



# Dependence of sooting characteristics and temperature field of co-flow laminar pure and nitrogen-diluted ethylene–air diffusion flames on pressure



Ahmet E. Karataş, Ömer L. Gülder\*

*Institute for Aerospace Studies, University of Toronto, 4925 Dufferin Street, Toronto, Ontario M3H 5T6, Canada*

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## ABSTRACT

Pressure dependence of sooting characteristics and the flame temperature field of pure ethylene and ethylene diluted with nitrogen in co-flow laminar diffusion flames was investigated experimentally. The pressure range for ethylene was from atmospheric to 7 atm and to 20 atm for nitrogen-diluted ethylene flames. Spectrally-resolved line-of-sight soot radiation emission measurements were used to obtain radially resolved temperatures and soot volume fractions by using an Abel type inversion algorithm. A constant mass flow rate of ethylene was maintained at 0.48 mg/s at all pressures to match the carbon flow rates of gaseous alkane fuels experiments reported previously. Visible flame heights, as marked by the luminous soot radiation, initially increased with pressure, but changed little above 5 atm. Maximum local soot volume fraction of ethylene flames seems to scale with pressure raised to the third power (about 2.8). This is argued to be a relatively stronger pressure dependence of maximum soot volume fraction as compared to other gaseous fuels. A similarly higher pressure dependence was observed when the maximum soot yields of ethylene and other gaseous fuels were compared. It was shown that the soot yield dependence of ethylene flames does not conform to the unified dependence on pressure which was demonstrated for gaseous alkane fuels recently. The sooting propensity of nitrogen-diluted ethylene flames was shown to be less than that of *n*-heptane flames diluted with similar amount of nitrogen. Flame temperature profiles and averaged temperatures of ethylene flames showed similar characteristics as the other gaseous fuels, however radial temperature gradients in ethylene flames were much higher than those in gaseous alkane fuel flames.

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## 1. Introduction

Soot aerosols exhausted into the atmosphere from air and land transportation engines constitute a significant portion of the particulate matter in the air. Soot aerosol, also called as black carbon, emitted to the atmosphere is not only an unwanted pollutant in the environment and is implicated in a number of health problems [1], but it also influences the thermal equilibrium of the planet. Deposition of soot aerosols on Polar Regions and the suspended soot particles in the atmosphere could be one of the major causes of the global warming originating from the human activity. Recent research efforts estimate the effect of soot on climate change to be second only to that of carbon dioxide, see for example [2].

Size limitations and fuel efficiency concerns dictate that most energy conversion devices based on combustion should operate

at pressures much higher than atmospheric. Available soot research results reported recently for a limited number of fuels (mostly gaseous) have shown that the pressure is one of the most significant parameters that influence soot formation [3]. A detailed description of the dependence of soot on pressure is not available and there is a lack of sound combustion and soot models that could be used for practical applications that operate at elevated pressures. For this reason, studies that would enhance our understanding of the effects of pressure on soot formation and oxidation are of great interest. Our current understanding of inception, growth, and oxidation of soot at pressures above atmospheric is quite limited, and tractable measurements at elevated pressures are needed to advance the field and provide a better understanding. The main objective of the current study is to investigate the effects of pressure on soot formation and temperature field in pure and nitrogen-diluted ethylene laminar diffusion flames at pressures above atmospheric, and compare the findings to similar measurements with gaseous and liquid alkane fuels. Ethylene is not a commercial

\* Corresponding author. Fax: +1 416 667 7799.

E-mail address: [ogulder@utias.utoronto.ca](mailto:ogulder@utias.utoronto.ca) (Ö.L. Gülder).

fuel or an important component of commercial fuels used in combustion engines. However, in majority of research studies on soot processes ethylene has been used as the fuel, and some of the empirical models for soot processes have been based on and verified with measurements in ethylene flames. During the combustion of liquid hydrocarbons, ethylene is one of the most abundant olefins as an intermediate species. For studies related to soot, ethylene could be used to mimic the sooting properties of aviation kerosene as a simple surrogate.

