

# Particle Size Distribution Functions of Soot Formed in Laminar Premixed *n*-Dodecane-Oxygen-Argon Flames

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## Abstract

*n*-Dodecane is an important component of jet fuel surrogate. In this study, we investigate experimentally the evolution of particle size distribution of incipient soot formed in laminar premixed *n*-dodecane-oxygen-argon flames. The flames are established on a porous flat flame burner with equivalence ratio equal to 2 and a maximum flame temperature of approximately 1800 K. Detailed size distributions are obtained by the burner-stabilized stagnation-flow (BSSF) sampling approach using a nano-scanning mobility particle sizer. The flame temperature profiles are determined for each separation distances between the burner surface and stagnation surface/probe orifice. As the size distributions are obtained using the recently developed BSSF approach, it is shown that the flames can be modeled using an opposed jet flame code without having to estimate the effect of probe perturbation. The measured and simulated temperature profiles show good agreement. The evolution of the soot size distributions for *n*-dodecane flames are similar to that obtained from ethylene flames. The size distributions are characteristically bimodal indicating strong, persistent nucleation over a large range of residence times in the flame. Under similar conditions, the nucleation mode in the *n*-dodecane flames is stronger than that in the ethylene flames.

## Introduction

Basic understanding of the reaction kinetic process of jet-fuel combustion is a critical element towards optimal design of aviation gas-turbine engines. Soot formation is an integral part of this kinetic process. Because jet fuels contain a large number of compounds, and the composition may vary from batch to batch, a direct kinetic description of their combustion behaviors, including soot formation, is not feasible. A viable approach is to use a fuel surrogate, containing five to six pure compounds, to mimic jet-fuel behaviors [1].\*

Typical jet-fuel surrogate mixtures contain mainly straight chained, branched and cyclic aliphatic hydrocarbons of which *n*-dodecane is an important *n*-alkane surrogate component [2]. In recent years, efforts have been directed at developing combustion reaction models for the surrogate fuel components [3-7]. At present, these models have been advanced to explain global combustion behaviors, such as ignition delay times [8], laminar flame speed [5, 9], and detailed time or spatial evolution of species concentrations resulting from fuel pyrolysis and oxidation in laboratory reactors [7, 10]. We expect that these models will have to be extended to include soot chemistry, but we note that reliable data for soot formation in *n*-dodecane flames do not exist.

Studies have shown that for a wide range of high-temperature combustion conditions, the oxidation kinetics of *n*-dodecane is governed, at least in part, by fuel cracking to smaller components ( $H_2$ ,  $CH_4$ ,  $C_2H_4$ ,  $C_3H_6$  etc), followed by the oxidation of cracked fragments [5, 11-13]. It is also expected that soot nucleation and growth starts from the

reactions of small, cracking products as far as *n*-dodecane is concerned. It is generally understood that the volume fraction of soot formed in laminar premixed flames is not particularly sensitive to fuel structure, since the fuel must undergo cracking before reaching the main flame zone and soot forms behind the flame [14-18]. In other words, reactions and especially the process of soot formation have almost no memory of the parent fuel structure in premixed flames.

It is unclear, however, whether the detailed particle size distribution function (PSDF) is also insensitive to the fuel structure. Recent studies on ethylene and other flames have shown that bimodality is the ubiquitous feature of nascent soot size distribution [19-33]. It is known that the detailed features of the size distribution is sensitive to the flame temperature [22], and that these features are indicative of various competing, elementary processes of soot formation [26]. At present, it is also unclear whether the various PSDF features observed for ethylene flames are applicable to *n*-dodecane flames.

Probe sampling in conjunction with a scanning mobility particle sizer (SMPS) has proved to be a useful tool in spatially resolving soot formation [19-21, 31, 33-35]. This technique allows the investigation of soot formation from particle nucleation to mass growth. On the other hand, probe sampling is inherently intrusive to the flame. In a recent study [32], we proposed a modified sampling approach in which the sample probe is also a stagnation surface that stagnates the burned gas flow downstream from the main flame zone of a burner stabilized flame. The method allows for intrusive soot sampling but the probe perturbation is captured quite rigorously as a boundary condition of the flame. The advantage of this technique is that the flame can be completely modeled using a quasi-1D opposed jet code.

The objective of this study is to provide a preliminary experimental database for soot formation in flames burning

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**Table 1.** Summary of flames studied.

| Flame | Mole fractions                  |                |       |                | Equivalence ratio, $\phi$ | Velocity, $v_0$ (cm/s) <sup>a</sup> | Maximum temperature, $T_f$ (K) <sup>b</sup> |
|-------|---------------------------------|----------------|-------|----------------|---------------------------|-------------------------------------|---------------------------------------------|
|       | C <sub>12</sub> H <sub>26</sub> | O <sub>2</sub> | Ar    | N <sub>2</sub> |                           |                                     |                                             |
| E1    | 0.025                           | 0.229          | 0.670 | 0.076          | 2                         | 4.94                                | 1807                                        |
| E2    | 0.025                           | 0.229          | 0.689 | 0.057          | 2                         | 6.58                                | 1875                                        |

<sup>a</sup> Cold gas velocity at the STP condition. <sup>b</sup> Corrected for radiation heat loss.

surrogate-fuel components. This study investigates experimentally the evolution of size distribution of nascent soot formed in two *n*-dodecane flames, by varying the cold gas velocity to achieve flame temperature variations. A liquid fuel system is developed that allows for effective fuel vaporization before being mixed with the oxidizer and diluent. Detailed particle size distributions, number density and volume fraction data are presented for each flame over a range of burner-to-stagnation surface separations. Additionally, numerical simulations were carried out using a recently proposed, detailed reaction model of *n*-alkane combustion [6] to examine the flame structure and conditions under which the PSDFs were probed. Temperature profiles are measured and compared to results of numerical simulations.

