

This doctoral thesis explores the challenge of developing fuel-flexible technologies for gas turbines, with the objective of supporting the decarbonization of electrical energy production. In recent years, lean premixed combustion systems have been extensively used in gas turbines for power generation, resulting in continuous and substantial reductions in NO_x emissions. Despite this advantage, swirl-stabilized burners used in these systems are known to be susceptible to flashback phenomena and to exhibit increased emission levels when operating with hydrogen-enriched fuel blends.

The power generation sector aims to run on pure hydrogen, but this shift will only occur gradually, with the hydrogen share in the fuel mix steadily increasing in the next few years. During this transition, gas turbines will operate with blends of natural gas and hydrogen. For this reason, it is crucial to design burners that can guarantee a stable flame and low emissions across a wide range of fuel compositions. Balancing flexibility, safety and emissions is one of the main engineering challenges in developing next-generation combustors. In this framework, three-dimensional reactive CFD simulations are an essential tool to explore how hydrogen affects combustion, from flame stability and temperature fields to pollutant formation. The present work applies state-of-the-art CFD methods to industrial-scale combustors under realistic operating conditions, addressing challenges rarely investigated in the literature.

The present thesis is organized into four main parts addressing these aspects in detail for different technologies.

Part I establishes the conceptual foundations of the study, outlining the objectives, theoretical background and the general methodology adopted throughout the research.

Part II focuses on the analysis of hydrogen addition effects in a diffusion-type industrial gas turbine combustor, identifying the operational constraints and technical limitations associated with hydrogen utilization without any modifications to the original configuration.

In Part III, the investigation shifts toward a premixed Dry Low NO_x (DLN) combustor. After assessing the influence of hydrogen addition, a retrofitting solution for the fuel injection system is proposed. This redesign aims to extend the operational lifetime of the turbine.

Part IV presents an experimental and numerical study performed on a Jet Burner developed at the Technical University of Berlin (TUB). A newly designed configuration is also proposed for this burner to achieve simultaneous stabilization of hydrogen and methane flames, paving the way for future optimization of dual-fuel systems.

This doctoral thesis contributes to the global effort of decarbonizing the energy sector by analyzing the hydrogen addition effects on different gas turbine technologies. Furthermore, it demonstrates the practical applicability of CFD to industrial combustors, and it proposes a series of fuel-flexible design solutions accelerating the transition toward hydrogen-ready and low-emissions power generation.