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Gulder, Omer L.; Thomson, Kevin; Snelling, David

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Influence of the Fuel Nozzle Material on Soot Formation and Temperature Field in Coflow Laminar Diffusion Flames

Ömer L. Gülder, Kevin A. Thomson and David R. Snelling

*National Research Council
ICPET, Combustion Research Lab., M-9
Ottawa, Ontario K1A 0R6*

Introduction

The important parameters that influence the formation of soot in laminar coflow diffusion flames are the parent fuel molecular structure, the flame temperature, the amount and nature of diluents either in the fuel or in the oxidizer, and the pressure [1].

Laminar coflow diffusion flames are very sensitive to initial conditions and perturbations [2-6]. Although coflow flames are 2-D, there has been a considerable effort for modelling these flames with detail chemical kinetics (see, e.g., [7]) and with skeletal kinetic mechanisms (see, e.g., [8]). These modelling efforts and comparisons among coflow burners of similar geometries require consistent and well-defined initial conditions. One of these is the material used for the fuel tube.

In the present study, we investigate the influence of different fuel tube materials (i.e., steel, aluminum, and pyrex glass) on soot formation, and the temperature field of laminar coflow diffusion flames. The spatially resolved soot volume fractions and soot surface temperatures are determined from tomographic reconstruction of spectrally resolved radiation from soot particles.

Theoretical Considerations

Single wavelength emission/absorption tomography of line-of-sight integrated measurements were used by Hall and Bonczyk [9] to reconstruct 2-D maps of soot concentration and temperature in a laminar diffusion flame. This approach was recently extended by De Iuliis et al. [10] by taking spectrally resolved measurements which yielded radially resolved spectral flame emission through an Abel inversion based tomographic reconstruction. The soot surface temperature diagnostic used in the current study is described in detail in [11]. As such, the discussion of the theory will be limited to extensions made to the methodology here.

The soot surface temperature measurement method is based on the analysis of the radiation transmitted along a chord $y = y_o$ in a flame [9,12]:

$$I_\lambda(y_o) = \int N_p(x, y_o) \alpha_\lambda^{(a)} B_\lambda[T(x, y_o)] \cdot \exp \left[- \int_x^\infty N_p(x', y_o) \alpha_\lambda^{(e)} dx' \right] \quad (1)$$

where $I_\lambda(y_o)$ is the integrated radiation emission along a chord of flame, $N_p(x, y_o)$ the local particle number density, $\alpha_\lambda^{(a)}$ the absorption cross section of a primary particle, $B_\lambda[T(x, y_o)]$ the Planck function, $\alpha_\lambda^{(e)}$ the extinction cross section of a primary particle, λ the wavelength of radiation, and T the temperature. The absorption coefficient of the primary particle is used as is consistent with Rayleigh-Debye-Gans/polydisperse-fractal aggregate theory of particle scattering and extinction [13-15], provided the primary particle is in the Rayleigh range, i.e. $\pi d/\lambda < 0.3$.

As a first approximation, the assumption is made that attenuation of the radiation emission is negligible. In effect the exponential in Eq.1 is assumed to approach one and can therefore be ignored. This may not be justified in this work since the flame does exhibit significant signal attenuation, as demonstrated by line-of-sight light attenuation experiments performed previously [35]. Therefore, to compensate for any experimental error due to attenuation, a correction is developed. If Eq.1 is modelled with and without the extinction term present, it becomes possible to correct the measured emission through the relationship,

$$I_{corrected}(y, \lambda) = \frac{I_{measured} \cdot (I_{model})_{noextinction}}{(I_{model})_{extinction}} \quad (2)$$

The model intensity is calculated using the temperature and absorption coefficients obtained from an initial analysis of the measurements, ignoring signal attenuation effects. Extinction of flame radiation is estimated from absorption coefficients ignoring any scattering contributions. Thus the path-integrated radiation intensities are calculated with and without flame attenuation for each measured chord and a corrected set of experimental intensities are calculated from Eq.2. The process can be iterated if necessary but the correction terms are small enough that this is not required.

