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Fuel effects on lean blow-out in a realistic gas turbine combustor

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ABSTRACT

Towards the implementation of alternative jet fuels in aviation gas turbines, testing in combustor rigs and engines is required to evaluate the fuel performance on combustion stability, relight, and lean blow-out (LBO) characteristics. The objective of this work is to evaluate the effect of different fuel candidates on the operability of gas turbines by comparing a conventional petroleum-based fuel with two other alternative fuel candidates. A comparative study of fuel properties is first conducted to identify physico-chemical processes that are affected by these fuels. Subsequently, large-eddy simulations (LES) are performed to examine the performance of these fuels on the stable condition close to blow-out in a referee gas turbine combustor. LES results are compared to available experimental data to assess their capabilities in reproducing observed fuel effects. It is shown that the simulations correctly predict the spray main characteristics as well as the flame position. The change in OH*-emissions for different fuel candidates is also qualitatively captured. An analysis of the flame anchoring mechanisms highlights the fuel effects on the flame position. Finally, the LBO-behavior is examined in order to evaluate the LBO-limit in terms of equivalence ratio and identify fuel effects on the blow-out behavior.

1. Introduction

Increasing concerns about air quality and the need for stable and diverse supplies of jet fuels have motivated significant research efforts on the development and certification of alternative jet fuels for aviation [1–3]. These efforts have been supported through national research programs [4–6] that enable collaborations between universities, governmental research agencies and engine manufacturers. The development of alternatives to conventional petroleum-derived aviation fuels is strongly constrained by the life cycle of commercial jet engines, the compatibility with the present supply infrastructure and the wide range of operating conditions over which safe and reliable combustion must be guaranteed [3]. Consequently, research efforts for the near-term solution have focused on the development of so-called drop-in fuels, which are readily usable as blends in the existing fleet [7]. The certification of alternative fuels through the ASTM D4054 standard [8] requires experimental test campaigns by engine manufacturers. The objective of these tests is to evaluate the influence of alternative fuel candidates for three key engine operability indicators: lean blow-out (LBO), cold start and high-altitude relight. However, the lack of the predictability of effects of physico-chemical properties of these candidate fuels on turbulent combustion processes results in expensive and long test campaigns. The development of computational fluid dynamics (CFD) tools to better understand these fuel effects in realistic configurations is thus crucial in complementing experiments and reducing cost and duration of the certification process of alternative jet fuels.

The LBO-performance is of primary concern due to the recent emphasis on lean-combustion strategies for emission reduction. Most of the early investigations on LBO focused on bluff-body flameholder configurations [9–11]. Due to limited optical access and absence of high-speed imaging techniques, experiments were used to support the development of semi-empirical correlations to relate LBO-criteria to equivalence ratio and other operating conditions. These correlations were based on three main theories for flame blow-out: (i) extinction of the recirculation bubble, which behaves as a well-stirred reactor [12], (ii) failure to ignite the incoming reactants in the shear layer of the recirculation bubble

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Nomenclature

χ	scalar dissipation rate
Δh_c	heat of combustion
γ_{LBO}	fuel/air ratio at LBO relative to that of Cat-A2
μ_l	liquid viscosity
ϕ	equivalence ratio
ρ_l	liquid density
σ_l	liquid surface tension
τ_{res}	residence time in the primary zone
We_d	droplet Weber number
P	pressure
T	temperature
$\widetilde{\dot{\omega}}_C$	filtered reaction progress variable production rate
$\widetilde{C}$	filtered reaction progress variable
$\widetilde{Z''^2}$	filtered mixture fraction variance
$\widetilde{Z}$	filtered mixture fraction
d	droplet diameter
q	fuel/air ratio
DCN	derived cetane number
FPV	flamelet/progress-variable
IRZ	inner recirculation zone
LBO	lean blow-out
LFL	lower flammability limit
LHV	latent heat of evaporation
NJFCP	National Jet Fuel Combustion Program
PDPA	phase-Doppler particle analyzer
PVC	precessing vortex core
PZ	primary zone
RR	Rosin–Rammler
SGS	subgrid-scale
SMD	Sauter mean diameter

