

Short Communication

A TERNARY FLAME SYSTEM FOR SOOT OXIDATION STUDIES

Haiqing Guo, Paul M. Anderson, and Peter B. Sunderland 

Department of Fire Protection Engineering, University of Maryland, College Park, Maryland, USA

A ternary flame system is presented that allows observations of soot oxidation in a hydrogen diffusion flame in the absence of hydrocarbons. A propylene/air laminar jet diffusion flame emits a soot column with a diameter of 3 mm that passes through a ring burner supporting a hydrogen diffusion flame. The soot oxidizes in a region that is 60 mm long, laminar, steady, axisymmetric, and accessible for optical and sampling diagnostics. Temperatures and soot loading can be controlled nearly independently in this region and a broad range of mixture fraction is encountered without interference from soot formation.

Keywords: Hydrogen; Laminar diffusion flame; Ring burner

INTRODUCTION

An improved understanding of pollutant and radiative emissions from flames and fires will require an improved understanding of soot nucleation, growth, and oxidation. A recent study compared the predictions of 36 detailed gas and soot kinetic models with measurements from eight laminar diffusion and premixed flames (Mehta et al., 2009). No model matched the measured peak soot volume fractions within a factor of five for all eight flames. Similar discrepancies were encountered by both Crookes (2006) and D'Anna et al. (2007).

Improved soot oxidation measurements could lead to improved rate models for both soot oxidation and soot formation. This is because most measurements of soot growth rates in flames are in regions with significant soot oxidation (e.g., Kim et al., 2004, 2008; Xu et al., 1997).

One of the most widely used models of soot oxidation rates is questionable because it did not consider soot, aerosols, or gas-phase reactions. Nagle and Strickland-Constable (1962) instead inferred soot oxidation rates by O₂ by observing the oxidation of various heated carbon rods in oxygen jets. This model disagrees with many soot aerosol measurements; for example, it overpredicts the measurements of Lee et al. (1962) and Puri et al. (1994), while underpredicting those of Park and Appleton (1973) and Camacho et al. (2014). Soot oxidation by O₂ has also been studied using thermogravimetric analysis

Received 11 March 2015; revised 2 June 2015; accepted 19 June 2015.

Address correspondence to Peter Sunderland, Department of Fire Protection Engineering, University of Maryland, 3104 J.M. Patterson Building, College Park, MD 20742, USA. E-mail: pbs@umd.edu

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(Jaramillo et al., 2014; Kalogirou and Samaras, 2010; Sharma et al., 2012), but temperatures were below 1000 K and this environment is very different from a flame.

Another widely used model is the OH mechanism of Neoh (1980) and Neoh et al. (1984), who observed a two-stage premixed flame system. After correcting for O₂ soot oxidation using the model of Nagle and Strickland-Constable (1962), OH was found to be the principal soot oxidizer, with an average collision efficiency of 0.13. Echavarria et al. (2011, 2012) used a similar premixed flame setup, but did not examine soot oxidation kinetics. In both studies soot deposition prevented the observation of long-term steady flames and uncertainties were increased because the soot oxidation region was only 5 mm long.

Soot oxidation rates have also been measured in hydrocarbon diffusion flames (Garo et al., 1990; Kim et al., 2004, 2008; Lee et al., 1962; Puri et al., 1994, 1995; Xu et al., 2003). Most of these measurements were in the presence of hydrocarbons, requiring significant corrections for soot growth. Some of the measurements were in very lean regions without hydrocarbons, but these involved low temperatures, low soot loadings, and late-stage soot that may not represent typical soot in diffusion flames.

Recognizing these gaps in understanding, the objective of this study is to develop a ternary flame system that allows soot oxidation to be observed in a diffusion flame in the absence of soot formation. Detailed measurements in this system could lead to improved soot oxidation models.

EXPERIMENTAL

This ternary flame system involves three flames burning steadily in air at 1.01 bar: a propylene diffusion flame, a hydrogen diffusion flame, and a soot flame. A sooting propylene/air laminar jet diffusion flame was established on a coflow burner (Santoro et al., 1983), consisting of concentric brass tubes with inside diameters of 14 and 101.6 mm. The fuel port had a blunt tip with a wall thickness of 1.5 mm. The flow of propylene (2.1 mg/s, 99.5% purity) through the inner tube was surrounded by coflowing air (1.18 g/s). The propylene flame had a luminous length of about 50 mm and emitted soot in a vertical column.

A ring burner was fabricated as shown in Figure 1. For this, a round brass rod was cut to length and drilled on center. The plenum groove was milled, and 41 jet holes and the tapered port were drilled. A short section of the rod was drilled on center and welded in place to form the plenum. The calculated pressure drop through each hole exceeded 10 times that across the plenum. The ring burner was positioned with its upper face 80 mm above the coflow burner and on the same axis. Hydrogen (1.48 mg/s, 99.9995% purity) was delivered to the ring burner with its flow (like that of the propylene and the air) controlled with a pressure regulator and a needle valve. Flow rates were measured with rotameters that were calibrated with a soap bubble meter.