Figure 1. Schematic of optical layout.

Experimental Apparatus

The experimental setup used in this study is shown schematically in Fig. 1. Radiation emission from soot in an annular diffusion flame (A) passes through a 3.1 mm diameter aperture (B) and is then focused by a 104 mm diameter achromatic cemented Jaegers lens (C) onto the entrance slit of a Jarrell-Ash Monospec 18 spectrometer (F) at 1:1 magnification. The spectrometer slit (E) is oriented vertically with a height of 0.5 mm and a width of 0.025 mm. The output from the spectrometer images onto a Princeton Instruments CCD detector (G). The large collection $f\#$ (40) ensures that there is a large depth of field, resulting in an acceptably small variation in flame cross-section viewed from the flame.

The laminar diffusion flame burner is of similar design to that previously used by present authors [5,16] and others [17-19]. It is shown schematically in Fig. 2. It consists of a 10.9 mm inner diameter fuel tube, centered in a 100 mm diameter air nozzle. The ethylene fuel flow rate is 194 ml/min and that of propylene is 40 ml/min at 21°C and 1 atm. Under normal conditions, with these flow rates both fuels provide laminar diffusion flames burning slightly under their smoke point conditions, i.e., no soot escapes from the tip of the flame. The air flow is 284 l/min. A flame enclosure made of flexible steel mesh protects the flame from air movements in the room, with optical access provided by an appropriate viewing port. The burner is attached to a positioning platform with accurate and repeatable positioning both vertically and horizontally. Three fuel nozzles, with identical dimensions but each made from a different material (steel, aluminum, and pyrex glass), have been used. Fuel nozzle surface temperatures have been measured by thermocouples. Dimensions of the fuel nozzle and the location of thermocouple measure-

Figure 2. Schematic of the coflow laminar diffusion burner layout.

Figure 3. Dimensions of the fuel nozzle tube and locations of the thermocouples. Fuel nozzle outer surface temperatures are listed in the table.

ments are shown in Fig. 3.

Horizontal scans of line integrated spectra were collected over a spectral range of 685 to 945 nm. Each data acquisition consists of a spectrum averaged from 5 one second exposures. The spectral images were binned vertically over the 0.5 mm slit height to improve the signal to noise ratio. The spectra were also binned horizontally (spectrally) into 25 nm bins. The spectrometer was calibrated with a strip filament lamp, allowing the spectra to be scaled to units of absolute spectral intensity [W/m^3 ster].

Results and Discussion

The one-dimensional tomography is performed on the data using a three-point Abel inversion method [20].

Figure 4. Comparison of the soot surface temperatures obtained from emission spectroscopy with and without extinction correction to CARS temperature measurements made on the same burner [16]. Also shown is the comparison of the soot absorption coefficient data (with and without extinction correction) obtained in this work to absorption coefficients measured by 2-D imaging [35].

Each wavelength binned intensity scan provides experimental values of intensity, I_λ , versus r . The inversion of this data returns the quantity dI_λ/dr which can be used to calculate the radial temperature profile. Figure 4 shows the temperature profiles calculated in this manner with and without radiation extinction taken into account. These temperature profiles are compared to temperatures measured by CARS nitrogen thermometry in the same flame. CARS measurements of temperatures in this flame were described previously [5]. The soot surface temperatures are in excellent agreement with the CARS data. Error bars on CARS data indicates the precision of the measurements and is about ± 25 K. Soot surface temperature data with and without radiation extinction correction do not show any significant difference, especially at higher radial locations. The maximum difference, about 20 K, occurs at the flame centerline at this axial location of 30 mm downstream. Similar agreements have been obtained at 10 and 20 mm downstream locations where CARS data were available [5]. The excellent agreement between the CARS data and soot surface temperature measurements support the choice of constant $E(m)$ with wavelength assumed in the analysis.

