Available online at www.sciencedirect.com
ScienceDirect
Proceedings of the Combustion Institute 000 (2016) 1–8
Proceedings of the Combustion Institute
www.elsevier.com/locate/proci

Flow field characterization of pressurized sooting swirl flames and relation to soot distributions

Klaus Peter Geigle [a,*], Redjem Hadef [b], Michael Stöhr [a], Wolfgang Meier [a]

[a] Deutsches Zentrum für Luft- und Raumfahrt e.V., Institut für Verbrennungstechnik, Pfaffenwaldring 38-40, D-70569 Stuttgart, Germany
[b] Université Larbi Ben M'Hidi, Institut de Génie Mécanique, 04000 Oum El Bouaghi, Algeria

Received 4 December 2015; accepted 21 September 2016
Available online xxx

Abstract

Mean and instantaneous flow fields were derived for sooting pressurized swirl flames, operated with ethylene/air in an aero-engine model combustor. Stereo particle image velocimetry served to deduce three velocity components and to identify locations of soot based on soot scattering. The measurements complement those of other quantities in the same flames published recently. Flow fields determined for cold and reactive conditions confirm conclusions drawn from application of other laser-based diagnostics: soot is mainly formed in the inner recirculation zone which recirculates reactive, hot unburnt reaction products, and partly transported into the high-velocity in-flow regions. Oxidation air injected after two thirds of the combustor forms a stagnation zone close to the combustor axis and splits into a portion flowing downstream toward the combustor exit and one transported upstream thereby affecting the local gas composition and temperatures in the inner recirculation zone. Analysis of the instantaneous images by proper orthogonal decomposition reveals the existence of a precessing vortex core which impacts the soot distribution. Presence of soot in high-velocity/high strain rate regions where soot formation is unlikely to occur can be explained as a result of transport. Flow field characterization and the correlation with soot presence, in complement of existing data, are expected to provide a valuable contribution to soot model validation.

Keywords: Soot; Flow field; Gas turbine; Model combustor; Pressure

---

1. Introduction

Expected more stringent emission legislation for kerosene combustion in aero-engines has driven considerable effort in recent years to better understand, model and predict soot formation in gas turbine combustors. Increasingly, numerical tools contribute to the understanding of processes leading to soot formation and oxidation in technical combustors [1,2]. Yet experiments remain essential to improve the predictive capability of soot modeling. Those can either serve to improve understanding of fundamental sub-processes such as soot inception, growth, and oxidation, as well as soot-turbulence interaction, or as validation data for

---

[*] Corresponding author. Fax: +49 711 6862 578.
E-mail addresses: klauspeter.geigle@dlr.de, klauspeter.geigle@gmx.de (K.P. Geigle).

http://dx.doi.org/10.1016/j.proci.2016.09.024
1540-7489

Please cite this article as: K.P. Geigle et al., Flow field characterization of pressurized sooting swirl flames and relation to soot distributions, Proceedings of the Combustion Institute (2016), http://dx.doi.org/10.1016/j.proci.2016.09.024