RESULTS AND DISCUSSION

The performance of the ring burner was tested with hydrogen and with methane for improved flame visibility. Flame asymmetries were present for ring flames shorter than 10 mm, while flickering occurred for those longer than 70 mm. Only flames longer than 25 mm had stoichiometric regions that extended to the burner axis. The stoichiometric length of the hydrogen flame used in the ternary flame system was determined with gas

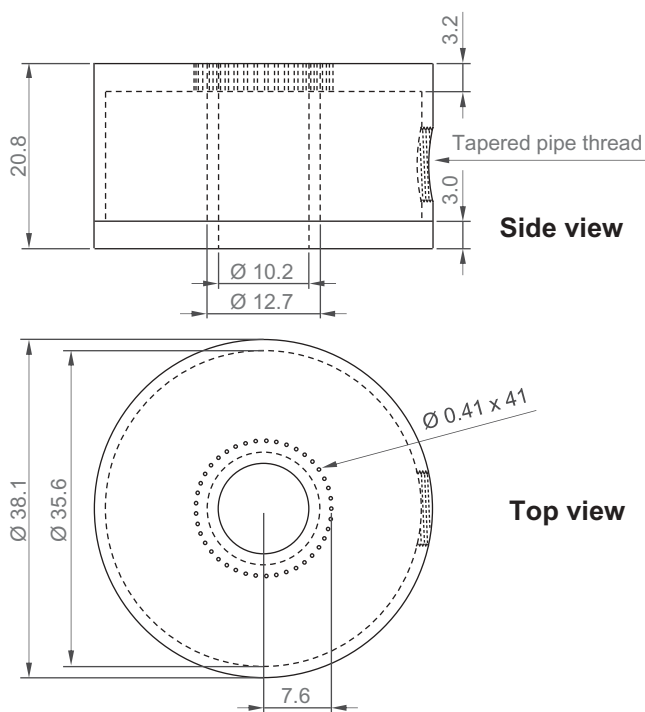


Figure 1 Schematic of the ring burner, with dimensions in mm.

chromatography to be approximately 30 mm, but visual confirmation was impossible owing to the dim and broadened reaction zones of the hydrogen diffusion flame.

Figure 2 is a color image of the ternary flame system. The soot flame was laminar, axisymmetric, and optically thin. It was steady to a height of 60 mm above the ring burner. It reached a maximum diameter of 3.3 mm at a height of 13 mm and then narrowed. The soot flame has been characterized with spatially resolved measurements, as reported in Guo (2015). These measurements (and their ranges) were as follows: temperatures (1500–1725 K), soot volume fractions (1–15 ppm), velocities (2–3 m/s), primary particle diameters (20–45 nm), and concentrations of N_2 , H_2O , CO_2 , O_2 , CO , and H_2 . This flame's open accessibility facilitates soot and gas sampling and optical diagnostics. It allows the observation of soot oxidation in a diffusion flame far separated from soot formation regions.

The temperature (measured with a K-type thermocouple) on the axis at the entrance to the ring burner was 300 °C, indicating that most of the gaseous products of the propylene diffusion flame had been replaced by N_2 and O_2 . This reduced the hydrocarbon and CO_2 concentrations in the soot flame, which otherwise would have contributed to soot formation and oxidation.

Soot loading and temperature can be controlled independently in the soot flame. Soot loading can be adjusted by changing the propylene flow rate or by using a different fuel. Temperature can be adjusted by changing the hydrogen flow rate or by introducing oxygen or diluent into the air or hydrogen supply. A variety of conditions have been tested by Guo (2015). The propylene supply was replaced with acetylene with flow rates of

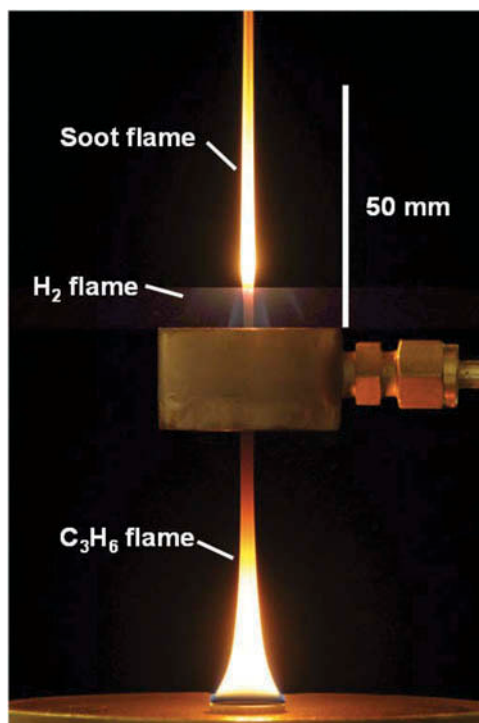


Figure 2 Color image of the ternary flame system. Owing to the hydrogen flame dimness, grayscales have been increased by a factor of 4.6 for heights above the ring burner of 0–8.5 mm.

2.2–2.6 mg/s. Hydrogen flow rates were varied from 1.5–2.2 mg/s. The resulting soot volume fractions were as high as 70 ppm, and the peak soot temperatures varied between 1200–1800 K. Modifications to this flame system could allow it to be used for studies of soot growth, nanoparticle processing, or other aerosol physics experiments.

FUNDING

This work was supported by the National Science Foundation (NSF) under grant CBET0954441.

ORCID

Peter B. Sunderland  <http://orcid.org/0000-0002-8262-7100>

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