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Experimental and numerical investigation of thermo-acoustic instability in a liquid-fuel aero-engine combustor at elevated pressure: Validity of large-eddy simulation of spray combustion

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A B S T R A C T

The feasibility of applying the large-eddy simulation (LES) of spray combustion to the investigation of the thermo-acoustic instability mechanisms in practical aero-engine combustors was examined, employing experimental data obtained from optical measurements. Single sector combustion tests using a staged fuel injector were conducted at the JAXA high temperature and pressure combustion test facility. An unstable operating condition exhibiting strong self-excited thermo-acoustic instability with a peak frequency of approximately 500 Hz and an amplitude more than 40 kPa was chosen for measurements of the dynamic pressure, in addition to OH-PLIF and OH* chemiluminescence studies. LES calculations were performed under the same conditions and the use of LES was validated based on comparisons of results with experimental data, considering the dynamic pressure and unsteady flame behaviors. In addition, a more detailed investigation was performed with the LES data, focused on unsteady characteristics such as velocity, evaporation rate, equivalence ratio and heat release rates. In general, LES was found to successfully reproduce the experimentally observed unsteady characteristics of pressure and flame structures during thermo-acoustic instability, though there were several discrepancies between LES and experimental results with regard to the oscillation amplitude and local flame behavior, such as the periodical flame flashback. In the LES data, the time evolution of the product of the flame surface area and the flame-area-averaged equivalence ratio were in good agreement with the overall heat release rate variations, suggesting a simple dominant mechanism for the thermo-acoustic instability. These results provide evidence for the feasibility of employing LES as a means of further exploring the effects of key physical parameters, such as the spatial distribution of fuel and its temporal variations, on combustion instability.

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1. Introduction

Combustion instability has become the primary technical challenge in the development of low-emission combustors for aero and land-based gas-turbine engines, since it has the capacity to cause catastrophic damage to the combustion chamber and other engine components. Despite a great deal of research regarding this issue over the past several decades (e.g., [1]), the problem is not yet fully solved, due to the attendant level of complexity. As an example, dynamic flame behavior in a jet-engine combustor is determined by many physical processes, such as fuel atomization and vaporization, fuel–air mixing, vortex/flame interactions and flame/acoustic interactions. These processes also take place under conditions of high temperature and pressure in engine combustors. In addition, fuel injectors meant for practical applications typically have complex geometries, such as multi-swirlers and staged fuel injections, to enhance fuel atomization and fuel–air mixing characteristics while achieving the desired level of flame stabilization. Understanding the driving mechanisms of combustion instabilities under practical conditions and configurations is definitely a critical

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issue in the development of low-emission jet engines, since a detailed understanding of these mechanisms allows one to consider the means by which to stabilize the combustor.

Laser diagnostics is a very powerful tool for understanding the dynamic processes in combustion flows, since it offers a high degree of temporal and spatial resolution. In order to apply laser techniques at elevated pressures, however, it is necessary to use high laser pulse energies and to prepare countermeasures for technical restrictions, such as light absorption, beam steering and spectrum broadening. Moreover, conducting an experimental analysis of self-excited combustion instability under elevated pressure conditions is a difficult task, since the high amplitude pressure oscillations may lead to failure of the combustion test rig and/or measurement apparatus. In addition, the operating costs of a high pressure/temperature combustion facility are high. Accordingly, there are only a limited number of studies that have utilized laser diagnostics to analyze combustion instability mechanisms in gas-turbine combustors at elevated pressures [2–5]. Dhanuka et al. [2] investigated the driving mechanism of a low-frequency (4–10 Hz) combustion instability occurring under off-design conditions in a single-sector combustor test with a practical lean premixed prevaporized (LPP) fuel injector. PIV (particle image velocimetry) and formaldehyde planar laser induced fluorescence (PLIF) measurements were carried out to assess the velocity field and flame structure characteristics, respectively. The results showed that, as the global velocity gradient decreased, the local velocity gradient in the mixing layer also decreased, making the flame more susceptible to perturbations from vortex shedding. Low frequency instabilities associated with unsteady flashback and liftoff of the flame base were observed under lower velocity gradient conditions. Additionally, lean-limit combustion instabilities at 15 Hz and yet another type of low frequency instability at 80 and 160 Hz were investigated by the same group [3,4]. Stopper et al. [5] used optical measurement techniques such as PIV, 1-D laser Raman scattering and OH-PLIF to study natural gas/air flames, employing a commercial swirl burner for industrial gas turbine combustors at elevated pressures. Combustion instability at 220 Hz was excited in one of the test conditions and, under the unstable condition, periodic vortex shedding was identified at the burner mouth in connection with a significant variation of the backflow of burned gas within the inner recirculation zone. In addition, significant periodic variations of the mixture fraction were observed in the inflow zone close to the burner. Boxx et al. [6] demonstrated the high repetition PIV/OH-PLIF measurement of unsteady combustion flow in a model gas-turbine combustor at 5 bars. Their results showed the potential of the high repetition laser technique to act as a diagnostic tool for unsteady combustion flow even under elevated pressure conditions. The former examples [2–4] focused on low-frequency instabilities in jet engine liquid-fuel combustors, while the latter studies [5,6] dealt with thermo-acoustic instabilities in gas-fuel combustors for industrial turbines. Our focus in this study was thermo-acoustic instability in a jet engine liquid-fuel combustor under elevated pressure, a target that has not been previously considered by other groups.