### Experimental methods

The experimental setup is similar to that described in a previous work [32]. Two lightly-sooting *n*-dodecane-oxygen-argon-nitrogen flames are stabilized at atmospheric pressure over a sintered porous plug with an outer diameter of 3 inches [31]. The flame was isolated from the ambient air by a shroud of nitrogen flowing at 43.6 cm/s (STP) through a concentric porous ring.

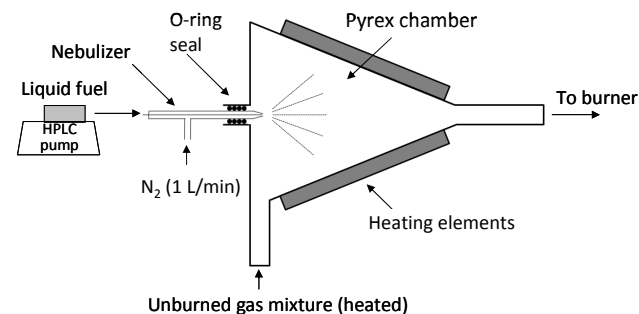
Soot was sampled on the centerline of the cylindrical flame in a spatially resolved manner with a positional accuracy of  $\pm 0.05$  cm. The sample probe is made of a stainless steel tube press-fit into a hole cut into a water cooled flat aluminum plate. A thin slit is cut into the bottom of the plate such that the sampling orifice in the stainless steel tube is exposed and is flush with the bottom of the plate. The plate is positioned parallel to the burner surface. The orifice is placed on the central axis of the burner. This sampling method creates a flame stabilized by heat loss to the burner surface, but the flow downstream diverges because of flow stagnation. For each burner-to-stagnation surface separation, the boundary conditions of this flame are defined, if the temperatures of the burner and stagnation surfaces are carefully determined, and the reactant composition and mass flow rates are given. As shown in [32], the flame is suitable for rigorous numerical simulation using a quasi-one dimensional opposed jet or stagnation flame code and detailed reaction kinetics.

Temperature of the burner and stagnation plate was measured by type-K thermocouples. For the stagnation plate, the thermocouple was embedded at the bottom of the plate facing the incoming gas flow. Care was taken to position the thermocouple flush with the bottom of the

plate so as to maintain a flat stagnation surface above the burner. For the burner temperature, the thermocouple was embedded at the bottom of the porous plug.

*n*-Dodecane was introduced to the reactant flow via a HPLC liquid pump (ChromTech Series III) with a maximum flowrate of 10 ml/min and  $\pm 2\%$  accuracy over the flow range. A nebulizer (Precision Glassblowing, Colorado USA) was used to aerosolize the liquid with mean droplet diameter of  $\sim 2$   $\mu\text{m}$ . The liquid was nebulized using a nitrogen flow at upstream pressure at 30 PSIG. At this pressure, the orifice in the nebulizer delivers a constant gas flow at 1 L/min (STP). The aerosol was introduced in a pyrex mixing/heating chamber where the atomized liquid is mixed with a oxygen/argon cross flow as shown in Fig. 1. The mixing chamber, the transfer line to the burner and the burner itself was maintained at a temperature of 220 °C to prevent *n*-dodecane from condensation. Unlike previous studies, the burner was not cooled. No trace of fuel condensation was seen inside the reactant delivery system. Also, the flame ignition and extinction response was approximately 3 second, close to the calculated residence time of the *n*-dodecane vapor in the delivery line, indicating that the fuel vapor stays in the vapor phase throughout. The mass flow rates of oxygen, argon and nitrogen were metered by critical orifices.

The reactant compositions are shown in Table 1. The equivalence ratio for both flames is kept constant at  $\phi = 2$ . The maximum flame temperature varies, however, by adjusting the total cold gas velocity. In each experiment, the burner was allowed to reach a steady-state temperature. The gas temperature was determined using a type-S thermocouple coated with a Y/BeO mixture to prevent surface catalysis. The diameter of the coated thermocouple wire was 125  $\mu\text{m}$ . The positional uncertainty of the thermocouple was  $\pm 0.03$  cm. Thermocouple radiation

**Figure 1.** Schematic of liquid vaporization chamber.

corrections were made using the procedure of Shaddix [36]. Uncertainty for the measured temperature was based largely on the uncertainty of the emissivity of the ceramic coating. Literature values for Y/BeO ceramic coating ranges from 0.3 to 0.6 [37]. The temperature reported is after correction for radiation heat loss and represents the mean value over that range of emissivity. The gas mixture properties were calculated iteratively by OPPDIF [38] using a detailed reaction model, JetSurF ver. 0.2 [6].

The flame sample entered the probe through the orifice and was immediately diluted with a cold nitrogen flow at 30 L/min. To ensure that particle losses were negligible in the sampling line, we used the particle dilution procedure identical to previous studies [20, 21]. The dilution ratio was calibrated by measuring the CO concentration using a gas chromatograph [31, 32]. Typical dilution ratio ranges from  $10^3$  to  $10^4$ . Visual observations of the soot accumulated over time on the sampling plate indicated that the soot from *n*-dodecane flames is “stickier” and more dense compared with soot produced from a similar ethylene flame [32], possibly due to a lower extent of carbonization for the *n*-dodecane flame soot.

A standard SMPS system from TSI was used to classify the flame aerosols. The SMPS consists of a single stage inertial impactor with an orifice diameter of 0.071 cm, a TSI 3077 charger and a 3080 classifier with a nano-Differential Mobility Analyzer (TSI 3085, nDMA) and a TSI 3025A ultrafine Condensation Particle Counter (UCPC). The UCPC has a lower mobility size limit of 3 nm due to small activation efficiency at smaller sizes. The sample and sheath flows through the DMA were 1.5 and 15 L/min, respectively. Corrections for diffusion losses in the transfer lines and DMA were made for as a function of particle diameter using the TSI AIM software.

