Fuel 220 (2018) 464–470

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Soot primary particle size dependence on combustion pressure in laminar ethylene diffusion flames

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ARTICLE INFO

Keywords:
Soot size at high pressures
High-pressure soot formation
Laminar diffusion flames at pressure

ABSTRACT

A multi-probe thermophoretic soot sampling system, installed inside a high pressure combustion chamber, was used to collect soot samples at elevated pressures from ethylene–air laminar diffusion flames. Ethylene was diluted with nitrogen at a ratio of 1/3 by mass, and a constant mass flow rate of ethylene-nitrogen mixture was maintained at pressures of 5, 10, 15, and 20 bar. Selected mass flow rate of ethylene, 0.72 mg/s, provided stable and non-smoking laminar flames with a height of about 16 mm at all pressures considered. Soot samples were collected on transmission electron microscope grids at three heights above the burner rim, 3, 8, and 12 mm. The images of the soot particles were captured by transmission electron microscope and the primary soot particle diameters were determined using an automated edge detection method. The mean primary soot particle diameter increased from the sampling height of 3 mm to 8 mm, which corresponds to the mid-height of the flames where the peak soot volume fractions are observed. The soot diameters decreased from the mid-height of the flame to the sampling location of 12 mm, near the tip of the flame. The mean diameter of the primary soot particles increased with increasing pressure up to 15 bar; at 20 bar, the mean soot diameter seemed to reach a plateau or start decreasing. Measured soot volume fractions at sampling locations of 3 and 8 mm above the burner rim indicate that, in view of the measured mean soot diameters at the same locations, soot number density should be increasing intensely with pressure.

1. Introduction

Combustion engines utilized to power aircraft and land-based transportation vehicles operate at elevated pressures for reasons of improved thermodynamic efficiencies. Soot, however, is one of the undesired by-products of combustion in gas turbine and diesel engines, in which the combustion mode is mostly non-premixed, and the soot formation rate is enhanced significantly by increasing combustion pressure. Although most of the soot is oxidized within the combustion chamber of these engines, a small amount of soot escapes the oxidative process and soot particles are released into the atmosphere in the form of particulate matter (also known as smoke or black carbon) from the engine exhaust. Damaging impacts of soot emissions on climate change and the health of humans have been well-documented as well as its harmful effects in combustion devices. Efforts to find solutions for the reduction and elimination of soot particle emissions are usually held back by a lack of sufficient comprehension of soot formation and oxidation processes. Experimental and computational studies in tractable flames could help to improve our understanding of the influences of various parameters on soot processes at elevated pressures.

Recently, there has been a strong interest in experimental and numerical high pressure soot studies, mostly using gaseous fuels, focussing on the influence of pressure on soot production with the aim of identifying and assessing the prevalent mechanisms and processes [1,2]. As a result, a relatively mechanistic portrayal of soot formation at elevated pressures is emerging [2,3]. However, the utility and the use of such depictions in dealing with practical combustion systems, either in modelling efforts or interpretation of the exhaust soot measurements, have yet to be demonstrated.

Soot particle size and morphology are crucial parameters in evaluating and appraising the influence of soot on the well-being of the planet and its inhabitants. Soot aggregate characteristics are essential information in assessing the radiation forcing of atmospheric black carbon [4] as well appraising the health effects on humans [5]. For the purpose of unravelling the underpinnings of the soot processes, the temporal history of primary soot particle size and soot aggregate morphology, which carry the trails of the soot processes through the course of combustion, could be followed [6]. These footprints, which could be inferred from the experimental results obtained by following the evolution of the size and morphology of the soot particles within

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https://doi.org/10.1016/j.fuel.2018.02.025
Received 17 December 2017; Received in revised form 29 January 2018; Accepted 6 February 2018

