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Short communication

Prevention of lean flame blowout using a predictive chemical reactor network control

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ABSTRACT

Optimization of efficiency and pollution control for gaseous species and particulate matter are common to any combustion system. Combustor lean blowout (LBO) is a concern for aircraft safety and for land-based gas turbines designed to operate at lean equivalence ratios to achieve better fuel efficiency and to limit NO_x emissions. This paper provides an experimental demonstration of model-based control applied to a laboratory jet-stirred reactor (JSR) approaching LBO. The approach uses (1) combustor temperature measurements, coupled with (2) the calculation of free radical concentrations in the reactor using a real-time chemical reactor network (RT-CRN) model as the reactor approaches LBO, which in turn (3) are used by a predictive control algorithm to achieve stable combustion. The RT-CRN represents the combustor as three perfectly stirred reactors (PSRs) in series with a recirculation pathway; the model inputs include real-time measurements of temperature and mass flow rates of fuel and air. In a series of experiments, the combustor is operated on a premixed methane-air mixture; after achieving stable combustion, the air flow rate is increased beyond the stable air-fuel ratio either as a step function or by ramping up linearly. The predictive RT-CRN control algorithm calculates the distribution of hydroxyl (OH) radicals in the free jet, impinging jet, and recirculation regions of the JSR in near real-time (~1 s delay), and determines the leanest stable state based on the OH uniformity in the combustor. As the OH shifts towards the recirculation region, the reactor approaches LBO, if this condition is detected the control algorithm injects additional fuel; reactor stabilization is achieved within a 5–15 s time frame. Although this proof-of-concept demonstration is performed for LBO control in a JSR with ceramic walls, the control methodology is applicable to other types of high-intensity recirculation stabilized combustors.

1. Background and relevance

Lean flame blowout (LBO) can be defined as the phenomenon of flame extinction due to the reduction of the fuel-air ratio beyond a minimum threshold limit at which a given geometry can sustain a flame. The NO_x and soot emissions can be controlled by lowering the flame temperature through leaning of the flame fuel-air equivalence ratio (Φ). However, by operating very lean, the combustors have limited margins between stable combustion and lean-flame instabilities leading to lean blowout. Lean-premixed concepts have been investigated by several aircraft engines developers [1,2], where the flame instability and extinction is a primary safety concern. Owing to the expensive and potentially dangerous implications, predicting and preventing LBO is of considerable interest to researchers and practitioners. Blowout has mainly been studied in terms of the residence time of reactants [3–5] and flame structures and corresponding strain rates [6,7]. The Damkohler number (Da) is used for LBO characterization; it is defined as the ratio of mixing time to the chemical time (τ_{mix}/τ_{chem}). For aerodynamically stabilized reactors, blowout occurs when the rate of entrainment of reactants into the recirculation zone cannot be balanced by the rate of their consumption [8]. *Da* non-uniformity can also lead to the onset of flow instabilities resulting in LBO [9]. Experimental and numerical studies have investigated species distribution in different combustor geometries, injector designs and fuel compositions e.g., [10–17]. The CFD models are computationally intensive and cannot be used for real-time calculations. Recently, fast phenomenological CRN and semi-empirical approaches [18,19] for aero-engine LBO prediction have been proposed.

Flame stabilization has been attempted using a variety of techniques – equivalence ratio modulation, fuel flow redistribution inside the combustor, usage of a secondary fuel, etc. These controllers can be classified based on if the controller injects energy into the system (active vs. passive) and if measurement data from the system is fed back to modulate the control signal (closed-loop vs. open-loop). Combustion

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control has been extensively studied in the literature [20], especially as it relates to fluid flow control [21–23]. Both, operating point control (OPC) and active combustion control (ACC) [24] have been proposed. In the OPC approach, the system maintains a certain flame parameter within an operating limit while in ACC, the objective is to limit combustion instabilities or to improve the combustion characteristics. Model-based feedback uses measurement in conjunction with a transfer function or a state-space model to determine an appropriate control signal. System identification, such as the eigensystem realization algorithm [25,26], yields linear reduced-order models that have been used to control cavity flow and combustion oscillations. Morgans and Dowling [27] used an open-loop transfer function (OLTF) to control thermo-acoustic instabilities in a Rijke tube experiment and in an atmospheric pressure combustor. Campos-Delgado et al. [28] tested model-based control of thermo-acoustic instabilities in a swirl-stabilized spray combustor using linear-quadratic-Gaussian (LQG) control, loop transfer recovery (LTR), and H_∞ loop-shaping. Some examples of model-based boiler control include artificial neural networks (ANN) [29] and model predictive control (MPC) [30]. In addition to the various model-based control strategies, there are also numerous studies that employ model-free control. The most common model-free combustion control is extremum-seeking control (ESC) [31], where a sinusoidal perturbation is added to the control signal to estimate the gradient of an objective function for optimization. ESC has been used to control thermoacoustic modes in an industrial scale 4 MW gas turbine combustor by Banaszuk et al. [32,33]. Kalman filters were later combined with ESC for dramatic performance improvement in thermo-acoustic instability control in a combustor experiment by Gelbert et al. [34]. ESC was also used earlier to tune PI controllers to stabilize a nonlinear acoustic oscillation model of a combustion chamber by Krstic et al. [35]. Other model-free strategies include the use of evolutionary algorithms to optimize noisy combustion processes by Buche et al. [36]. These methods were also used to tune the parameters of a model-based H_∞ controller in a combustion experiment by Hansen et al. [37].