Mobility measurements can overestimate the true size of particles smaller than 10 nm because of inherent limitation of the empirical Cunningham slip correction [39]. This correction does not account for (a) the transition from diffuse to secular scattering [40], and (b) the van der Waals gas-particle interactions; both effects are expected to be important for particles below 10 nm in diameter [39]. A nanoparticle transport theory [39-41], in which these effects are accounted for, gives a parameterized relation between the mobility diameter  $D_{p,SMPS}$  and true diameter  $D_p$  as follows:

$$\frac{D_p}{D_{p,SMPS}} = \tanh\left(1.4566 + 0.010892D_{p,SMPS}\right) \times \left(1.0721 - \frac{0.4925}{D_{p,SMPS}}\right) \quad (1)$$

In the above equation,  $D_{p,SMPS}$  has units of nm. All diameters presented hereafter are corrected according to the above equation. The particles studied were assumed to be spherical. In a previous study [19], we used atomic force

microscopy to investigate morphology. The results showed that nascent soot formed in similar premixed flames were liquid-like.

### Computational Method

The flame chemistry was simulated using JetSurF (version 0.2) [6]. This high-temperature kinetic model includes 194 species and 1459 reactions and was developed to predict the combustion properties of normal alkanes up to *n*-dodecane. The base model of  $H_2/CO/C_1-C_4$  combustion is the USC-Mech II (111 species, 784 reactions) [42], developed over the last decade through a series of kinetic modeling studies [43-51].

The stagnation flow used in these experiments has a separation-to-diameter ratio  $\ll 1$ , suitable for quasi-one dimensional simulation using OPPDIF [38]. In an earlier study of similar ethylene flames, we showed that the numerical formulation implemented can account for entire temperature profiles in the flame for all burner-to-stagnation surface separations studied [32]. The advantage of this combined experimental and computational method is clear, in that the boundary conditions are well defined and the inherent flame perturbation due to probe sampling can be accounted for quantitatively.

Boundary conditions are defined as follows. At the burner exit, defined as  $x = 0$ , the flow is a uniform plug flow with fixed mass flux and temperature equal to the measured burner temperature  $T_b$ . Each species has an inlet mass fraction defined as  $Y_{k,0}$ , and the boundary condition is constructed so that the mass flux of each species is  $\dot{m}_0 Y_{k,0}$ . These flow boundary conditions can be expressed as

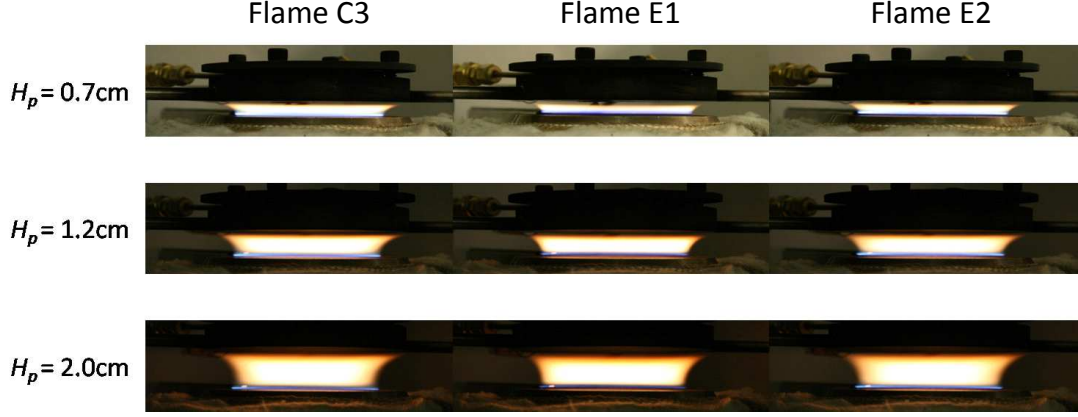
$$F = \rho u / 2 = \dot{m}_0 / 2, \quad (2)$$

$$G = \rho v / r = 0, \quad (3)$$

$$\rho Y_k (u + V_k) = \dot{m}_0 Y_{k,0}, \quad (4)$$

where  $\rho$  is the mass density,  $u$  is the axial convective velocity,  $r$  is the radial coordinate,  $v$  is the radial convective velocity, and  $V_k$  is the axial diffusion velocity of species  $k$ . The plate, located at  $x = H_p$ , is treated as a no-slip wall, so  $u$ ,  $v$ , and  $V_k$  are all 0, and it has a fixed temperature  $T_i$  equal to the measured plate temperature.

The simulation used windward differencing, multicomponent transport and thermal diffusion. Heat release rates and transport properties were solved using Sandia CHEMKIN [52] and TRANSPORT [53]. Adaptive mesh resolution was used and it was found that the flame is sufficiently resolved with roughly 200 points. Radiation correction was carried out as discussed in detail by Egolfopoulos [54] and described in Abid et al. [32]. The radiation heat loss due to soot in these lightly sooting flames is negligible, and so only radiation loss by gas phase species is considered in the simulations.

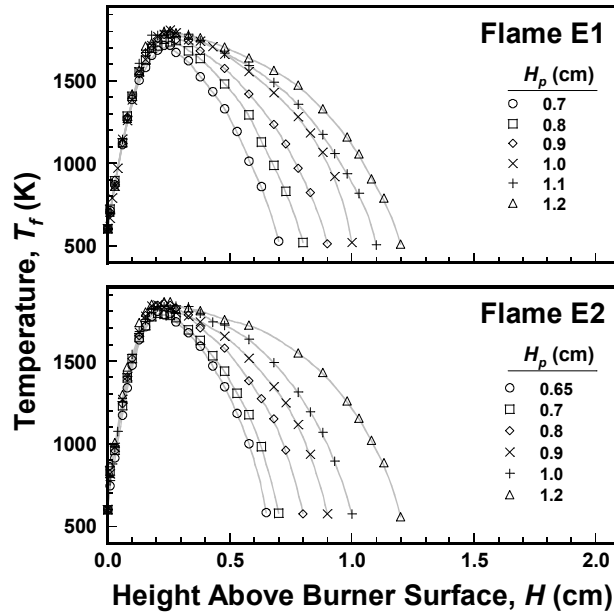


**Figure 2.** Visual images of the flames studied. Flame C1 is an 16.3% ethylene-23.7% oxygen-argon flame ( $\phi = 2.07$ ) at atmospheric pressure ( $T_{f,max} = 1837$  K) and a cold gas velocity of 8 cm/s [32]. Conditions of Flames E1 and E2 are provided in Table 1.

