PHD THESIS FOR 2022

Subject:

Experimental Investigation on the formation and oxidation of fine particles in Rich-Burn, Quick-Mix, Lean-Burn Combustors

Scientific thematic: Soot formation and oxydation, NO formation, high-pressure combustion, Sustainable aviation fuels

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Key words: High-pressure kerosene/air and SAF/air combustion, spinning combustion technology, soot, NO, laser diagnostics

About the program of the PhD thesis

State of the art

Safran Helicopter Engines has recently developed and patented a new spinning combustion technology (SCT). This innovative technology improves ignition and blow-off capabilities and enables combustor weight reduction, without compromising turbine nor combustor lifetime. This technology has been embedded in the ARRANO engine, which exhibits CO_2 reduction about 15% compared to the previous engine generation. To further promote this highly promising technology, the next step is to assess SCT performances in terms of NOx and soot emissions when burning fossil fuels (kerosene) but also promising liquid fuels such as Sustainable aviation fuels (SAF). Indeed, new aeronautical technologies entering the market today must comply with international regulations and answer the public environmental concern about global warming and human health. To assist Safran in this development phase, a research program between Safran helicopter Engines and the CORIA research laboratory aims to design, manufacture, test and model advanced low-NOx and low soot/ particles injection system for SCT.

The SCT technology is based on the multi-point injection concept, which has already demonstrated large low-NOx capabilities in large aircraft combustors. The challenge is now to guarantee low soot emission as well, which may be detrimental to other pollutant reduction. Several fuel injections systems will be designed and experimentally tested for quantifying their combustion efficiencies as well as their capacities to reduce NOx and soot emissions. these ones will be operated in a Rich-Burn, Quick-Mix, Lean-Burn (RQL) high-pressure combustor which offer promising benefits for the reduction of gaseous and soot pollutants. As a reminder, a RQL concept is based on the principle that the primary zone of the combustor operates more efficiently and provides better flame stability when rich mixing ratios are used. Thus, rich combustion in the primary zone at the injector outlet will improve the stability of the flame while producing and maintaining a high concentration of hydrogen and hydrocarbon radical species. Second, the high air-to-fuel ratios will minimize the production of nitrogen oxides (NOx) due to relatively low temperatures and low concentration of oxygen-containing intermediate species. The fluid issued from the rich primary zone will then have a high level of partially oxidized and partially pyrolyzed hydrocarbon species, hydrogen, carbon monoxide and soot particles. In order to significantly reduce these undesirable pollutants, the addition of oxygen in the combustion chamber at the exit of the primary zone represents a good opportunity to efficiently oxidize these products and thus to reduce these pollutants. To achieve this, a significant amount of air injected through the combustor walls to be mixed with the primary fluid produces a lean combustion before the exit plane of the combustion chamber. Ideally, this results in the emission of an effluent composed of the main combustion products (CO_2, H_2O, N_2, O_2) and pollutants (NOx, CO, HC, soot) in very small quantities.

Research and innovation actions are therefore necessary to improve the architectures of these injection systems. In addition to efforts to study the formation of NOx, it is becoming imperative to quantify the soot production and oxidation processes following the recent stringent international regulations on particle emissions and this over the full operating range of these injection systems. Soot formation in flames is a very complex phenomenon involving various physical and chemical processes. At present, it is commonly accepted that the decomposition of the fuel during its oxidation will lead to the formation of various species including small hydrocarbon radicals, acetylene as well as atomic and molecular hydrogen. Radical species will then recombine to form larger hydrogen-rich structures that will lead to soot precursors by polymerization. A stage called nucleation then allows to pass from a molecular system to a particulate system and leads to the obtaining of the first spherules which will then undergo various interactions and heterogeneous reactions through surface growth, coagulation, agglomeration and oxidation processes. Many activities were performed in the past to study the properties of turbulent swirled premixed or non-premixed flames operating at mostly atmospheric pressure and with gaseous fuels and their impact on the formation of gaseous and particulate pollutants [ ]. In addition, recent efforts examining the effect of air dilution on soot oxidation are underlined in the literature. Despite information obtained in these studies, the detailed understanding of the above-mentioned processes on soot production and oxidation in realistic combustors still remains a challenge, especially due to the complex interactions between aerodynamics, physical mixing and chemical kinetic processes. Significant deficiencies in the predictive capabilities of existing models for aircraft combustion are still found due to the limited understanding of these processes. The development of computer models and simulation tools to study aircraft combustion and to design new engine concepts is then hampered by the lack of diagnostic tools to deepen the understanding of the control processes under relevant engine conditions. It is then imperative to develop and have efficient diagnostic techniques for the high pressure and temperature regimes relevant to gas turbines. Since several years, various laser diagnostics were developed at CORIA and applied in high-pressure high-temperature operating conditions, providing in particular and for the first time a full detailed characterization of time-resolved, simultaneous, multi-dimensional flow field and scalar distributions including temperature fuel molecules, key intermediate combustion species, pollutant precursors and pollutants like NOx and soot. Successful implementation of these diagnostics is in the current thesis in an RQL combustor equipped with innovative SCT injection systems is then expected to provide benchmark experimental data of high fidelity for traditional aviation fuels (Jet A1 kerosene) and emerging future sustainable aviation fuels (SAF) that will be used to develop and validate the future predictive capability aircraft combustion models ensuring efficient and clean combustion.

