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Soot measurements by two angle scattering and extinction in an N_2-diluted ethylene/air counterflow diffusion flame from 2 to 5 atm

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Abstract

The soot formed in an N_2-diluted ethylene/air counterflow diffusion flame at elevated pressure was investigated using two angle light scattering/extinction technique. To provide a well-controlled pressurized environment for the flame, a novel pressure vessel was built with the required optical access. The soot parameters were measured along the centerline of the counterflow flame. These properties included soot volume fraction (f_v), primary particle diameter (d_p), population averaged radius of gyration (R_g) and number density of primary particles (n_p). The Rayleigh–Debye–Gans theory for Fractal Aggregates (RDG-FA) was used to retrieve these properties from scattering and extinction measurements. Soot volume fraction was measured via light extinction from 2 to 5 atm while maintaining the same global strain rate at all pressures. Scattered light from soot particles was measured at 45° and 135° and primary particle diameter was calculated using scattering/extinction ratio and the radius of gyration was determined from the dissymmetry ratio. Soot volume fraction, primary particle diameter and radius of gyration all increased with pressure while the number density of primary particles decreased with increasing pressure.

Keywords: Counterflow diffusion flames; Soot parameters; Scattering; High pressure

1. Introduction

Carbonaceous particles formed in combustion processes play an important role in the performance of combustion systems. They can increase heat transfer to the walls of the internal combustion engine and reduce the operational efficiency. These ultra-fine particles are not only considered as a contributor to global warming but can be a serious risk for human health [1]. To develop strategies to reduce soot emissions, it is important to understand the soot formation pathways and oxidation processes at conditions similar to those of practical systems. The morphology of the soot influences the toxicology [2] and airborne lifetime [3]. Additionally, morphological parameters can be

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a sensitive validation metric for soot formation/oxidation models.

Most practical combustion devices operate at high pressure in order to reduce overall size and to improve their thermodynamic efficiency. Soot emissions are strongly influenced with combustion pressure. Soot formed at atmospheric pressure yields a morphology well characterized in the literature [4–7]. Little is known about the effects of pressure on soot morphology. Most of the flames studied at high pressure are coflow flames in which the valuable conclusion obtained is the relation between the soot volume fraction and the pressure [8–11]. For example, McCrain and Roberts [8] studied methane–air and ethylene–air coflow flames at pressures up to 25 atm and 16 atm, respectively, and found that the local peak soot volume fraction scales with pressure as $P^{1.2}$ for methane and $P^{1.7}$ for ethylene flames. Flower and Bowman [12] studied ethylene/air flames in Wolfhard–Parker burner up to 2.5 atm using light scattering/extinction technique. The results showed that primary particle diameter and number density of primary particles increased with pressure. Peak soot volume fraction and integrated soot volume fraction at a fixed vertical height increased with pressure to a power 1.7 ± 0.3 and soot yield at a fixed location scaled with $P^{0.7 \pm 0.3}$. Steinmetz et al. [11] studied effects of pressure on primary particle diameter in a coflow burner up to 16 atm using light scattering and extinction technique. The diameters of primary particle increased faster with pressure in the annulus of flame than those on centerline.

Laser Induced Incandescence (LII) is another non-intrusive technique for studying soot volume fraction and particle size distribution [13,14], but uncertainties arise at high pressure due to lack of understanding of the effects of pressure on the heating and cooling mechanisms of particles. Thomson et al. [15] investigated a coflow flame at high pressure using LII and found that the effective particle size increased from 5 atm to 40 atm. Increase in effective particle size does not confirm increase in primary particle diameter which can be investigated by light scattering technique as carried out in this study. Although, high pressure can be achieved in co-flow flames, they inherently have some challenges such as heat loss to the burner [16] and buoyancy instabilities [17].

Two angle scattering in conjunction with light extinction technique proposed by De Iuliis et al. [7] have been widely used to study soot formation in different co-flow flames at atmospheric pressure [5,18,19]. Measurement of the scattering signal at two angles (θ, $180-\theta$), and application of Rayleigh–Debye–Gans (RDG) theory allow inferring soot parameters. In this study, an experiment is developed to investigate the effects of pressure on soot parameters in a counterflow diffusion flame. Counterflow burner has been used for high pressure flame studies to a significantly high pressure of 3 MPa [20,21]. A counterflow flame is relatively immune to buoyancy-induced instabilities and allows the residence time to be controlled, thus controlling the soot yield, both very important as pressure increases. Laser scattering and extinction is used to simultaneously measure the soot volume fraction, primary particle and population averaged soot radius of gyration in an N_2-diluted ethylene/air diffusion flame at elevated pressures. RDG theory for Fractal Aggregates (RDG-FA) is used to calculate the soot properties from scattering and extinction measurements.

2. Experimental apparatus

A novel apparatus is designed and built specifically for studying soot morphology at high-pressure. Figure 1 shows a schematic and actual picture of this combustion chamber and the optical setup used to collect scattered light. The pressure vessel has four curved windows, providing 160° of optical access; important as this vessel will be used for multi-angle scattering measurements in a follow-on study. The counterflow burner is mounted on a 3-axis translation stage, to allow for optimal alignment within the pressure vessel and with the incoming laser beam. Fuel, air and inert are supplied through connections at the bottom flange. The exhaust is through the top and pressure is controlled by an electronically controlled back-pressure regulator. Scattered light collection optics are attached to a rotary stage which is supported on four miniature vertical translation stages attached to the pressure vessel and allow fine alignment of the rotary stage in the horizontal plane. The rotary stage enables collecting the scattered light at different angles.

The counterflow burner consists of two concentric straight tubes of internal diameter of 8.1 mm and these tubes are separated by 8.2 mm which is kept constant in this study. The nitrogen/ethylene stream is introduced through the bottom tube while the air stream from the top tube and flow rates are adjusted to maintain equal momentum flux. The global strain rate, a, is defined as the mean exit velocity of the air divided by half of the separation distance between nozzles [22] and is maintained at $30\ s^{-1}$ for all pressures by increasing the mass flux with pressure. In order to minimize entrainment of ambient air, a velocity-matched shroud flow of nitrogen flows through the outer tubes, having an internal diameter of 28 mm. The ethylene is diluted with nitrogen such that the ethylene mole fraction is 0.3 and the oxidizer side is hydrocarbon free dry air. The stoichiometric mixture fraction is $Z_{st}=0.184$, and thus the flame sits on the oxidizer side of the stagnation plane. These values are chosen to have measureable soot loading at all the pressures considered in this study. The flow rates of the main streams at different pressures are shown in Table 1.