

Complete conversion of ethane to soot in a coflow laminar diffusion flame at 3.65 MPa

Paul M. Mandatori, Ömer L. Gülder*

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

Received 30 January 2007; received in revised form 18 May 2007; accepted 12 June 2007

Available online 20 July 2007

1. Introduction

One of the parameters that significantly influence soot formation in combustion is pressure. Most combustion engines used for transportation and propulsion, as well as power production, operate at pressures approaching (and sometimes exceeding) 10 MPa. For example, current aviation gas turbines operate under conditions approaching 4 MPa. In spite of this fact, our insight into the formation mechanism(s) of soot is very limited, even at atmospheric pressures. There seems to be no reliable method of scaling the extensive experimental data obtained at atmospheric pressure to elevated pressures. Information on soot formation in laminar diffusion flames, obtained at elevated pressures, has the potential to shed some light on soot formation in turbulent diffusion flames at high pressures. This can be accomplished by exploiting the similarities between laminar and turbulent flames.

Our efforts to understand the influence of pressure on soot formation rates in gaseous fuel flames have been providing extensive data on the sooting structure of laminar diffusion flames as a function of pressure [1–3]. During the study of soot formation in laminar diffusion flames of ethane, we have observed an anomalous occurrence at a chamber pressure of 3.65 MPa, which is close to the vapor pressure of ethane at room temperature. At 3.65 MPa, the flame gradually developed into a big mass of glowing car-

bon, filling the top of the burner. The aim of this brief communication is to report this anomalous observation.

2. Experimental

The experimental high-pressure combustion chamber and the laminar diffusion flame burner used in this study are described in detail in [1,2]. The design pressure of the chamber is about 11 MPa, and its internal diameter and internal height are 0.24 and 0.6 m, respectively. Optical access into the chamber is achieved through three ports at 0°, 90°, and 180° locations, allowing line-of-sight measurements, 90° scattering measurements, and imaging experiments. The co-flow burner has a fuel nozzle exit diameter of 3.06 mm and an air nozzle diameter of 25 mm. Sintered metal foam elements are included in the fuel and air nozzles to straighten and reduce instabilities in the flow and to create a top hat exit velocity profile as the gases leave the foam elements. Fig. 1 shows the details of the experimental diffusion flame burner. The soot and temperature measurement method used in this study is explained in detail in [1–3].

The ethane flow rate was selected to match the carbon mass flow rate of the studies performed previously with methane [1] and propane [2] diffusion flames at elevated pressures. A constant mass flow rate of ethane of 0.516 mg/s, which corresponds to 0.412 mg/s of carbon mass flow rate, was maintained at all pressures. Ethane's saturation vapor pressure at 293 K is 3.73 MPa [4]; therefore the measurements were limited to pressures lower than 3.73 MPa.

* Corresponding author. Fax: +1 (416) 667 7799.

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

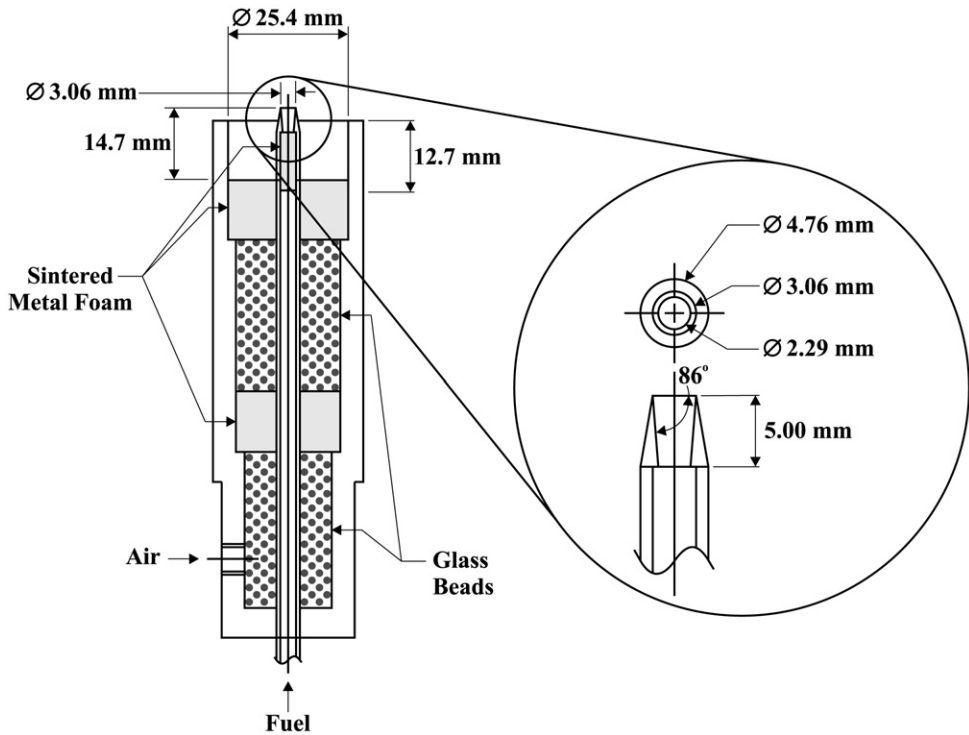


Fig. 1. Details of the co-flow laminar diffusion flame burner used in this study.

