1 Introduction

1.1 Motivation

Global air traffic has doubled in size every fifteen years in the past four decades and will continue to do so (ICAO, 2016). Gas turbines are the primary power source for aircraft propulsion (Farokhi, 2014). Furthermore, the application of power generating gas turbines may grow due to the increasing use of renewable energies. In that scenario, fast-starting gas turbines with highly efficient part-load capability can provide a remedy to cover the peak times or situations with a temporary lack of renewable sources such as wind or sun.

The increasing application of gas turbines for propulsion and power generation faces permanently stricter regulations for pollutant emissions (BDL, 2017, EPA, 2017). To secure profitable operation, as well as to meet the regulatory requirements, gas turbine manufacturers have to improve low-emission combustion technologies. Besides, the overall efficiency of the engines must be continuously increased to reduce fuel consumption and associated emissions. In both of these efforts, the combustor plays a central role and is the subject of numerous research and development activities. In addition to these, aviation pursues the reduction of its environmental impacts by improving the aerodynamics of airplanes as well as by developing more efficient routes facilitated by performance-based procedures and advanced avionics.

The overall efficiency of gas turbines can be increased by:

1. Improving the thermal efficiency of the simple Joule–Brayton cycle by higher pressure ratios and higher turbine inlet temperatures.
2. Carnotization of the simple Joule–Brayton cycle: Recuperation of the exhaust gases, multistage compression with intercooling, multistage expansion with sequential combustion.
3. Enhancing the efficiency of the engine components.
4. Optimizing the interaction of the engine components.
5. Raising the propulsive efficiency, in the case of aircraft engines, by a higher bypass ratio.

The gas turbine combustor interacts directly with two other major engine components, i.e., the compressor and the turbine. During the progress of the flow through the combustor, the working fluid experiences aerothermal changes with velocity and temperature variations spanning over an order of magnitude. The combustion device must ensure an efficient and safe functionality at different operating points, which can be far apart from each other. Such a combustor requires an optimal treatment of several multiphysics phenomena involving complex flow guidance, preparation and mixing of fuel with air, cooling of liner walls, and expressly low-emission and stable combustion.

As a central component of the gas turbine, the combustor is involved in numerous innovative concepts. The subject of the present research work is a compact combustor with angular air supply. This concept adopts measures to improve the interaction of the combustion system with the upstream compressor and downstream turbine. In the next section, the technical history of this idea is reviewed, and its principal features are introduced.

1.2 State of the Art in Gas Turbine Combustion

Traditionally, the gas turbine combustion systems used nonpremixed flames because of their reliable performance and stability characteristics. The severe drawback of this type of combustor is the production of very high levels of thermal nitrogen oxides (NOx) (Correa, 1998). Modern machines employ low-emission combustion technologies, including lean-burn (LB) and rich-burn quick-quench lean-burn (RQL). RQL techniques are applied widely in propulsive engines because of a good compromise between the emission and stability characteristics. They are mainly hampered by soot formation and incomplete mixing between fuel-rich combustion products and air. Thus, the RQL technology faces increasing challenges to comply with the current emission regulations and seems to reach its technological limit in the foreseeable future. Despite promising emission characteristics, the catalytic combustion could not gain acceptance because of the high cost as well as durability and safety issues (Lefebvre and Ballal, 2010).

Among these three technologies, LB combustion appears to be the most promising technology for most practical systems at present. It is employed in nearly all land-based and increasingly in large aircraft engines but also in boilers, furnaces, and internal combustion engines. LB technology features first and foremost reduced NOx emissions. The reason is the operation of the primary combustion zone with excess air. Accordingly, the average flame temperature, and therefore the thermal NOx formation, is reduced. (Dunn-Rankin, 2011).

The improved emission properties of the LB concept are at the costs of low reaction rates, the hazard of lean blow out, high sensitivity to mixing quality as well as thermoacoustic instabilities. The latter are unsteady flow oscillations, which can reach sufficient amplitudes to interfere with engine operation. In extreme cases, they cause total failure of the system due to excessive structural vibration and heat transfer to the chamber (Huang and Yang, 2009). These issues can seriously impair the stability and reliability of the LB combustion. Thus, in contrast to land-based gas turbines, the widespread application of LB combustion in aircraft engines still requires more maturing of this technology. Nevertheless, with respect to a long-term application, the unconventional combustor model addressed in the present thesis is studied in the context of LB technology.

