Soot formation in laminar diffusion flames at elevated temperatures
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Soot Formation in Laminar Diffusion Flames at Elevated Temperatures

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INTRODUCTION

The important parameters that influence the formation of soot in laminar diffusion flames are the parent fuel molecular structure, the flame temperature, the amount of diluents either in the fuel or in the oxidizer, and the pressure. In some previous diffusion flame soot studies, temperature effects were examined by substituting argon in place of nitrogen in the air, *e.g.* Schalla and McDonald [1], and by nitrogen dilution of the fuel, *e.g.* Gomez and Glassman [2], Santoro and Semerjian [3], Boedeker and Dobbs [4].

Two issues related to the influence of inert diluents on soot formation remain unclear. The first of these is the relative importance of the two effects, namely, lowered fuel concentration and lowered flame temperature, when an inert diluent is added to the fuel. The second issue is that whether the flame temperature influence can be properly examined by adding inert diluents to the fuel, or by replacing some portion of nitrogen in air with a higher specific heat inert gas.

In the present study, which complements our previous work [5-7], we focus on (a) the influence of flame temperature on soot formation in flames in which the fuel flow rate was kept constant as the flame temperature was varied by varying the temperature of reactants, and (b) the temperature sensitivity of different fuels. Also reported are the data obtained on flames burning at their smoke points at all temperatures considered. Propylene, ethylene and isooctane were used as fuels. Data obtained with propane in our previous study [5] have also been used in the assesment of the temperature sensitivity of different fuels. The line-of-sight average soot volume fractions have been determined by laser extinction measurements, and soot particle temperature measurements have been made using a disappearing filament pyrometer.

EXPERIMENTAL METHODOLOGY

The experimental set-up is the same as used in our previous work [5]. The fuel nozzle of the burner is a stainless-steel pipe of 3 mm inner diameter. Air is supplied from a concentric converging nozzle of 100 mm inner diameter. Both air and fuel streams are heated by regulated electric heaters. The line-of-sight average soot volume fractions along the centerline of the flames were measured by the transmission of a multi-line laser beam made of three wavelengths, GaAlAs (830nm), He-Ne (632.8nm), and Ar-Ion (515nm). The optical path length, *e.g.*, the flame diameter, was measured by a reading telescope with an eyepiece. Further details of the experimental rig and the soot temperature measurements are given in [5].

RESULTS AND DISCUSSION

The line-of-sight average soot volume fraction profiles, as a function of axial position, of ethylene flames at four different reactant temperatures are shown in Figure 1. The fuel mass flow rate is 3 mg/s in all cases. This rate corresponds to a smoke point flame at T_r =300 K, but at higher reactant temperatures some amount of unoxidized soot escapes from the tip of the flame, Figure 1. The change in the maximum soot volume fraction for a change in reactant temperature from 673 K to 300 K is about 40 percent, and the corresponding change in adiabatic flame temperature is about 148 K.

Santoro and Semerjian [3] studied the effect of flame temperature on soot formation in a concentric co-flowing diffusion flame by adding nitrogen to the fuel and keeping the fuel flow rate constant. They added sufficient nitrogen (nitrogen-to-fuel ratio 2.29 by volume) to ethylene to reduce the adiabatic flame temperature from 2369 K (for pure ethylene) to 2223 K. A depression of 146 K in the adiabatic flame temperature of this ethylene flame provided an order of magnitude reduction, from 11 ppm to approximately 1 ppm, in the amount of maximum soot concentration. In our experiments with ethylene, at constant fuel flow rate, the change in the adiabatic flame temperature from T_r =673 K to T_r =300 K is 148 K. Corresponding change in the maximum soot volume fraction is very small as compared to the results of Santoro and Semerjian [3] for the same amount of temperature change. The maximum soot volume fraction reduces to 7.8 ppm from 13.3 ppm, a decrease about 40 percent, Figure 1. Since the two studies were carried out on similar diffusion flames, the only possible explanation for this significant discrepancy is the dominant influence of dilution on soot formation due to the inert diluent added to the fuel in the study of Santoro and Semerjian [3].