numerical models. Numerous studies in fundamental flames exist; however, there is an increasing need for data sets derived from flames which exhibit technical features such as pressure, turbulence and swirl. Those data sets should preferably include soot and temperature, and beyond that as many quantities as possible. A combination of both, technical conditions at well-defined boundary conditions, and detailed characterization by accurate optical diagnostics, remains challenging. Recently, we presented a series of publications characterizing such a semi-technical combustor which exhibits the mentioned technical features [3–5]. It also offers the option to inject additional oxidation air downstream of the primary combustion zone which mimics dilution or quench air as employed in aero-engine combustors. The data set includes mean and instantaneous distributions of soot, OH and PAH as well as temperatures measured by laser-induced incandescence (LII), laser-induced fluorescence (LIF) and coherent anti-Stokes Raman scattering (CARS). In addition, correlations exist where two complementary techniques were applied simultaneously. The current study adds information on the velocity field which is important for several reasons: soot formation depends strongly on local gas composition, temperature and the time history of the respective fluid element. The instantaneous flow field is an essential quantity impacting those parameters via turbulent mixing. Resulting quantities as residence times, velocity gradients (strain) and dissipation contribute to the local thermochemical state which eventually leads to soot formation or oxidation of precursors prior to forming soot [6–8]; high strain rates reduce the formation of soot precursors PAH (polycyclic aromatic hydrocarbons [7]), and consequently soot. Turbulent fluctuations impacting these mentioned pathways therefore directly result in the strong soot intermittency determined in turbulent flames (for example [9–12]). The direct correlation of flow field and soot distribution, however, is further complicated by the different time scales of soot chemistry and turbulence. Soot chemistry is typically described as a relatively slow process on the order of several milliseconds (for example [13–15]). Dependent on the location in the flame, time scales of the flow field cover a significantly wider range from sub-milliseconds close to the flame front to multiple milliseconds in the inner recirculation zone, which rather would require a time-resolved determination of the correlation of soot and flow field. However, for combustion simulation the non-reacting, and subsequently reacting flow fields are the first quantities to validate turbulence modeling prior to employing chemistry modules. Application of particle image velocimetry (PIV) to sooting flames is challenging due to strong flame luminosity, and the number of publications showing application of PIV to sooting flames for validation purposes is limited (for example [8,16,17]). The focus of this work is to complement the existing data set with mean velocity distributions and statistics, and provide additional insight into processes related to soot formation in complex flames by correlating soot distributions to the flow field.

2. Setup

2.1. Burner

The burner used in this study has been presented in detail in a recent publication [4] and is only briefly described here. The injector consists of a pair of annular air swirl nozzles separated by a ring of 60 tiny fuel-injection channels ($0.5 \times 0.4\,mm^2$). Ethylene is introduced through these inlets, the central air outlet has a diameter of 12.3 mm and the outer air nozzle measures 19.8 mm. The combustion chamber has a square cross section of $68 \times 68\,mm^2$ and is 120 mm long. The water-cooled metal posts holding the quartz windows, which serve for good optical access, have an additional air duct of 5 mm inner diameter allowing injection of additional oxidation air after two thirds of the combustor. The four radially-injected jets meet on the combustor axis and form a stagnation zone. The water-cooled top plate of the combustion chamber has a cylindrical exhaust hole (diameter 40 mm, length 24 mm), linked to the combustion chamber by a curvature. 3-mm-thick quartz windows allow for excellent optical access to the flame. Both combustion air flows are supplied by separate mass flow controllers. Those, and controllers for fuel and oxidation air (Bronkhorst) were calibrated in-house resulting in an accuracy of clearly better than 1% of the maximum flow.. All fluids are injected at ambient temperature.

The combustor is mounted in a water-cooled steel pressure housing with large optical access ($60 \times 120\,mm^2$) from four sides. The pressure can be adjusted by partially blocking the exhaust port with a movable piston. An air flow through the gap between the combustion chamber and the pressure housing serves as air cooling for the windows of the combustion chamber.

Among the operating conditions characterized recently by other diagnostics, two were specifically selected for the current study (Table 1). Primarily, this is the so-called reference point at 3 bar, $\phi = 1.2$, with 40% additional oxidation air and 30% of the combustion air passing through the central air nozzle, 70% through the annular air passage. This operating point was characterized without combustion, yet fuel present, with and without additional oxidation air, as well as with combustion. In addition, a leaner case at $\phi = 0.9$ of lower soot content, and less luminosity, was studied enabling a detailed data analysis including correlations of instantaneous soot distributions with velocity fields. For both conditions the full suite of optical

Please cite this article as: K.P. Geigle et al., Flow field characterization of pressurized sooting swirl flames and relation to soot distributions, Proceedings of the Combustion Institute (2016), http://dx.doi.org/10.1016/j.proci.2016.09.024