1.2.1 Short Helical Combustor

The subject of the present research work is the concept of an annular gas turbine combustor as shown schematically in Fig. 1.1. The central idea is the utilization of angular momentum of the airflow discharging from the rotor blades of the last compressor stage. Accordingly, the Outlet Guide Vanes (OGV) do not deflect the flow entirely in the axial direction, as is done in the case of conventional machines. Thus, the flow discharges into the combustor with a circumferential

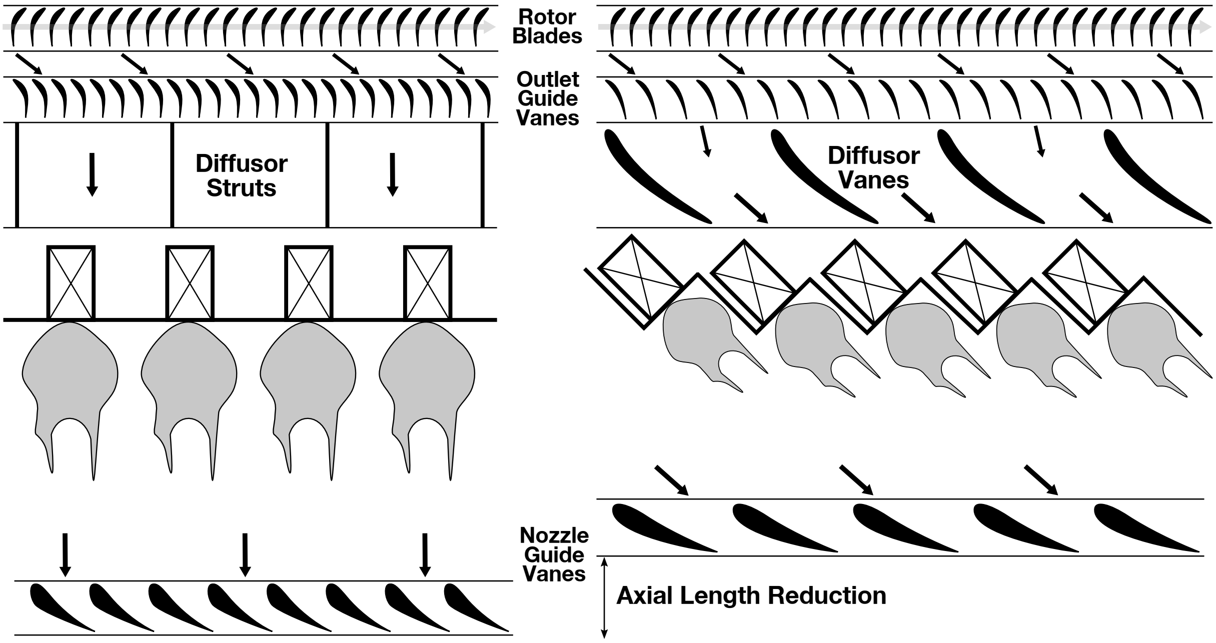

Figure 1.1: Schematic comparison of a conventional annular gas turbine combustor (left) with the Short Helical Combustor (right). Solid arrows indicate the flow path. Reproduced from Negulescu (2013).

component. In the case of an annular combustor, a helical flow pattern would be established. This property, in turn, can be adopted to reduce the axial length of the combustor.

The overall performance and efficiency of such an engine can be improved by several aerothermal and structural properties. In particular, because of the shorter axial extent of the combustor, the total length of the engine can be reduced. In addition to the weight reduction, better integration of the combustor and a more rigid shaft with improved rotor dynamics are expected as well. Furthermore, because of the tilted burner arrangement, a smaller deflection angle is required at the vane cascades upstream and downstream of the combustor. Accordingly, the number of OGV and Nozzle Guide Vanes (NGV) can be reduced. Thereby, smaller total pressure loss, as well as lower cooling air demand is expected. Another substantial advantage is the enhanced transversal exchange of heat and combustion products between the adjacent flames via advection and radiation. Hence, a reduction of pollutant and noise emissions together with higher stability and startup flexibility might be achieved.

Seippel (1943) was the first to patent a gas turbine combustor design with such an angular air supply. In a similar context, Negulescu (2013) proposed the Short Helical Combustor (SHC). Many other similar configurations have also been patented by almost all major gas turbine manufacturers (Burd and Cheung, 2007, Buret et al., 2009, Hall, 1961, Mancini et al., 2007, Schutz et al., 1999, Tangirala and Joshi, 2015). Commonly, in all those publications, the well-established concept of swirl-stabilized combustion was followed. Accordingly, the combustor dome features a staggered arrangement. The axes of burners were then tilted against the rotor axis to adapt to the angled flow coming from the upstream compressor. A new element due to the staggered design is the sidewall. It is located in the primary combustion zone and gives rise