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Soot measurements in candle flames

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ABSTRACT

Soot volume fractions and soot temperatures have been measured for the first time on candle flames. Measurements on laminar steady flames were carried out using candles with wick diameters of 2, 3 and 4 mm. Wick length was varied between 4 and 10 mm. The shape of the candle flame was obtained from CH* spontaneous emissions. Measured flame heights show an increase with wick dimensions, approaching an asymptotic value for increasing wick lengths. Soot volume fractions were obtained from laser extinction measurements with the Modulated Absorption/Emission (MAE) technique. A deconvolution technique and a regularization procedure were applied to the data. Radial profiles of soot volume fractions increase when varying the wick dimensions; this effect is produced by the greater amount of fuel released by the wick. Radially integrated soot volume fractions were also calculated, presenting a similar behavior to the soot volume fraction radial profiles. The peak integrated soot volume fraction was found at approximately half the flame height, independent of the wick dimensions and burning rates. Soot temperature was obtained from emission measurements at two different wavelengths considering the attenuation of the soot particles in the optical path length. A deconvolution and regularization procedure was carried out in order to obtain temperature profiles for different heights in the flame. The observed increase in soot production and soot temperature profiles was directly related to the higher burning rate experienced by the candle. The results show that peak integrated soot volume fractions are proportional to both the mass loss rates and the flame heights.

1. Introduction

Soot production modeling has experienced a considerable development as the computational power has increased and as more sophisticated experimental techniques have allowed the measurement of soot concentrations within flames with greater spatial resolution. These two factors have allowed the development of detailed models and have given researchers access to more complete databases for model validation. Soot models are critical in combustion applications like gas turbines, IC engines, and fire safety. The main goal of this work is to build a set of reliable soot volume fraction and temperature measurements in candle flames, to be used in the validation of soot production models. Candle flames have been chosen for several reasons. Firstly, they involve the combustion of condensed phase waxes, whose molecules have a carbon number n, C_nH_{2n+2}, typically ranging between 19 and 36 [1,2], which is larger than that of the hydrocarbon fuels which are usually used in soot production experimental measurements [3–5]. The waxes used in candles are therefore representative of larger and complex hydrocarbon fuels like the ones found in fire safety or some turbine applications [6–9]. Secondly, in spite of the complexity of the solid and gas phase processes that occur when candles are burning, they are safe and simple devices, being attractive from an experimental point of view.

Historically, candles have been one of the most common lighting technologies in the world. They have been studied since the XVII century by scientists like Francis Bacon, Humphry Davy, and Michael Faraday [10]. More recently, research has been carried out on candle flames for different applications and different conditions, including electric field effects [11], flame flickering [12], microgravity experiments [13,14], smoke point measurements [15], fire safety [16,17], flame shape analysis [1], and numerical models [17,18].

Light extinction measurements were carried out on candle flames with different wick diameters and lengths. Flame dimensions were estimated using CH* emissions images. Soot volume fractions and temperatures were quantified using the Modulated

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Absorption/Emission technique. This article describes the experimental setup and the data processing techniques and presents results for all the experimental conditions.

2. Experimental

The experimental procedure followed in this work was based on a previous study on candle flames in order to obtain comparable results, particularly regarding the influence of the wick length [15]. The previously published experiments were replicated to validate the current experimental results. The optical diagnostics carried out in this research project will serve as a complement to the work by Allan et al.

Experimental measurements were carried out on Sasolwax 6203 paraffin wax candle flames. The candles were manufactured by the authors. When the candles were molded, the wick was fixed at the center of the mold to ensure a consistent wick position in the wax cylinder. The average candle diameter was 64 mm. Three different wick diameters were used: 2, 3, and 4 mm. For each wick diameter, 5 different initial wick lengths were used, ranging from 5 to 10 mm. Table 1 shows all the experimental conditions and the main experimental results. Prior to the start of the measurements, the candle was allowed to burn for 2–3 min to ensure that wax had flowed into the entire wick. After this, the flame was extinguished, the wick was cut to the desired length, and the wick was placed in a vertical position. The candle was re-ignited and measurements commenced after steady burning was achieved. Only laminar flames under the smoke point were measured. To prevent damage to the wick, the candles were extinguished by manually directing a jet of nitrogen on the wick until no noticeable flames were present.