To assist in understanding the combustion instability mechanism, there have been a number of attempts to perform large-eddy simulations (LES) of gas-turbine combustion instabilities over the past decade [7–11], based on new developments in computer performance and simulation methods. Huang and Yang [7,8] applied LES to the study of the lean-premixed combustion field in a model swirl-stabilized gas-turbine combustor, and showed that the inlet temperature, equivalence ratio and inlet swirl all strongly affect the flow development, as well as combustion dynamics such as recirculation flow and acoustic oscillation behaviors in the combustor. Hermeth et al. [9] also performed LES for a lean swirl-stabilized gas turbine burner to analyze the mechanisms triggering combustion instabilities. They investigated the effects of equivalence ratio fluctuations on the dynamic flame response under an acoustic forcing by using two types of fuel–air mixture configurations in a lean swirl-stabilized combustor, and revealed that both technically and fully premixed cases exhibit similar mean pulsated and nonpulsated flame shapes, but show differences in the global and local flame responses. Very recently, LES has been applied to combustion fields in more complex full annular combustors. Fureby [10] performed LES to predict the flow, mixing and combustion characteristics in an 18 burner full annular combustor, and found that the combustor exit impedance and swirler and fuel characteristics influence the combusting flow through the acoustics of the annular combustor. Wolf et al. [11] also applied LES to the study of the combustion field in a 15 burner full annular combustion chamber, and verified that LES captures the azimuthal modes that develop in these chambers, both in the frequency and amplitude range. In all of the above-mentioned LES studies, however, gaseous fuel was used and therefore the introduction of spray combustion has not been fully studied with regard to exploring combustion instability mechanisms in aero-engine combustors burning liquid fuel. Although LES of spray combustion in aero-engine combustors has been demonstrated by several research groups [12–16], these techniques have not been extended to elucidate combustion instability mechanisms.

The objective of the present work was to examine the feasibility of applying LES of spray combustion to the study of thermo-acoustic instability mechanisms in aero-engine combustors under practical conditions. For this purpose, a single sector combustion test of a staged fuel injector was conducted at the high temperature and pressure combustion test facility of Japan Aerospace Exploration Agency (JAXA). An unstable operating condition exhibiting strong self-excited thermo-acoustic instability was chosen for the investigation and dynamic pressure and optical image measurements (OH-PLIF and OH* chemiluminescence) were performed. In parallel, LES was carried out for the unstable condition. Comparisons between the experimental and LES data were made based on the dynamic pressure and unsteady flame behaviors as a means of assessing the feasibility of using LES. Subsequently, a more detailed investigation of the unsteady velocity and temperature fields was performed using the LES data. Finally, a possible driving mechanism for the thermo-acoustic combustion instability is discussed, based on the unsteady characteristics of velocity, equivalence ratio and heat release rate distributions obtained from the LES data.

2. Experimental arrangements

2.1. Combustion test configurations and conditions

The experimental work was performed using a test rig located at the JAXA high temperature/high pressure combustion test facility. This rig is capable of operating at pressures up to 1.0 MPa with an air temperature between 600 (maximum air flow rate of 2.5 kg/s) and 1273 K (maximum air flow rate of 0.45 kg/s). An optically accessible single-sector combustor (Fig. 1(a)) was installed in the pressure casing duct. The axial length of the combustor is 190 mm. The upstream (left hand) region of the combustor is used for visualization purposes and quartz glass plates are installed on the top and both sides of this section, while a stainless steel plate with a pressure transducer mount is installed on the bottom. The downstream (right hand) region consists of a two-dimensional converging nozzle with multiple fine diagonal orifices for film-cooling. Figure 1(b) shows a schematic of the entire test rig.

A low-NOx staged fuel injector developed by Yamamoto et al. [17,18] was mounted on the inlet face plate of the combustor, as

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