Also shown in Fig.4 is the absorption coefficient, $N_p \alpha_\lambda^{(a)}$, from which soot volume fraction can be calculated. The absorption coefficient data are compared

to absorption coefficients obtained by 2-D imaging on the same burner [16]. The agreement is very good except at the peak. The peak value measured by radiation emission spectroscopy is higher by about 10% than 2-D extinction measurements possibly due to the finer effective spatial resolution of the former. Since the soot concentration predictions are very sensitive to calculated soot temperatures, this agreement further supports the constant $E(m)$ assumption made in soot temperature calculations. Absorption coefficient data with and without radiation extinction correction do not show any significant difference, Fig.4.

Figure 5. Soot volume fraction profiles of propylene as a function of radial location in the flame at downstream locations of 4, 6, and 8 mm with three different fuel nozzle materials. The inset shows the photographs of the propylene flames with three different nozzle materials. The glass nozzle produces a sooting flame and soot escapes from the flame tip (middle photograph).

Propylene Flames

Radial soot volume fractions of the propylene flames with three different burner materials are shown in Fig.5, for downstream locations of 4, 6, and 8 mm, and in Fig.6, for downstream locations of 10, 12, 14, 16, and 18 mm. At lower downstream locations, Fig.5, soot concentrations produced by the glass fuel nozzle are much higher than those with the aluminum and steel nozzles. Peak soot concentrations of the glass nozzle are 70-80% higher than those of the aluminum nozzle, whereas the soot concentrations of the steel nozzle flame are 17-28% higher than those of the aluminum nozzle. Similar concentration differences are observed at higher heights as shown in Fig.6. At the chosen flow rate of propylene, the diffusion flames on aluminum and steel nozzles burn slightly under the smoke point height.

However, with the glass burner at the same fuel flow rate, the propylene flame burns above its smoke point and soot escapes from the tip of the flame, inset in Fig.5.

Figure 6. Soot volume fraction profiles of propylene as a function of radial location in the flame at downstream locations of 10, 12, 14, 16, and 18 mm with three different fuel nozzle materials.

Radial profiles of the soot surface temperatures are shown in Fig.7, for downstream locations of 4, 6, and 8 mm, and in Fig.8, for downstream locations of 12, 14, 16, and 18 mm. At all downstream locations, soot surface temperatures of the glass nozzle flame are consistently lower than those of the aluminum and steel nozzle flames. At lower locations the differences are about 25 to 80 K at radial distances larger than 1 mm, Fig.7. At higher downstream locations differences in temperature grow towards the tip of the flame and at the 18 mm plane, the difference is about 200-250 K, Fig.8. The soot surface temperatures of the aluminum nozzle flame are slightly higher than those of steel nozzle throughout the flame, Figs.7 and 8.

The observed behaviour of the soot concentrations and soot surface temperatures can be explained in terms of the thermal conductivities and emissivities of the fuel nozzle materials. The flame heats up the fuel nozzle by conduction and radiation. In turn, the fuel nozzle dissipates this heat by conduction along axial upstream direction while, at the same time, transferring some of it to the fuel stream by convection inside the nozzle and to the air stream adjacent to the outside the fuel nozzle, effectively raising the temperatures of reactant gases. The ratio of heat dissipated by conduction to heat transferred to the reactant gases is dependent on the thermal diffusivity of the nozzle material. Thermal diffusivity of aluminum is about 9 times higher than steel, and about 250 times higher than that of glass [21]. Therefore, steel and aluminum fuel nozzles dissipate

Figure 7. Soot surface temperature profiles of propylene as a function of radial location in the flame at downstream locations of 4, 6, and 10 mm with three different fuel nozzle materials.

Figure 8. Soot surface temperature profiles of propylene as a function of radial location in the flame at downstream locations of 12, 14, 16, and 18 mm with three different fuel nozzle materials.

heat by conduction faster than it is convected to the reactant gases. The glass fuel nozzle heats the reactant gases more than the aluminum and steel, and thus the soot formation, which takes place through the pyrolysis of the fuel, is enhanced as the reactant temperatures are elevated in the soot inception region lower in the flame. Further, the radiative heat absorbed by the fuel nozzle is directly proportional to the emissivity of the material. Glass, steel, and aluminum have emissivities about 0.9, 0.5, and 0.2, respectively [22], and their radiative heat

gains are proportional to these values. Thus, higher emissivity and lower thermal conductivity of the glass nozzle lead to the sooting behaviour seen in Figs.5 and 6.