[13] and (iii) local flame extinction by aerodynamic effects [14]. The review by Shanbhogue et al. [15] describes the blow-off mechanism as a two-stage stochastic process: as the overall equivalence ratio approaches the LBO-limit, the occurrence of local flame extinction increases and close to blow-off the flame behavior is mainly dominated by auto-ignition with successive extinction and re-ignition of the recirculation bubble. Studies of flame stability in swirl-stabilized burners, relevant for modern aviation combustor designs, are more recent and limited. Similar to bluff-body configurations, early work focused on the development of correlations to predict flame stability limits [16]. Compared to simple bluff-body flames, swirl was found to have a beneficial effect on the flame stability [17]. Ateshkadi et al. [18] studied the flame stability in a more complex swirl-stabilized spray combustor and extended the correlation initially proposed by Plee and Mellor [10]. This study indicated that for low gas temperatures, the flame stabilization is controlled by the liquid evaporation rate while at elevated temperatures mixing between fuel and oxidizer is the controlling stabilization process. The effect of liquid fuel was further highlighted by studies in canonical swirling burners [19,20] comparing the LBO-behavior of gas and liquid fueled combustors. Several studies were performed to quantify effects of fuel properties on the LBO-limit in model combustors [16,21–23]. These studies indicate the beneficial effect of lowering the flash point and the adverse effect of an increase in viscosity on the LBO-performance.

Further understanding of the transient blow-out process has only been rendered possible recently by advances in high-speed imaging. Muruganandam and Seitzman [24,25] used high-speed OH*-chemiluminescence imaging to investigate the behavior of a swirled premixed burner close to blow-off. The flame blow-off was found to have several precursor events in which cold gases were captured by the recirculation zone, resulting in a reduction of the heat release and a change in the flame shape. Using simultaneous high-speed stereo-PIV and OH-PLIF measurements, Stöhr et al. [26] showed that the LBO-behavior in swirled combustors is closely related to the temperature of the recirculation zone and the flame root dynamics; flame extinction was found to occur when the flame root was extinguished by its interaction with the precessing vortex core (PVC) for a duration that exceeds a PVC period. Measurements of the heat release in a swirled bluff-body premixed burner close to blow-off [27,28] and during blow-off [29] revealed that local extinction of the flame in the most intense turbulence regions and entrainment of fresh reactants from the downstream end of the recirculation region progressively reduce the capability of the recirculated flow to ignite the incoming reactants, eventually leading to complete extinction behavior.

Due to the intrinsic transient nature of the LBO-process, comparatively few attempts have been made to evaluate the blow-out behavior through numerical simulations. Such simulations have now become possible using large-eddy simulations (LES) and only recent advances in combustion modeling and computational resources have enabled the computation of transient processes in complex configurations [30,31]. LES of blow-out in the swirl-stabilized spray flame of Cavaliere et al. [20] was performed by Tyliszczak et al. [32] using the LES-CMC model. Blow-out was triggered by a sudden increase in the air mass flow rate and LES was shown to be able to capture the local flame extinction and the subsequent blow-out process. Global extinction in a non-premixed swirl-stabilized burner [20] was studied using the LES-CMC model [33]. The ability of LES to reproduce the experimental blow-off curve was evaluated by performing multiple simulations at different loading parameters. LES was found to predict blow-off limits in terms of air mass flow rate with a 25% accuracy and to reproduce the experimental trends in terms of blow-off duration. The detailed study of the flame front behavior during blow-off revealed that progressive extinction of the flame front on the stoichiometric iso-surface eventually lead to complete flame extinction.

The objective of the present work is to evaluate the capability of LES-methods to describe the sensitivity of LBO to fuel properties in a well-controlled but realistic combustor rig. To this end, a conventional petroleum-derived Jet-A fuel and two alternative fuel candidates are considered. Following the description of the experimental configuration (Section 2) and numerical setups (Section 3), the study consists of three parts:

- Section 4 presents an *a-priori* analysis of the effects of fuel properties on the physical and chemical processes: evaporation and ignition in canonical 0D and 1D configurations.
- Section 5 examines fuel effects on flame stabilization at stable conditions close to blow-out and presents comparisons of LES-results to available experimental measurements.
- Section 6 investigates the transient LBO-behavior through dynamic response simulations. In contrast to previous LES studies, LBO is triggered by reducing the injected fuel flow rate.

The paper finishes with conclusions.

2. Experimental configuration

2.1. Referee combustor rig

The combustor is designed to reproduce important features of a realistic gas turbine combustion chamber in terms of injection system design and air flow staging. A picture of the referee combustor is shown in Fig. 1 and geometric details of the combustion chamber are provided in Fig. 2. The injection system consists of two outer axial swirlers and an inner radial swirler with a pressure-swirl atomizer nested in the center. The atomizer