Soot volume fractions were estimated using Modulated Absorption/Emission (MAE) measurements [19]. No previous reports of soot volume fraction or temperature measurements with this technique on candle flames have been found in the literature. The light source was a 1400 mW diode laser at a wavelength λ = 660 nm. The beam was expanded and passed through the flame. Extinction measurements were obtained projecting the beam over a frosted glass screen. A CCD camera was used to capture the images, using a 660 nm bandpass filter (10 nm FWHM) to avoid capturing emissions from other sources. The camera was synchronized with the laser beam using a modulator at a 10 Hz frequency, to obtain sequential images of emission and absorption by the soot particles, both under flame and no flame conditions [19]. Soot temperature was estimated from emission measurements at two different wavelengths using another CCD camera with 660 nm and 800 nm bandpass filters (10 nm FWHM). A different CCD camera was devoted to CH^* chemiluminescence measurements. This camera was mounted with a narrowband filter centered at 431 nm (10 nm FWHM). Fig. 1 shows a schematic of the experimental setup. The images had a spatial resolution of 0.16 mm × 0.16 mm for the MAE measurements, 0.09 mm × 0.09 mm for the emission measurements and 0.26 mm × 0.26 mm for the CH^* measurements. Additionally, mass loss measurements were done with a 0.1 mg resolution and 1 Hz frequency analytical scale.

3. Data processing

3.1. Flame height

Flame geometry was estimated using a segmentation model [20] to clearly distinguish the presence of the flame on an image. The model generates a composite image from a set of CH^* images, by applying the following probability function:

$$Pb(x,y) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(\frac{(G(x,y)-\mu)^2}{2\sigma^2}\right). \quad (1)$$

$G(x,y)$ is the intensity of the i-th pixel in the original image, μ is the mean intensity value of the pixels of the original image and σ is their standard deviation. For each of the measurements, μ and σ were calculated using over 25 images. The contour of the reaction zone is generated from a comparison between each modified pixel and a specific threshold value ξ. Where the probability $Pb(x,y)$ is larger than ξ, that particular pixel is considered as a flame. The threshold value was determined based on inspection of the acquired images. Flame heights and other dimensions are obtained from these images. These dimensions are defined in Fig. 3a, and follow Ref. [1].

3.2. Soot volume fractions

The transmissivity of the soot particle cloud within the flame is obtained from light extinction (LE) measurements, accounting for both the emission and absorption of radiation by the flame. The MAE technique was used, which is based on alternate absorption and emission measurements on the same wavelength and optical path [21,19]. By working with images under four different conditions (flame - laser on, S; flame - laser off, S'; no flame - laser on, I_0; no flame - laser off, I'_0), this technique allows eliminating part of the background noise and fluctuations. 25 pairs of images were averaged for each measurement. The transmissivity τ_λ is calculated as:

$$\tau_\lambda = \frac{S - S'}{I_0 - I'_0}. \quad (2)$$

Table 1
Experimental conditions and main experimental results. See Fig. 3 for definitions.

D_{wick} (mm)	L_{wick} (mm)	MLR_{ave} (mg/s)	h_f (mm)	β_{max} (ppm mm^2)	D_f (mm)	T_{max} (K)
2	5	0.72	12.68	46.24	4.746	2059
2	6	0.82	16.35	52.43	5.478	2152
2	7	0.82	17.90	58.22	5.622	2159
2	8	0.88	18.30	63.30	4.990	2138
2	10	0.99	19.71	95.87	6.210	2191
3	5	1.03	16.71	52.60	5.488	2137
3	6	1.10	21.04	78.36	6.941	2018
3	7	1.17	23.79	81.06	5.234	2125
3	8	1.32	25.06	97.12	6.688	2123
3	10	1.35	28.11	101.21	7.429	2263
4	5	1.40	22.72	77.31	7.185	2097
4	6	1.63	29.89	111.47	6.699	2033
4	7	1.87	33.10	112.27	5.966	2051
4	8	1.94	37.22	114.63	6.698	2159
4	10	2.12	39.46	134.64	8.893	2068