In order to illustrate the response of the sooting behaviour of different hydrocarbons to flame temperature changes, normalized maximum soot volume fraction values are plotted against increases in adiabatic flame temperatures in Figure 2. Normalized maximum soot volume fraction is the ratio of the maximum soot volume fraction per unit fuel flow rate, ppm/mg/s, at a given reactant temperature normalized with respect to the value at T_r = 300 K. The adiabatic flame temperature increase is the difference between the adiabatic flame temperature at a given reactant temperature and the adiabatic flame temperature at T_r = 300 K.

Data obtained with the three fuels used in this study, and the propane data from our previuos study [5] indicate that olefinic fuels (ethylene and propylene) exhibit lower temperature sensitivity as compared to alkanes (propane and isooctane), Figure 2. Gomez and Glassman [2] noted that aromatics and dienes show lower temperature sensitivity as compared to the aliphatics; but they did not differentiate among different aliphatic groups. To our knowledge, this is the first observation of the differing temperature sensitivities of the two aliphatic groups.

CONCLUSIONS

Obtained data from smoke point flames and flames at fixed fuel flow rates at different reactant temperatures using ethylene, propylene, isooctane, and propane as fuels lead to the following conclusions:

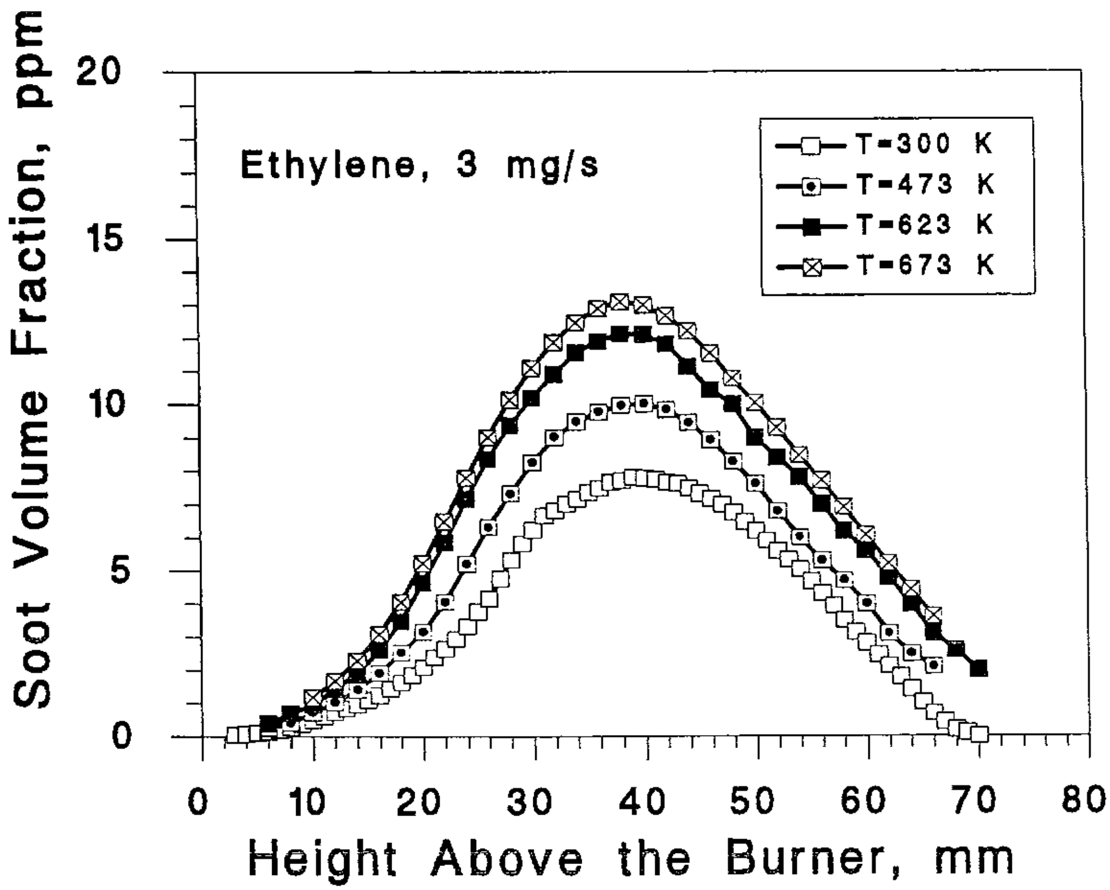

Figure 1. The line-of-sight average soot volume fraction profiles as a function of axial position, of ethylene flames at four different reactant temperatures.

1. Olefins (propylene and ethylene) show a lower sensitivity to flame temperature as compared to alkanes (isooctane and propane).
2. Maximum soot volume fractions and soot formation rates increase with increased flame temperature as noted by others; but the observed changes are not as large as the changes measured by other investigators by adding an inert diluent to the fuel to alter the flame temperature. In previous diffusion flame studies in which the temperature effects were examined by nitrogen dilution of the fuel, the observed effects on soot formation are due to dilution as well as the temperature. For this reason, results of such previous studies should be reevaluated.

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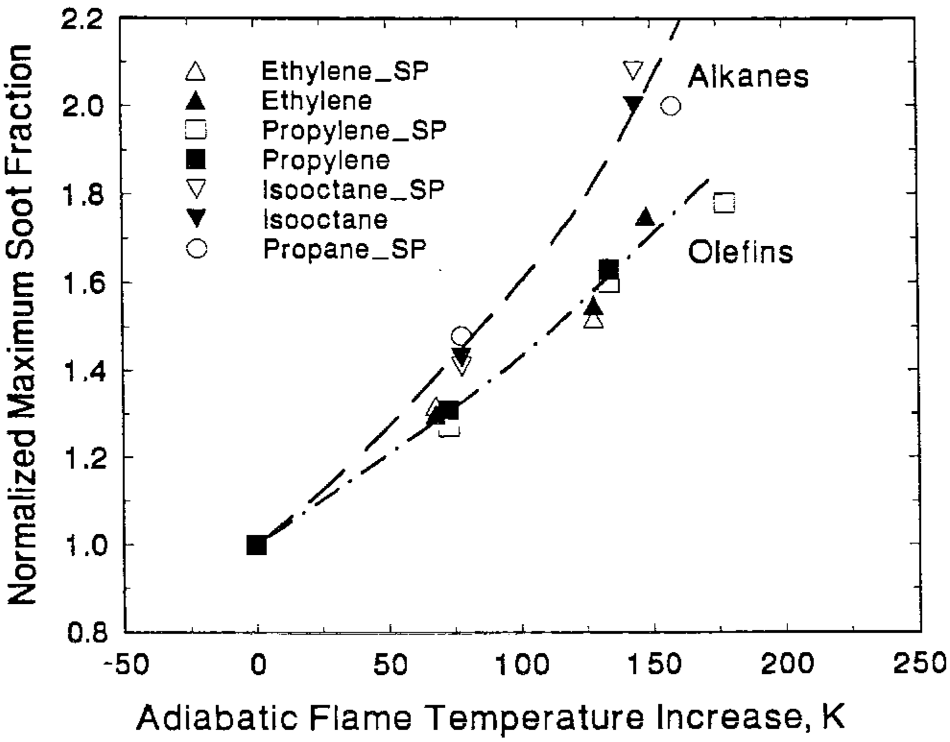

Figure 2. Temperature sensitivity of the alkanic and olefinic hydrocarbons studied in this work. In the legend, fuel names followed by an SP refer to a smoke point flame. Others are flames at fixed fuel flow rates at different reactant temperatures. Normalized maximum soot volume fraction is defined in the text.

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