### Results and Discussion

Images of the flames studied (E1 and E2) are presented in Fig. 2 for three burner-to-stagnation separations  $H_p = 0.7, 1.2$  and  $2.0$  cm. Visually these *n*-dodecane flames do not differ from an ethylene flame (C3) observed previously [32], as seen in the figure. In all cases, the burner issues an unburned gas, which travels upward towards the stagnation surface. Flow diverges toward the stagnation surface. As discussed earlier, the sample probe is located on the stagnation surface along the center axis of the flame. Each burner-to-stagnation separation yields a different flame because of different degrees of flow divergence and heat loss into the stagnation surface. Hence, the temperature profile must be measured for each  $H_p$  values, as will be reported below.

Temperature profiles measured over a range of  $H_p$

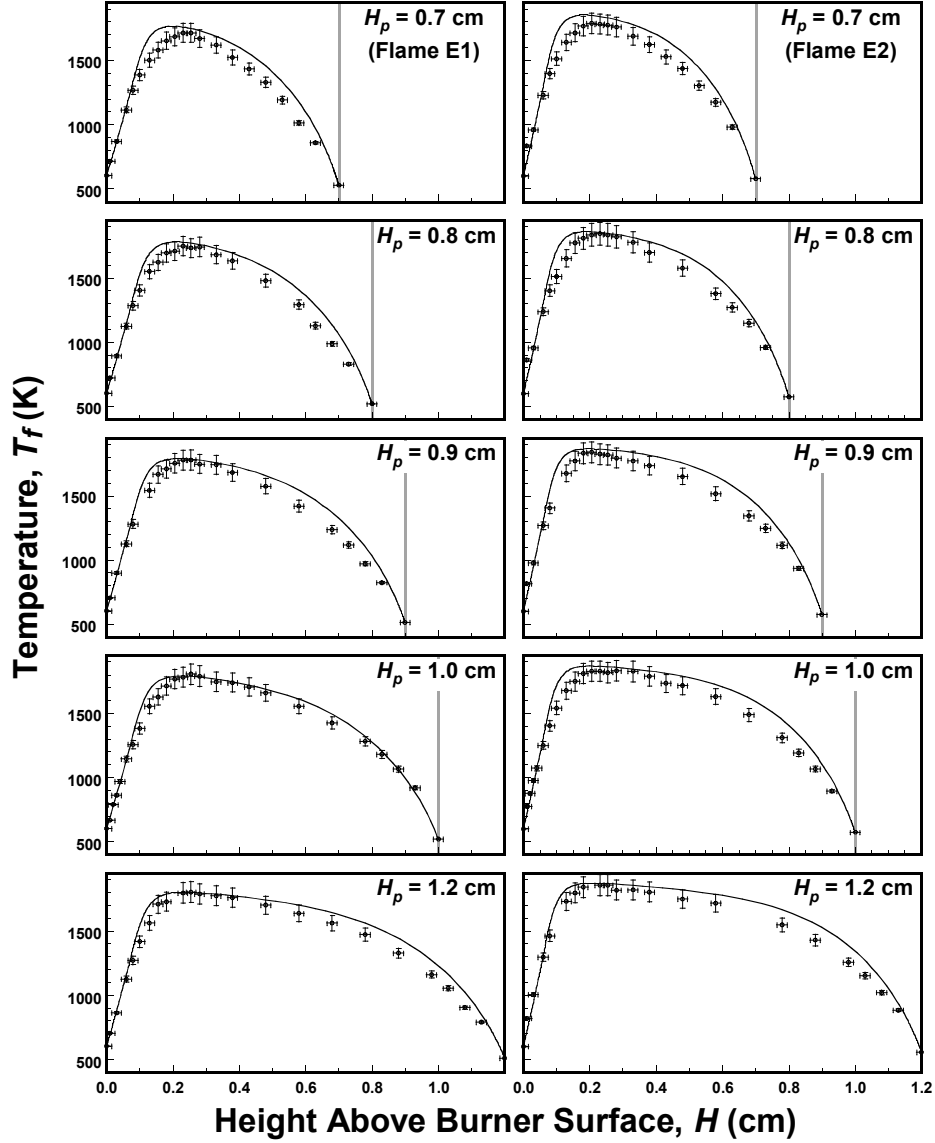


**Figure 3.** Measured, radiation-corrected temperature as a function of height above the burner. Symbols are experimental data; lines are drawn to guide the eye.

values are reported in Fig. 3 for both flames. As seen, both flames show similar trends of a sharp temperature gradient just above the burner surface, unaffected by the presence of the stagnation surface. Because of a lower unburned gas mass flux, the maximum flame temperature for Flame E1 is lower than that of Flame E2 by about 70 K. In all cases, the temperature drops to that of the stagnation surface, essentially quenching high temperature chemical reactions a few millimeters downstream from the reaction zone.

The shape of these temperature profiles are captured very well by the simulated temperature profiles. Fig. 4 shows the comparison between the simulations and the experimental data. The  $x$ -error bars on the measurements ( $\pm 0.03$  cm) represent the uncertainties due to finite thermocouple bead diameter and micrometer positioning. The  $y$ -error bars shown are based on the uncertainty due the wire emissivity. As seen, the simulated maximum temperature predicts the measurements well, except the preheat region where the measured temperatures are somewhat lower than model predictions. Towards greater distances from the burner surface, the simulated temperature is again larger than the experimental data. These discrepancies could be caused by thermocouple positional uncertainty, since the fine wire is bent slightly by the convective flow and the degree to which it bends is sensitive to the local flow velocity. In the preheat region, the larger predicted temperature could also be caused by uncertainties in JetSurF. We note that this is the first time this reaction model is being compared to combustion observations under fuel-rich sooting conditions. Nonetheless, the overall agreement shown in Fig. 4 is encouraging, keeping in mind that only the boundary temperatures, the reactant composition and mass flux were used as input parameters in the numerical simulations.