One of the earlier studies of pure ethylene laminar diffusion flames on a co-flow burner was conducted by Flower and Bowman [4] at elevated pressures from atmospheric to 10 atm. Their main measurements were line-of-sight temperatures and integrated soot volume fractions along the flame centerline. Similar measurements were reported by McCrain and Roberts [5] conducted with a co-flow burner fueled by pure ethylene, and the pressure range was extended to 16 atm. Experiments of Lee and Na [6] with a similar configuration were done at pressures up to 4 atm. The experimental results reported by Darabkhani et al. [7] covered the same pressure range considered in [5] using a similar experimental rig. There are concerns related to the tractability of measurements in these studies with ethylene in laminar diffusion flames at elevated pressures. In studies reported in [4,5,7] the flames were non-smoking at pressures of atmospheric and a few atmospheres, meaning that the flames were burning below their smoke-point heights with less than smoke-point fuel mass flow rate. However, at pressures above a few atmospheres the fuel mass flow rates were no longer corresponding to non-smoking flames [4,5,7]. It is well-established that the smoke-point fuel mass flow rate varies strongly with pressure and decreases as the pressure is increased, as explained in detail in a recent review [3]. For high pressure soot experiments with laminar co-flow diffusion flames the fuel mass flow rate should be carefully selected. The fuel mass flow rate should be such that it should not exceed the smoke-point mass flow rate at the highest pressure of the experiment. This is essential for tractable soot measurements that are conducted for the purpose of assessing the effect of pressure on soot processes. Diluting the ethylene with an inert gas delays the onset of smoking [8] and allows a higher fuel mass flow rate to be used in the experiments, however the sooting behavior of pure ethylene is desirable as a reference bench-mark at elevated pressures. Further, it would be interesting to see whether the sooting characteristics of ethylene with pressure conform to the unified behavior of gaseous alkane fuels reported recently [9]. The only studies with pure ethylene in a tractable manner at elevated pressures were reported by Panek et al. [10] and Guo et al. [11] up to 5 and 8 atm, respectively, with an ethylene flow rate of 0.48 mg/s. Guo et al. [11] reported maximum soot volume fractions and integrated soot concentrations up to 8 atm; the temperature field within the flame envelope was not measured and soot yield information was not provided. Measurements reported in Panek et al. [10] have been repeated at 1, and 5 atm; and further measurements were done at 3 atm and at 7 atm with the same ethylene flow rate in the current work.

A series of tractable high pressure laminar flame soot studies has been reported by the senior author's group in recent years. Thomson et al. [12] and Joo and Gülder [13] studied methane laminar diffusion flames at pressures up to 40 atm and 60 atm, respectively. These were the first detailed data sets of radially resolved soot concentration and soot temperature measurements in laminar co-flow diffusion flames at elevated pressures. Measurements in propane diffusion flames using the same experimental setup as [13] were reported by Bento et al. [14]. Propane experiments were limited to the pressure range from atmospheric to 7.3 atm, and the measured soot and temperature profiles were comparable to those in [12] for the lower pressure range. The measurements were extended to ethane flames in [15] and the maximum pressure

was 33 atm, and the results displayed similar behavior to that of methane flames although the soot concentration levels were much higher at similar pressures. Joo and Gülder [8] reported soot and temperature field measurements in nitrogen-diluted ethylene flames up to 35 atm [8]. Fuel to nitrogen mass ratio in diluted ethylene stream was 5 and this dilution ratio permitted to have non-smoking flames up to 35 atm. In a more recent report, it was shown that the high pressure soot yield data from laminar methane, ethane, and propane diffusion flames could be scaled, and the scaled maximum soot yields display a unified dependence on pressure [9]. Available experimental data show that the scaled maximum soot yield increases with pressure initially, but as the pressure further increases it reaches a plateau asymptotically, approximately at the critical pressure of the fuel [9]. First tractable measurements at elevated pressures with a liquid hydrocarbon were conducted in laminar diffusion flames of pre-vaporized *n*-heptane [16]. The fuel was diluted with a constant amount of nitrogen to have non-smoking flames up to 7 atm.

In the current study, the effects of pressure on sooting characteristics and temperature field of pure ethylene–air diffusion flames are studied. Further experiments were done with ethylene diluted with nitrogen for the purpose of comparison to similarly diluted *n*-heptane flames at pressures above atmospheric, reported by the current authors previously [16]. Results are compared to the characteristics of other gaseous and liquid fuels, and similarities and differences are discussed in terms of maximum soot volume fraction, soot yield, and temperature profiles within the flame envelope.

## 2. Experimental method

The experimental setup used in the current study is documented in detail previously, see for example [12–14,16]. Only a brief description, consisting of essential details, will be given here. The burner used is a circular co-flow laminar diffusion type burner which is commonly used in other similar studies [17]. Its inner diameter at the burner rim is 3 mm and the outer diameter decreases gradually to a tapered fine edge to prevent any recirculation zones forming. The material of the burner is stainless steel and the burner tube has an insert of metal porous material to help to minimize the flow non-uniformities. The co-flow air nozzle is about 25 mm in diameter, and the air channel is also fitted with porous material for the same purpose upstream of the burner exit.

The burner described above is mounted inside a high-pressure combustion chamber designed to be operated up to 110 atm pressure. Optical access to the chamber is provided through three optical quartz windows positioned at about the mid-height of the cylindrical chamber and are installed in the sidewall to provide line-of-sight and 90° scattering measurements. The internal diameter of the combustion chamber is about 240 mm whereas its height is 600 mm. The burner is fixed within the combustion chamber, and the chamber is mounted on an automated translation stage with vertical and horizontal movement capability so that the combustion chamber can be positioned as desired with respect to the stationary optical system for measurements.

The optical measurement technique is based on the analysis of spectral emission of radiation from the soot particles formed within the flame envelope. The original version of this technique has been known as two-color pyrometry, and the details of this refined method, known as soot spectral emission (SSE), is explained in detail by Snelling et al. [18]. Briefly, the flame is mapped point by point with a line-of-sight measurements of spectral radiation from 690 nm to 945 nm. Measurement resolution was 0.05 mm in horizontal direction (along the radius of the flame) whereas it was 0.5 mm in vertical direction. At each point at least 3 images of 1 s duration each were captured and both left and right sides of the

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