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Experimental and numerical studies of a lean-burn internally-staged combustor

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Abstract A lean-burn internally-staged combustor for low emissions that can be used in civil aviation gas turbines is introduced in this paper. The main stage is designed and optimized in terms of fuel evaporation ratio, fuel/air pre-mixture uniformity, and particle residence time using commercial computational fluid dynamics (CFD) software. A single-module rectangular combustor is adopted in performance tests including lean ignition, lean blowout, combustion efficiency, emissions, and combustion oscillation using aviation kerosene. Furthermore, nitrogen oxides (NO_x) emission is also predicted using CFD simulation to compare with test results. Under normal inlet temperature, this combustor can be ignited easily with normal and negative inlet pressures. The lean blowout fuel/air ratio (LBO FAR) at the idle condition is 0.0049. The fuel split proportions between the pilot and main stages are determined through balancing emissions, combustion efficiency, and combustion oscillation. Within the landing and take-off (LTO) cycle, this combustor enables 42% NO_x reduction of the standard set by the 6th Committee on Aviation Environmental Protection (CAEP/6) with high combustion efficiency. The maximum board-band pressure oscillations of inlet air and fuel are below 1% of total pressure during steady-state operations at the LTO cycle specific conditions.

1. Introduction

Lower emissions have become one of the key characteristics of advanced civil aviation gas turbine engines over the past 30 years.[1] A number of new combustor design strategies, including lean premixed prevaporized (LPP), rich-quench-lean (RQL), and lean direct injection (LDI),[2,3] are being investigated widely in order to meet the more and more stringent international standards on civil aviation engine emissions set by the International Civil Aviation Organization (ICAO). All the standards, including CAEP/2 (Committee on Aviation Environmental Protection), CAEP/4, CAEP/6, and CAEP/8, demand reducing emission of NO_x without increasing emissions of carbon monoxide (CO), unburned hydrocarbon (HC), and smoke, and CAEP/6 standard is working for engines of a type or model of which the date of manufacture of the first individual production model is after December

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31, 2007.[4] The market demands civil aviation engines with emissions levels below 50% of international standards for getting commercial success, which brings great challenges to the development of ultra-low emission combustors.

In the design of ultra-low emission combustors, lean-burn technology holds the potential of reducing NO_x emissions as compared to rich-burn technology, especially at a high operation pressure ratio (OPR).[5] Low emission combustors adopting lean-burn technology combined with an internally-staged concept have been developed in the past 15 years, including the twin annular premixing swirler (TAPS) combustor by General Electric (GE),[6] the lean-burn combustor by Rolls-Royce (RR),[7,8] and the lean staged combustor by Kawasaki Heavy Industries (KHI).[9,10] The TAPS combustor has been used in the GEnx-1B/2B engines with NO_x levels 52% below CAEP/6 standard while maintaining good CO, HC, and smoke emissions.[11]

In this paper, a novel lean-burn internally-staged combustor with low emissions is designed beginning with a mountain of CFD (Computational Fluid Dynamics) simulation work to design and optimize the main stage used as the fuel/air premixing device. Using a single-module rectangular combustor, the combustion performance is systemically investigated experimentally, including the lean ignition performance under normal and negative inlet pressures, the lean blowout performance at the idle condition, the gas emissions and smoke emission under the conditions of raised inlet temperatures and pressures, as well as combustion efficiency and combustion oscillation. The fuel split proportions between the two stages are also studied experimentally. The present work also includes numerical simulations to predict NO_x emission to compare with the test results.

2. The combustor design

2.1. General design

The internally-staged combustor is a single annular layout, and the dome is comprised of two stages – the pilot stage and the main stage. The pilot stage is located in the centerline of the combustion chamber and the main stage surrounds coaxially the pilot stage. The pilot stage adopting a diffusion flame is used for easy and reliable light-off during ground starting, rapid relighting of the combustor after a flameout in fight, extending lean blowout limits, increasing combustion efficiency at low power conditions, and reliably igniting the main stage fuel/air pre-mixture at high power conditions. The main stage adopting a premixed flame is used to reduce NO_x emission at high power conditions.[12] Fig. 1 shows the schematic of the internally-staged combustor.

Lean-burn technology is used in the combustor design for its great advantage in reducing NO_x emission. In the aerothermodynamics design, the combustion equivalence ratio is 0.67 under the take-off condition which is chosen as the design point with the total air flow rate through the pilot and main stages being 64% W_a (where W_a is the liner total air flow rate). To improve the margins on lean blowout and combustion efficiency at low power conditions, the pilot stage local equivalence ratio is 2.0 under the idle condition with the total air flow rate through the pilot stage being 10.7% W_a. Another 4.5% W_a is used to cool the dome of the combustor and the remaining 31.5% W_a is used as the liner wall cooling air and the dilution air.

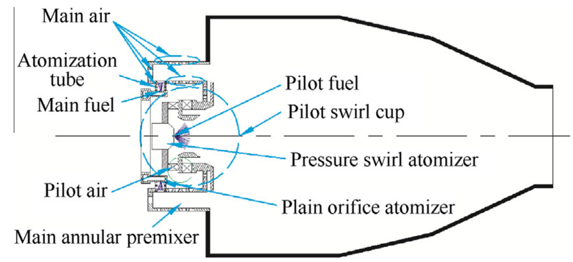

Fig. 1 Schematic of the internally-staged combustor.

2.2. The pilot stage design

The pilot stage is a typical swirl cup design which refers to the CFM56 engines swirl cup studied in Refs.[13,14]. A pressure swirl atomizer with dual counter-rotating radial swirlers is used to atomize the fuel. The formation of a central recirculation zone, the prevention of fuel coking, and the spray quality and distribution are concerned in the design of the pilot swirl cup. The parameters of the pilot swirl cup following our previous relevant study are shown in Table 1. In Table 1, SN is the swirl number, FN is the flow number, Δp_f is the fuel nozzle pressure drop, and the rotating direction is defined as looking downstream from the incoming flow direction.

2.3. The main stage design

The main stage includes one annulus as premixer formed by two steel pipes of different radii, and there are a number of fuel orifices drilled circumferentially in a single row which inject the fuel radially outward into the annulus passage. In order to improve the fuel/air mixing level, each fuel orifice is surrounded by a tube with straight holes, and the air through the holes advantages atomizing the fuel. There are a number of straight and inclined holes on the annular surfaces and the dome of the main stage. Furthermore, the air injected through the inclined holes can form swirl within the annulus passage, and hence the fuel can be premixed with air and prevaporized in the annulus passage. Fig. 2 shows the schematic of the main stage.

2.4. Numerical study of the main stage

The main stage is used to premix fuel with air before entering into the chamber to lead a premixed flame to lower NO_x

Table 1 Parameters of the pilot swirl cup.

Parameter	Value
Primary swirler air (%)	40
Secondary swirler air (%)	60
Primary SN	0.85
Secondary SN	0.62
Primary swirler rotating direction	Clockwise
Pressure swirl atomizer FN (kg/(h·MPa$^{0.5}$))	25
Spray rotating direction	Clockwise
Spray angle (°) (Δp_f = 1.0 MPa)	75