The fuel nozzle outer surface temperatures as measured by thermocouples are shown in Fig.3. The inner surface temperatures of the nozzles are expected to be much higher than these, especially for the glass nozzle (the inner surface temperatures were not measured because a thermocouple would disturb the fuel flow which would subsequently distort the whole flame). However, the nozzle outer surface temperatures shown in Fig.3, when considered with the thermal diffusivities of the three materials, give a rough indication of the relative magnitudes of heat dissipation by axial conduction along the fuel pipe for the three different nozzles.

As a result of the foregoing discussion one would intuitively expect that the soot surface temperatures will be higher for the glass nozzle flame than for the other two metal nozzle flames. It should be noted that heat loss from the soot laden flames by soot radiation is significant and may account for 20 to 30% of the total chemical heat release depending on the soot concentration [23]. As a result of higher soot concentrations, the glass nozzle flame loses much more heat by radiation in the past soot formation region than the other two metal nozzle flames, and hence has lower soot surface (and gas) temperatures as shown in Figs.7 and 8. As a consequence of significantly lower temperatures in the upper half of the flame, soot oxidation slows down and eventually stops leading to soot escape from the tip of the flame of the glass fuel nozzle, inset in Fig.5.

Ethylene Flames

The soot concentration profiles of ethylene flames with different fuel nozzle materials display results similar to those of propylene. However, the difference between soot concentrations of the glass nozzle flame and the metal nozzle flames decrease with an increase in downstream distance, Fig.9. At 10 mm downstream location peak soot concentration of glass nozzle flame is about 80% higher than that of the aluminum nozzle, and this decreases to about 50% at downstream location of 40 mm, Fig.9. The soot concentration differences between different fuel nozzle material flames diminish by the time the flame tip is reached and all three nozzles produce flames burning just under smoke point conditions and no soot escapes from the flames, contrary to the propylene flame with the glass fuel nozzle.

The ethylene flames of three different fuel nozzles show smaller differences in soot surface temperatures at downstream locations of 5, 10, and 20 mm, Fig.10, than the corresponding propylene flames. This is expected because of the lower soot concentrations, and

Figure 9. Soot volume fraction profiles of ethylene as a function of radial location in the flame at downstream locations of 10, 20, 30, and 40 mm with three different fuel nozzle materials.

hence reduced radiative heat losses, in ethylene flames as compared to propylene flames. At 30, 40, and 50 mm downstream locations, Figs.10 and 11, soot surface temperatures of the glass nozzle flame are lower than the metal nozzle flames by about 50 K. Soot surface temperature profiles of the aluminum and steel nozzle flames are almost identical, Figs.10 and 11.

Figure 10. Soot surface temperature profiles of ethylene as a function of radial location in the flame at downstream locations of 10 and 20 mm with three different fuel nozzle materials.

It seems that the nozzle heating of the flame exerts a significant influence on the soot formation/oxidation and the temperature field of the whole flame in propy-

Figure 11. Soot surface temperature profiles of ethylene as a function of radial location in the flame at downstream locations of 5, 10, 20, and 30 mm with three different fuel nozzle materials.

lene and ethylene flames. The influence is more severe in the case of the smaller more highly sooting propylene flame. Whereas on the larger flame (ethylene) the influence is mainly in the lower half of the flame. In the upper half of the ethylene flame these effects are not as high as they are in propylene flames. It should also be noted that the radiative heat transfer to the fuel nozzle is greater for the propylene flame than the ethylene flame due to two factors: The soot concentrations are higher in the propylene flame, and due to the smaller height of the propylene flame the propylene fuel nozzle sees a larger viewing angle of radiation than the ethylene flame does.

Concluding Remarks

The influences of the nozzle material on structure of soot and temperature fields in laminar coflow diffusion flames are not trivial and should be taken into account in comparisons of temperature and soot fields obtained on burners at different laboratories as well as in the modelling of the laminar diffusion flames.

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