To understand the effect of the boundary conditions on the flame response, a sensitivity analysis was performed by perturbing (a) the cold gas velocity, (b) the temperature of the burner exit, and (c) stagnation plate for Flame E1 with  $H_p = 1.2$  cm, as shown in Fig. 5. Panel (a) shows a deviation of maximum flame temperature by  $\sim 100$  K from



**Figure 4.** Comparison of measured (symbols, radiation corrected) and simulated (lines) temperature profiles at selected burner-to-stagnation surface separations. Left column shows data for Flame E1 and right column shows data for Flame E2.

the base case for Flame E1 when the mass flux is perturbed by 20 %. Note that the extent of the perturbation is substantially larger than the uncertainty of our flow measurements, which is around 2%. Additionally, the effects of perturbing the burner exit temperature or the plate temperature by 100 K (again, substantially larger than the uncertainty of our temperature measurements) have a small effect on the entire temperature profile. Two conclusions may be drawn from these numerical analyses. First, with the experimental setup the flame is not affected significantly by boundary condition perturbations. Second, the observed, minor discrepancies seen in Fig. 4 are probably not caused by uncertainties in the flame boundary conditions.

The major and minor species profiles computed for Flame E1 at the  $H_p$  value of 1.2 cm are shown in Figs. 6 and 7 respectively. These profiles are typical for fuel-rich flames and are qualitatively similar for all  $H_p$  values studied. For major species, all of the mole fraction profiles computed are nearly constant in the post flames, with the exception of  $H_2$ . Computational, the use of a stagnation surface causes  $H_2$  mole fraction to undergo notable changes towards the stagnation surface. This is caused by perturbation of thermodynamic equilibrium due to a rapid decrease in the local flame temperature. All of the free radical concentrations also drop rapidly, as shown in Fig. 7.

What is perhaps more interesting is the benzene mole fraction profiles computed for these flames. Fig. 8 shows that the presence of the stagnation surface causes the

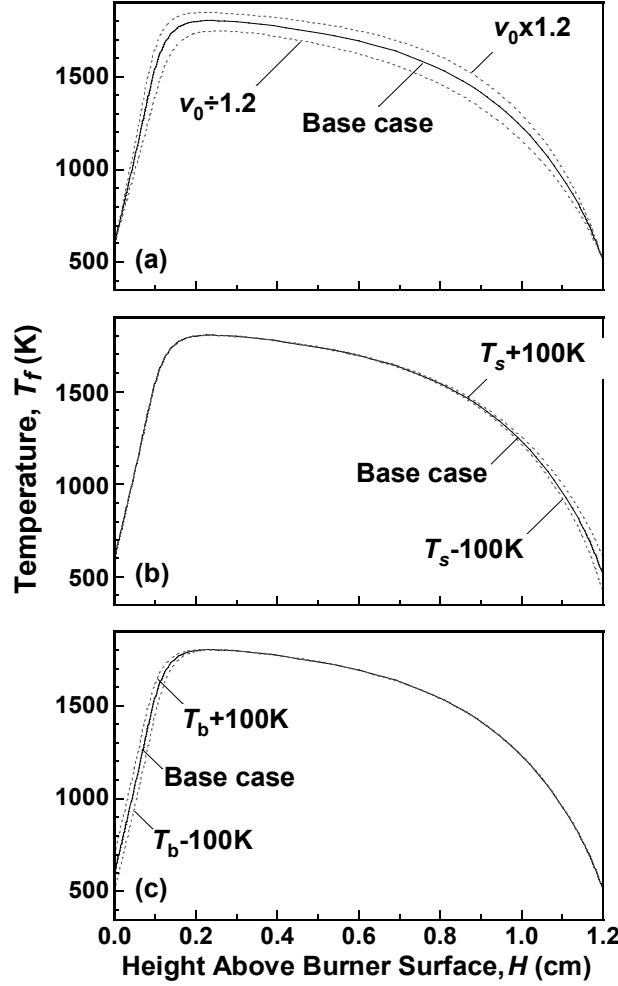


Figure 5. Computational sensitivity analysis for Flame E1 with  $H_p = 1.2$  cm by perturbing (a) the mass flux, (b) the stagnation plate temperature  $T_s$ , and (c) the burner exit temperature  $T_b$ .

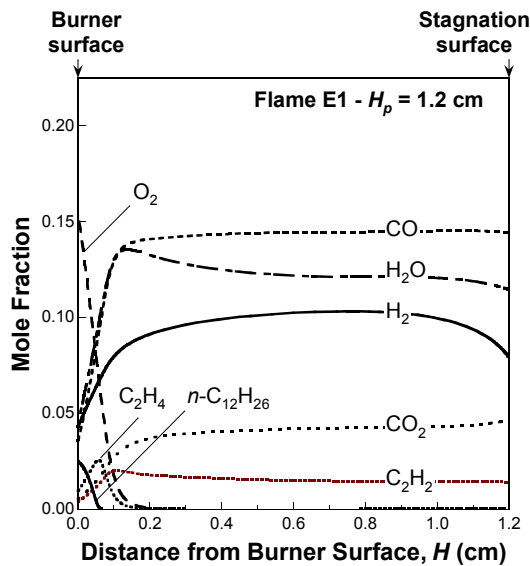


Figure 6. Mole fraction profiles of major species computed for Flame E1 with  $H_p = 1.2$  cm.