2. Experimental setup

The experimental setup uses an atmospheric pressure, single-jet JSR, fired on methane. JSRs provide a strongly recirculating combustion field that fills much of the reactor. This environment is useful for studying chemical-kinetic driven effects that are relevant to practical, high-intensity, back-mixed combustion systems, especially the primary combustion zone of gas turbine engines. Two of these effects are blowout and NOx formation. The original stirred reactor of Longwell and Weiss [3] was developed to study the problem of engine blowout. Later, JSRs were used to study NOx formation and reduction in lean-premixed combustors, e.g., [38].

The total volume of the reaction chamber of the JSR used here is 15.8 cm^3. The walls of the JSR are ceramic (cast from alumina, Al_2O_3). The balance of the JSR setup consists of a stainless steel premixer/injector manifold and an Inconel nozzle block, see Fig. 1. The flow rates of air and fuel into the premixer are controlled by two mass-flow controllers (MFCs) operated by National Instruments MyRio module via a LabVIEW environment. The air is supplied from the filtered shop airline regulated at 50 psig at the inlet of the MFC. The fuel is supplied from a high-pressure cylinder, again regulated to a pressure of 50 psig upstream of the MFC. Under all air/fuel flow rates, the air-fuel premix enters the reactor cavity through a 2 mm nozzle at sonic velocity. Temperature in the recirculation zone is measured using an R-type thermocouple (TC), with an alumina coating to prevent catalytic effects. The thermocouple data is relayed to the LabVIEW interface using a TC-DAQ (Omega Systems).

3. Computational model

CRN models have been used to study blowout and pollutant formation in laboratory reactors and gas turbine engines, e.g. [18,38–47]. Recently, Kaluri et al. [48] reported model-based monitoring and real-time prediction of LBO for the present JSR. The approach used combustion temperature measurements, coupled with the RT-CRN to interpret the data as it is collected, see Fig. 1. The jet-flame region is modeled as an adiabatic PSR1 with relatively small volume. The jet impinging region, i.e., a near post-flame zone, is modeled as PSR2. The recirculation zone is modeled as an assigned (i.e., measured) temperature stirred reactor (PST3), owing to the heat transfer from the burning gases to the reactor walls. The three reactors cover the full volume of the JSR. The temperature input is provided by the R-type thermocouple measurements. During the transition from higher to lower Φ, the reactor wall is hotter than the gas, resulting in heat transfer into the system. The volumes and the flow splits of the individual CRN elements are determined based on the CFD solution of Karalus [47]. The single-jet JSR used in this study has a recirculation ratio of 75%; that is, the average fluid particle passing through the JSR makes four passes through the reactor before being exhausted based on the jet entrainment calculation [49–51], and later confirmed by CFD modeling [52,53]. The CRN configuration is based on the reactor behavior under stable combustion ($T > 1700$ K). The time-dependent trends for the predicted free radical concentrations in each CRN element are available with a time resolution of ~1 s. The CRN code used here is developed in-house [54,55]. One of the major advantages of this code is in the implementation of the fast convergence algorithm, which enables near-real-time chemical kinetic calculations in complex CRN arrangements [56,57]. In this work, a detailed chemical kinetic mechanism GRI 3.0 is used [58].

4. Control algorithm

The control algorithm is based on time-resolved trends of OH concentrations during transient combustor operation, i.e., as the rector cools, the peak OH concentration (thus, the flame) moves downstream. The work of Karalus et al [59,60] is basis of using the OH as a parameter for the control methodology; CFD and CRN modeling was used to examine the behavior of the active species chain carriers (H, O, and OH) as the combustion gas flowed through the JSR, from the jet flame (PSR1), to the jet impingement zone (PSR2), to the recirculation zone (PSR3). As the fuel-air equivalence ratio was decreased from that corresponding to lean combustion at 1800 K to lean blowout, the active species were found to be delayed in their peak concentrations to later convective times as phi was decreased. As the JSR approached lean blowout, the induction time from get inlet to the peak in H-atom concentration increased and OH was the longest surviving active species. The amount of OH remaining late in the flow cycle around the JSR and available for entrainment into the jet appeared to play a key role in maintaining ignition [48]. Thus, our work has focused on using OH as the control parameter and comparing its behavior in the zones of the JSR as lean blowout is approached. The active species are known to be essential for ignition and OH is known to remain into the near post-flame region [61,62]. The RT-CRN model [63], shown in Fig. 1, compares the OH radical concentrations in the different reactor zones, and the ratio of OH concentrations in the jet-flame zone to the recirculation zone is used as a criterion for the LBO proximity. Three distinct events are shown during the reactor transition from a stable operating condition to LBO: Event-1: OH radical concentration in PSR1 drops steadily and decreases to a value equal to OH radical concentration in PST3 (OH concentration is nearly uniform in the JSR); Event-2: OH radical concentration in PSR1 drops abruptly (blowout in jet-flame region); Event-3: OH radical concentration in PSR2 drops abruptly below that in PST3 (global LBO). In the current work, the primary objective of the control algorithm is to operate the reactor at the lowest stable Φ, i.e., at closest to uniform OH concentration. Thus, the computed OH ratio of PSR1/PSR3 (rOH) of unity is used as the operating set point. For operational stability, a tolerance of 5% is considered acceptable ($rOH = 1 \pm 0.05$).