3. Results and discussion

During the soot concentration and temperature measurements at a pressure of $P = 3.65$ MPa an interesting phenomenon occurred. Once a stable laminar ethane flame was achieved at this pressure, line-of-sight point measurements were taken with a radial spacing of $50\ \mu\text{m}$ and axial spacing of $0.5\ \text{mm}$, Fig. 2a. It should be noted that due to the high thermal capacity of the high-pressure vessel it takes about 30 min for the system to reach thermal equilibrium and the flame to become fully stable. However, at 3.65 MPa, it took about 90 min to stabilize the flame and the flame remained stable for the next 38 min.

During the data collection, the flame is monitored with a closed circuit video system to ensure that the flame is stable during the measurements. After approximately 38 min of data collection, massive carbonization on the burner tip was noticed, Fig. 2b. Once the carbonization was noticed, various pictures and short video clips were taken of the process. Selected pictures of the process in chronological order are given in Figs. 2b–2f. The carbonization on the burner tip was in the shape of a half-sphere or dome. At first, Figs. 2b–2d, the flame was still protruding through the center of the annular carbon mass. However, as time elapsed, the dome of soot completely

covered the entire burner tip and the flame was not visible, Figs. 2e and 2f. At this point, the fuel flow was not turned off, and it seemed that the fuel was still pyrolyzing underneath the dome of soot, because the dome of soot was still glowing. It is possible that the fuel was going through a dehydrogenation process and the hydrogen was burning through the porous structure of the soot with the air diffusing in around the burner rim [5].

Once the fuel flow was turned off, the mass of carbon cooled and was no longer glowing, Fig. 3. This entire process describes an interesting and previously unreported, to our knowledge, observation of massive carbonization of gaseous fuels under high pressure. It suggests that pressure alone can cause a gaseous fuel to completely clog a fuel nozzle in a combustion application. This has implications for many practical combustion systems.

It should be noted that at a slightly lower pressure, at 3.34 MPa, the maximum conversion of the fuel's carbon to soot was about 28% at flame mid-height [3]. The flame was still a nonsmoking diffusion flame; that is, all the soot produced was oxidized within the luminous flame envelope. As in other gaseous-fuel laminar diffusion flames, soot formation and hence the maximum concentrations of soot increase significantly with pressure [1–3,6,7]. As the soot concentrations increase, the heat loss

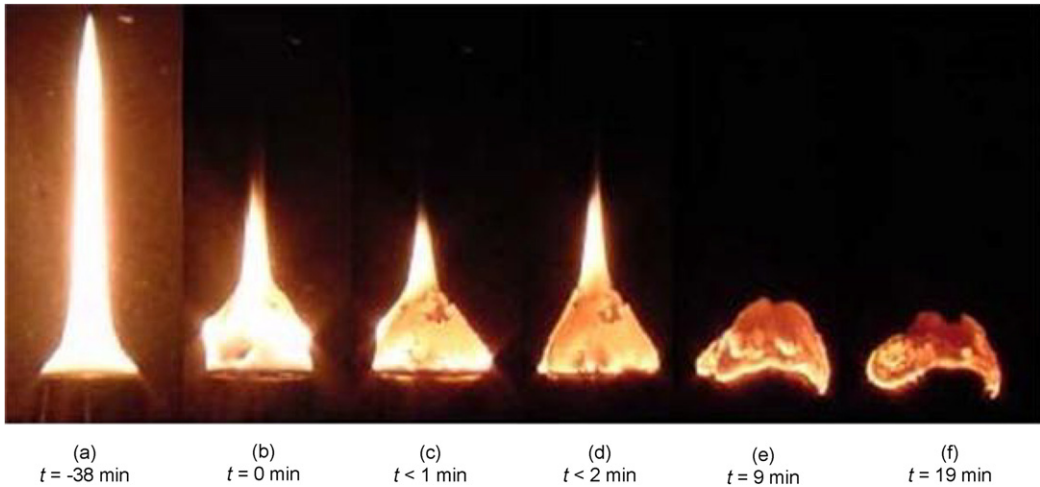


Fig. 2. Pictures showing the development of the diffusion flame at 3.65 MPa into a glowing solid carbon mass. (a) The normal appearance of the diffusion flame when it is first stabilized at 3.65 MPa with a visible flame height of approximately 10 mm; (b–d) the flame starts burning through an opening in the center of a glowing solid establishing itself as an annular structure on the tip of the burner; (e and f) a visible flame no longer exists and the solid structure keeps glowing.