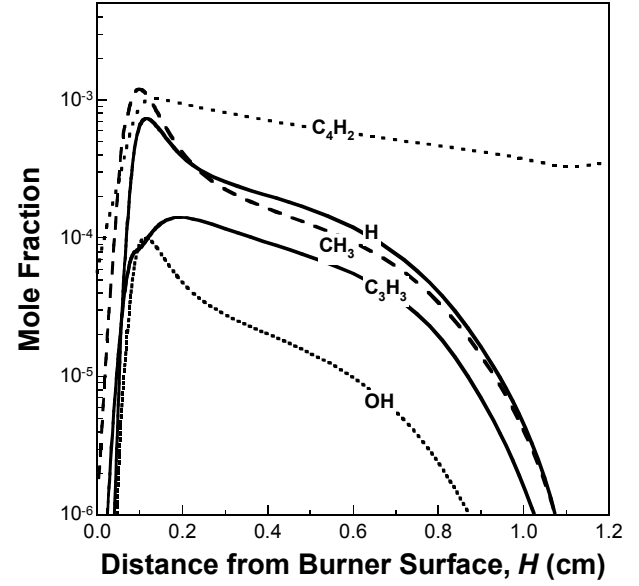


Figure 7. Mole fraction profiles of selected minor species computed for Flame E1 with  $H_p = 1.2$  cm.

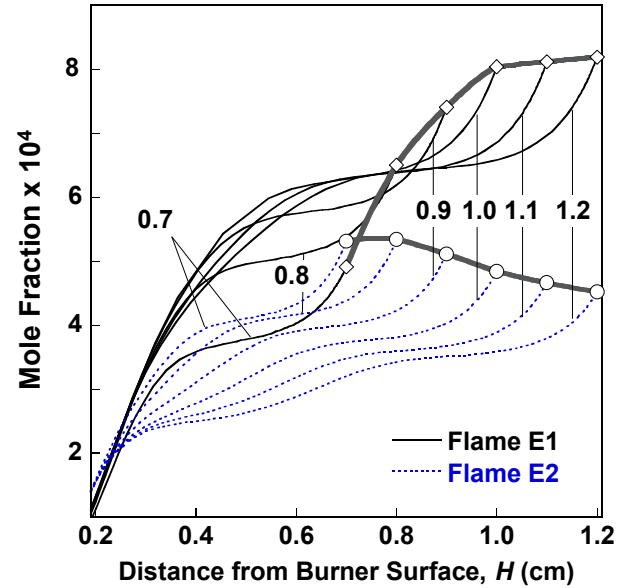


Figure 8. Benzene mole fraction profiles (thin lines) computed for Flames E1 and E2 at selected  $H_p$  values. Symbols and thick lines indicate the benzene mole fraction at the stagnation (sampling) surface.

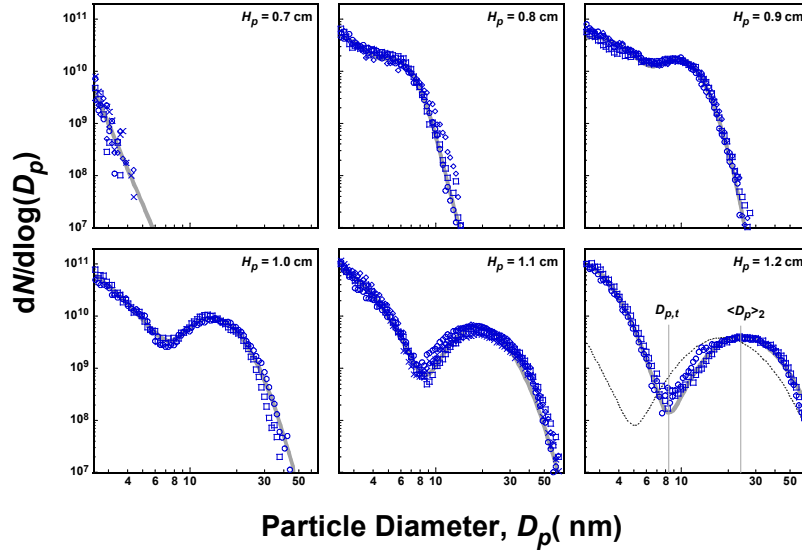
benzene mole fractions to vary widely as a function of  $H_p$ . This variation is certainly caused by both temperature and local flow velocity. Towards the stagnation surface, benzene concentration undergoes a rapid rise, again because of cooling and reduced rates of fragmentation. It is worth noting that had benzene concentrations been measured at the stagnation surface (or by a probe), its concentration would exhibit an apparent increase in the post flame of E1, but it would decrease with increasing distance from the

burner in Flame E2. This behavior has been discussed early [55], and can be attributed to the influence of flame temperature on the competition between molecular weight growth and fragmentation. In any case, in our earlier studies of ethylene flames under comparable conditions, we demonstrated that if the concentration of soot precursors, i.e., the aromatics, does not decay in the post-flame regime, the soot size distribution would be bimodal. The cause for the bimodality is the persistent particle nucleation which competes with particle size growth by coagulation [21, 22].

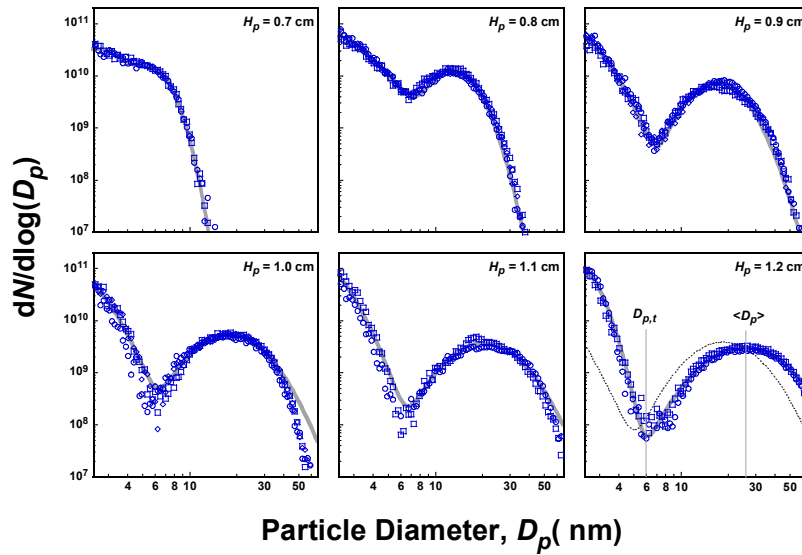
Indeed the PSDFs measured for both *n*-dodecane flames are bimodal, as shown in Figs. 9 and 10 for Flames