Thesis description

The objective of the PhD thesis is thus to study experimentally the mechanisms of formation and oxidation of fine particulates (soot) and gaseous pollutants (NO) on helicopter fuel injection systems which adopt the spinning combustion technology (SCT). Two injection systems will be designed and built during this program.

The objectives of the PhD thesis are oriented to:

* Quantify combustion performances of the spinning combustion injection systems with various optical measurement diagnostics under realistic operating conditions (i.e., pressure chamber up to 18 bar).
* Quantify the role of the spray formation and the subsequent mixing of fuel and air in the primary zone on combustion and soot production.
* Study the impact of the secondary air on the oxidation of soot particles.
* Investigate the production of soot and NOx emissions in terms of soot volume fraction, size and number distribution and species concentration respectively.
* Study the impact of the fuel composition by performing a comparative analysis of performances between kerosene and SAF combustions.
* Propose developments paths for low-emission (NOx and soot) spinning combustion injection systems by improving our understanding on the role of the underlying physico-chemical generating mechanisms governing the combustion performances and reduction of pollutants in an SCT combustor architectures.

The PhD position is open at INSA Rouen Normandie/CORIA laboratory.

Program of the PhD thesis (36 months):

The experimental study will be carried out on the HERON combustion bench (High PrEssuRe facility for AerO-eNgines combustion) of the CORIA laboratory equipped with the SCT injection systems supplied by SHE. This combustion bench will be adapted by inserting a rich-quench-lean (RQL) combustor sector based on an advanced cooling mixing concept including effusion cooling and row of secondary air inlet holes in the mixing zone. Experiments will be performed with liquid kerosene (Jet A1) and SAF fuels. Detailed measurements of scalar parameters (velocity, flame structure, fuel evaporation, spray pattern, pollutant concentration) with be acquired by various advanced laser diagnostics under thermodynamic conditions relevant to modern helicopter combustion chambers. A focus will be carried out on measurements of soot and NO pollutant concentration inside and outside the combustion chamber. All these measurements will provide a precious insight on the underlying physical mixing and chemical kinetic processes governing high-pressure RQL combustion and to obtain a detailed-evaluation of the performances of new fuel injection systems. Experimental studies performed with laser diagnostics will lead to get detailed information on:

- ***Aerodynamics field (velocity distribution:*** This one will be measured by high-speed PIV diagnostic (10 kHz repetition rate).
- ***Flame structure and fuel/air mixing:*** OH-PLIF diagnostic will be used to study the flame structure. Distribution of the kerosene fuel vapor will be also measured with the PLIF-fuel diagnostic simultaneously with OH-PLIF measurements to get for the first time, a detailed understanding of the mixing of fuel vapor with air downstream from the injector. The correlation of these distributions (OH, fuel) will get information on the consumption of the fuel inside the combustion chamber, giving then the opportunity to quantify precisely the efficiency of the combustion process.
- ***Spray formation:*** The spray characterization (size and velocity of droplets) will be carried out by PDPA (Phase Doppler Particle Analyzer).
- ***NO distribution:*** Detection of nitric oxide inside the combustor will be performed using the NO-PLIF diagnostic. This technique will be combined to the PLIF-OH to correlate the impact of the structure of the flame front on the pollutant reaction rate.
- ***Soot distribution***

Measurements of the soot volume fraction inside the flame will be measured by LII (laser-induced Incandescence) diagnostic. For specific operating conditions, the coupling of this technique with the static light scattering diagnostic will be implemented in order to quantify the soot size production inside the flame.

Furthermore, global measurements at the combustor exit will be undertaken by gas sampling for measuring the gaseous concentration indices (mg/g fuel) of CO, CO2 and NOx and ex-situ size distributions of soot particles determined by SMPS at the burner outlet.

Profile and requirements

- MSc or equivalent in the field of fluid mechanics, combustion and optical measurements
- Applicants must have a solid knowledge of code development (Fortran, python…) for code development of data processing.
- Ability to work in a team, as well as independently
- Ability to solve complex problems.
- Good communication skills (both written and verbal) in English
- CORIA is a "zone with restricted access" (ZRR). Access to CORIA is conditioned by the authorization of the Senior Defence and Security Official.

Application

Interested candidates are invited to send the following documents

- CV
- Letter of motivation

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