominate charge loss mechanism [9]. Recombination cross-section and rates for H_3O^+ have been measured by many researchers [28–33].

2.2. Plasma sheath

A short description of plasma sheaths and their behavior will be presented here for background. In short, the plasma sheath is a thin layer of plasma next to any surface immersed in plasma that transitions the potential from the plasma potential to the surface potential. The sheath arises due to the different thermal velocity and flux of ions and electrons. A flame is a weakly ionized plasma as mentioned. The electrons and ions are created within the reaction zone via chemi-ionization. Without an energizing field, the charged particles have low energies, 0.19 eV for a 2210 K flame, assuming thermal equilibrium. To a first order, the current flux per area of ions and electrons is,

$$\begin{aligned} J_i &= n_i e v_i \\ J_e &= n_e e v_e \end{aligned}, \tag{1}$$

where J is the current flux per area, e is the particle charge, n and v are the number density and thermal velocity, the i and e subscripts denote ions and electrons, respectively. The ratio of electron to ion flux, assuming quasi-neutral plasma, is simply the velocity ratio which is proportional to the square root of the mass ratio.

$$\frac{J_e}{J_i} = \frac{v_e}{v_i} = \sqrt{\frac{m_i}{m_e}}. \tag{2}$$

The ion mass is orders of magnitude larger than the electron mass, resulting in a disproportionate flux. In the example flame, the electron flux is 186 times larger than the H_3O^+ ($m_i = 3.16 \times 10^{-26}$ kg) flux. This difference can also been seen from their thermal velocities. For a temperature of 0.19 eV, H_3O^+ has a thermal velocity of 1570 m/s, while an electron has a thermal velocity of 300,000 m/s. This flux and velocity disparity creates the plasma sheath at a surface immerged in the plasma. Inside the plasma sheath, the quasi-neutral assumption is no longer valid and large electric fields and charge separation occurs.

Consider an unbiased or floating surface. The electron flux to the surface is much larger Thus at some initial time zero when the surface is first exposed to the plasma, the surface becomes negatively charged with respect to the plasma. This negative surface potential in turn repels electrons and attracts ions. The ion collection causes the surface potential to rises with respect to the initial negative potential at time zero. The surface potential thus rises and adjusts to retard the flux of electrons and increase the flux of ions to the surface until the fluxes balance, resulting in no net current. This adjustment occurs quickly, and can generally be considered instantaneous. The surface is now "floating" in the plasma at the floating potential, V_f which is below the plasma potential, V_p. The transition from the plasma potential to the floating potential occurs in a thin sheath layer next to the surface. Inside the sheath the local potential monotonically decreases from V_p to V_f as particles move toward the surface. The particle distribution inside the sheath is not uniform, typically resulting in increased ion density and decreased electron density closer to the surface. Thus the sheath is not quasi-neutral. This type of sheath is commonly called an ion sheath, or a negative sheath as the potential change is negative. Outside the sheath, the plasma is undisturbed and quasi-neutrality is maintained. Any flux of particle to the sheath edge is due to purely random thermal motion. The effect and presence of the surface does not impact the bulk plasma. In reality, there is not a sharply defined edge to the sheath. The definition is akin to a fluid boundary layer where the edge may be taken at 95% or 99% of the bulk potential.

Now consider the case of a biased electrode at a potential V. A positive electrode (anode) will collect a net electron current, and a negative electrode (cathode) will collect a net ion current. In both situations, the thermal electron flux is still much higher compared