E1 and E2, respectively. In these figures, the different symbols designate multiple runs and the overlap of symbols shows that the data are highly reproducible. For the lower temperature flame (E1), with  $T_{f,max} = 1807$  K, the transition to bimodality occurs at higher  $H_p$  values than that for Flame E2, as expected because of a larger standoff distance of the reaction zone. Like the ethylene flames, these PSDFs can be described by a bi-lognormal distribution closely, as shown by the lines of Figs. 9 and 10,

$$\frac{dN}{d \log D_p} = \sum_{i=1}^2 \frac{N_i}{\sqrt{2\pi} \log \sigma_i} \exp \left\{ -\frac{\left[ \log \left( D_p / \langle D_p \rangle_i \right) \right]^2}{2 (\log \sigma_i)^2} \right\}, \quad (5)$$



**Figure 9.** Evolution of particle size distribution functions at increasing burner-to-stagnation surface separations for Flame E1. Symbols are experimental data; lines are bi-lognormal fits to data. The dashed line plotted for  $H_p = 1.2$  cm is taken from [32], measured for a comparable ethylene flame (C3) with  $T_{f,max} = 1837$  K.



**Figure 10.** Evolution of particle size distribution functions at increasing burner-to-stagnation surface separation for Flame E2. Symbols are experimental data; lines are bi-lognormal fits to data. The dashed line plotted for  $H_p = 1.2$  cm is taken from [32], measured for a comparable ethylene flame (C3) with  $T_{f,max} = 1837$  K.

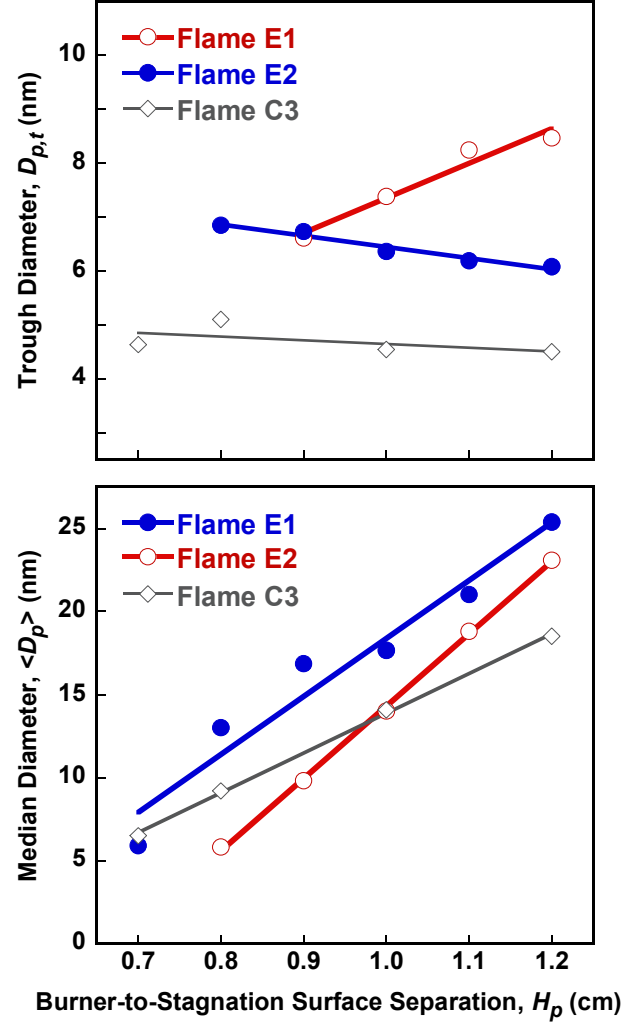
where  $\sigma_i$  is the geometric standard deviation of the  $i^{\text{th}}$  mode, and  $\langle D_p \rangle_i$  is the median diameter of that mode. Mode 1 corresponds to the nucleation mode, and mode 2 is the growth mode. Several additional features emerge from these PSDFs, all of which are similar to the ethylene flames reported earlier [31]. Recall that the main difference between the two flames studied here are their maximum flame temperature. Although many of the features are qualitatively the same, quantitatively the fine details of the PSDFs are indicative of the competition of various elementary particle processes [26].

For Flame E1,  $T_{f,\text{max}} = 1807$  K, and for Flame E2,  $T_{f,\text{max}} = 1875$  K. Two important features emerge as we compare the PSDFs of the two flames: the lower temperature flame has larger median particle diameters for the growth mode, as seen by the difference in  $\langle D_p \rangle_2$  values of Fig. 11; and the transition from mode 1 to mode 2 occurs at larger particle size, as shown by the difference in  $D_{p,t}$  values. The difference in the median particle diameter is consistent with the concentrations of benzene computed for the two flames. As shown in Fig. 8, the benzene mole fraction of Flame E1 is notably larger than that of Flame E2.