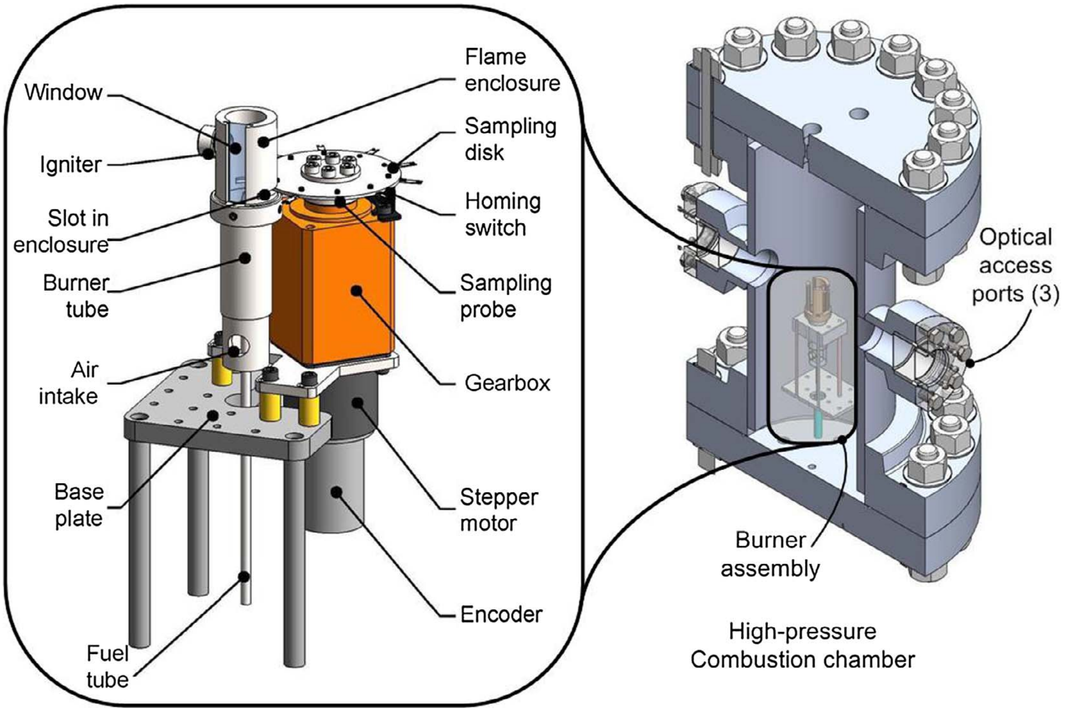

Fig. 1. Cross section of the high-pressure combustion chamber with the thermophoretic sampling system and the burner assembly. The details of the sampling system and the burner assembly are shown in the blowout view on the left.

tractable flames, can provide means to understand better the soot formation processes. While studies regarding the effects of pressure on global soot parameters (such as soot concentration) are more abundant, only a few experimental studies have been conducted on the effects of pressure on soot particle size and morphology, mainly due to difficulties in designing experimental apparatus that will sustain tractable diffusion flames and permit measurements using various diagnostic techniques [1].

To our knowledge, Flower and Bowman [7] reported first measurements of primary soot particle size in laminar diffusion flames at pressures above atmospheric using static-light scattering. Using a Wolfhard-Parker burner, they found that the mean particle size increases with pressure from atmospheric to 2.5 bar. However, it is problematic to assign the changes in soot size to pressure only, because the flames they probed were not tractable; the fuel mass flow rate was not kept constant as the pressure was increased. Kim et al. [8] reported primary soot particle size measurements by thermophoretic sampling, and subsequent analysis by electron transmission microscopy (TEM), on the centerline of diluted ethylene-oxygen laminar diffusion flames. They concluded that primary soot particle size increases with pressure in laminar diffusion flames. However, they did not keep the fuel mass flow rate constant at all pressures in their experiments. In addition, it should be noted that the fuel-oxygen diffusion flame structure is radically different than that of the flames using air as the oxidant at elevated pressures [9].

In one of the first applications of laser induced incandescence (LII) at elevated pressures, Thomson et al. [10] measured the primary soot particle size in tractable laminar methane-air flames between 5 and 40 bar. Similarly to previous two studies [8,9], they observed a steep increase in primary soot particle size from 5 to 40 bar. However, as explained by the authors [10], what is measured with LII is the effective primary soot particle size, due to the fact that the shielding effect on heat conduction between aggregated particles and the surrounding gas could not be accounted for. In a more recent work, Steinmetz et al. [11] reported primary soot particle size measurements in nitrogen diluted ethylene-air laminar diffusion flames at pressures up to 16 bar using light-extinction and scattering techniques. They found that the primary soot particle diameters increased about 40 fold from 4 bar to 16 bar. Similar to Thomson et al. [10] results, Steinmetz et al. [11] explained that what is measured is something in between the primary soot particle size and soot aggregate size.

Soot aggregate morphological data and primary soot particles diameter measurements performed in diesel engine combustion chambers are generally affected by the parameters such as engine load, global equivalence ratio, crank angle, injection pressure, and engine speed. As a result, it is a formidable challenge to interpret the results to isolate and ascertain the effect of pressure on the soot particles because these competing parameters cannot be controlled independently [12–14].

It seems that the use of the current LII and the light scattering/extinction techniques in soot size and aggregate morphology measurements are not possible because of the challenges in quantifying the uncertainties introduced at elevated pressures. As a consequence of the present optical limitations of LII and light scattering, thermophoretic sampling and TEM analysis, although intrusive, seem to be one of the plausible methodologies for investigating the influence of pressure on the primary soot size and morphology in tractable flames [15,16]. The first thermophoretic soot sampling measurements, to the authors' knowledge, in tractable high-pressure laminar diffusion flames of methane-air were reported by Vargas and Gülder [15,16]. The mean soot primary particle size in a methane diffusion flame, measured at a constant height of 3 mm above the burner exit at all pressures, decreased about 35% from 2 to 10 bar [16].

Measurements of mean primary soot particle size, soot temperature, and soot volume fraction in nitrogen-diluted ethylene-air diffusion flames at pressures up to 20 bar were conducted and results are reported in this paper. A high pressure combustion chamber, suitable for sustaining stable and tractable laminar diffusion flames with various fuels, was modified to be fitted with a multi-probe thermophoretic soot sampling system. Soot samples collected at various pressures on TEM grids were analyzed to infer the primary soot particle size at selected heights within the flames at a pressure range from 5 to 20 bar by processing the soot aggregate images captured by TEM. The observed changes in the primary soot size are discussed considering the associated temperatures at different pressures.