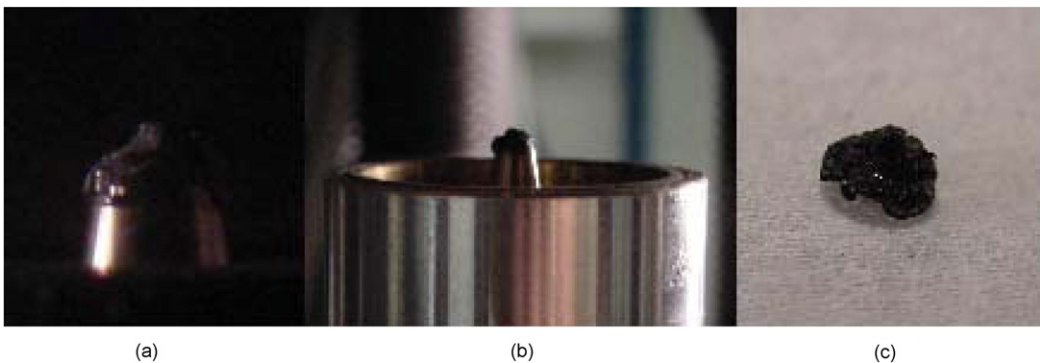


Fig. 3. Carbon mass when the fuel flow stopped: (a) and (b) show carbon buildup attached to the burner tip; (c) shows carbon buildup detached from the burner tip.

from the flame by radiation increases, thus lowering the flame temperatures. This leads to slower oxidation rates of soot, and eventually oxidation cannot keep up with soot production, leading to a smoking diffusion flame [7]. However, this mechanism does not explain our observation, because a nonsmoking diffusion flame can be stabilized for more than an hour at 3.34 MPa with ethane at a fuel flow rate of 0.516 mg/s.

A possible explanation can be provided by the fact that the soot formation region moves closer to the burner tip as pressure is increased [1–3]. Then, at high enough pressures, the soot formation zone moves further down into the fuel nozzle, where soot begins depositing on the inner wall of the fuel nozzle near the tip. Since the nozzle wall temperature would be much cooler than the gas temperatures where soot forms and grows, the soot particles could be moving toward

the wall of the burner as a result of thermophoresis. As the particles migrate and stick to the burner nozzle wall, an annular soot mass forms at the tip of the burner. Once the annular deposit of the soot mass reaches a certain size, it interferes with the flame, changing its shape and size. Then a smaller flame burns through the center opening of the soot mass, Figs. 2b–2d, and in a few minutes, the soot mass completely covers the fuel nozzle, Fig. 2e.

Blade surface erosion and degradation by carbon particles is a serious concern for modern gas turbine engines [8]. Past investigations have concentrated on the problematic erosion of blade surfaces by relatively large, and mainly noncarbon, particles. It is not certain whether submicrometer- and micrometer-sized carbon particles (soot or large soot agglomerates) can damage the blade surfaces by erosion. However, carbon chunks from coke deposition as

a result of coke formation due to thermal instability of heated jet fuel (liquid) before injection are one of the causes of blade erosion. If there exists fuel vapor within the heated fuel lines (as a consequence of, for example, cavitation), then large masses of soot can form if the temperature and the pressure inside the fuel vapor bubbles are high enough to support fast pyrolysis, leading to high concentrations of soot precursors. The larger carbon chunks formed through gas phase pyrolysis could be another source of particles that might be causing erosion in turbine blades. It should be noted that the propensity to soot is much higher for aviation jet fuels than for ethane.

Acknowledgments

We acknowledge an infrastructure grant provided by the Canadian Foundation for Innovation (CFI) for building the high-pressure combustion vessel and associated components. Operational funds for this work

have been provided by the Natural Sciences and Engineering Research Council (NSERC) and AUTO 21.

References

- [1] K.A. Thomson, Ö.L. Gülder, E.J. Weckman, R.A. Fraser, G.J. Smallwood, D.R. Snelling, *Combust. Flame* 140 (2005) 222–232.
- [2] D.S. Bento, K.A. Thomson, Ö.L. Gülder, *Combust. Flame* 145 (2006) 765–778.
- [3] P.M. Mandatori, M.Sc. thesis, Institute for Aerospace Studies, University of Toronto, Canada, 2006.
- [4] E.W. Lemmon, A.R.H. Goodwin, *J. Phys. Chem. Ref. Data* 29 (2000) 1–39.
- [5] F. Liu, K.A. Thomson, H. Guo, G.J. Smallwood, *Combust. Flame* 146 (2006) 456–471.
- [6] L.L. McCrain, W.L. Roberts, *Combust. Flame* 140 (2005) 60–69.
- [7] W.L. Flower, C.T. Bowman, *Proc. Combust. Inst.* 21 (1986) 1115–1124.
- [8] W. Tabakoff, A. Hamed, M. Metwally, *J. Gas Turbine Power* 113 (1991) 607–615.