In Flame E1, the larger values measured for the diameter at the trough  $D_{p,t}$  is accompanied by somewhat greater intensities of the nucleation mode. This can be attributed to a greater extent of increase in the precursor concentration as predicted for benzene. Although benzene is not likely to be the nucleating species, its spatial variation is indicative of the variations of larger, polycondensed aromatics [55]. Numerical sensitivity analysis done by Singh et al. [26] on the shape of these bimodal distributions indicates that the position of the trough is strongly influenced by the nucleation rate and the size of the nuclei. In addition, a longer residence time in Flame E1 can also contribute to the increased nucleation mode intensity. Considering the separation distance of  $H_p = 1.2$  cm, the residence time for a parcel of fluid exiting the burner to reaching 0.1 cm below the stagnation surface is  $\sim 70$  ms for Flame E1 and  $\sim 50$  ms for Flame E2. The longer residence time allows for prolonged nucleation resulting in a stronger nucleation tail for Flame E1. Meanwhile the coagulation of the particles in the growth mode becomes increasingly insignificant as it is indicative by their number densities dropping well below that of the particles of the nucleation mode.

For both flames, the nucleation modes appear to be stronger than that in a comparable ethylene flame ( $T_{f,\text{max}} = 1736$  K), as shown for  $H_p = 1.2$  cm in Figs. 9 and 10, indicating that the nucleation strength in these *n*-dodecane flames is stronger in the postflame region than the comparable ethylene flame. The difference may be attributed in part to the somewhat shorter residence time, around 40 ms, for flame C3, in comparison with 70 and 50 ms in Flames E1 and E2, respectively.

The volume fraction and particle number density may be derived from the PSDF data. The results of both flames



**Figure 11.** Particle diameter at the trough and median diameters of the growth mode of the soot PSDFs obtained from bi-lognormal curve fits. Data for Flame C3 is from ref. [32].

are shown in Figs. 12 and 13, respectively. Again, the trends are similar to that seen in a similar ethylene flame (Flame C3) [32]. The final volume fraction for both *n*-dodecane flames is around  $10^{-8}$  and the number density of soot in these flames is around  $10^{10}$   $\text{cm}^{-3}$ . Again, the constant number density observed for Flame E1 whereas a decreased number density in Flame E2 at larger burner-to-stagnation surface separations are consistent with differences observed for the nucleation strengths between the two flames. With these data in conjunction with detailed temperature profiles, both measured and simulated, these flames are suited ideally for validating detailed soot models at a high resolution.

## Conclusions

Detailed particle size distribution, temperature profiles, volume fraction and number density data were measured for two premixed *n*-dodecane-oxygen-argon flames at

equivalence ratio  $\phi = 2$  and atmospheric pressure in a burner-stabilized stagnation flow setup. The experimental temperature profiles are compared to simulations using the OPPDIF flame code. The results compare well with each other. The qualitative feature of the particle size distributions observed for the two flames, including the persistent bimodality, is similar to earlier observations made for similar ethylene flames, again indicating the insensitivity of soot formation to detailed fuel structure in premixed

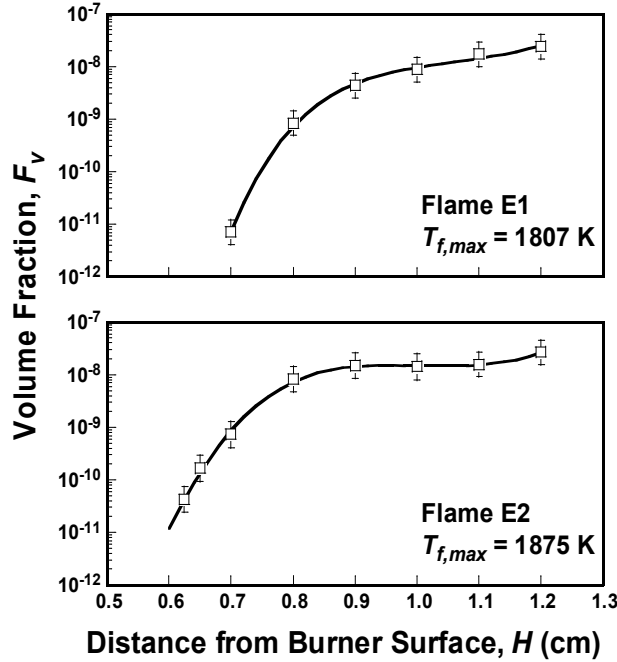


Figure 12. Soot volume fraction observed for Flames E1 and E2.

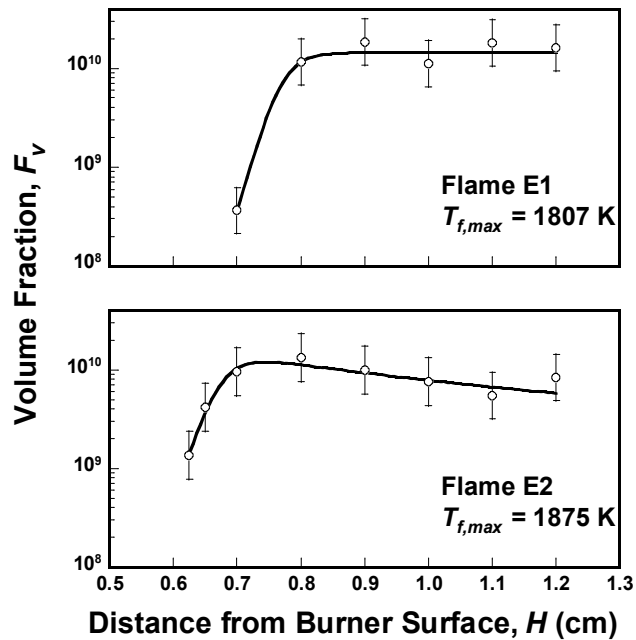


Fig. 13. Number density profiles observed for Flames E1 and E2.

flames. The fine, quantitative feature of the soot PSDFs in the *n*-dodecane flames can be different from that in an ethylene flame under comparable conditions. For example, the PSDFs of the current *n*-dodecane flames exhibit stronger nucleation intensities in the post flame region and the trough of the bimodal distributions occurs at larger particle size than that of the ethylene flame.

With the ability to quantify the flame boundary condition and eliminate the unquantifiable probe perturbation to the flame, the flame structure and species profiles can be predicted with a high level of confidence. Hence, these data provide a reliable experimental database to model soot formation from flames of real-fuel surrogate components.

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