Development of a low-NO_x Micro-Mixing Gas Turbine Burner for High-H_2 Content Blends

A. Di Nardo, E. Giacomazzi, M. Cimini, G. Troiani,
G. Calchetti, D. Cecere
eugenio.giacomazzi@enea.it
TERIN-DEC-CCT Laboratory, ENEA, C.R. Casaccia, S.M. di Galeria (Rome), Italy

Abstract

Aiming to a new and original burner geometry for gas turbines, potentially capable of operating with mixtures of natural gas and hydrogen in the range 0-100% H_2 with limited NO_x emissions, this work focuses on a device operating with a H_2 content larger than 50% by volume. The geometry was initially designed by means of several RANS simulations, optimizing reactants mixing and reducing the risk of flashback; LES simulations of some specific conditions were performed to check potential combustion dynamics issues. Then, the suggested solution was partially tested experimentally on a prototype.

Introduction

In the context of moving towards less reliance on fossil fuels, gas turbine plants operating with hydrogen/methane blends represent an important solution for decarbonizing the thermal power generation sector and for the sustainability of the energy transition [1]. However, it is important to emphasize that to have a significant impact on reducing CO_2 emissions, it is necessary to work with blends containing a high proportion of hydrogen.

When discussing fuel-flexibility currently, it refers to the ability of a gas turbine to operate with hydrogenated blends, where hydrogen is mixed with other gaseous fuels. These blends range from hydrogen-enriched natural gas (HENG) to ammonia. Although their tendency to exhibit thermos-acoustic instabilities, DLE (Dry Low Emissions) combustion technologies are the state of art to operate gas turbines with pollutant emissions below the limits set by the European Industrial Emission Directives (IED).

The maximum allowable concentration of hydrogen in DLE gas turbines varies significantly from one manufacturer to another [2]. The variation is due to differences in combustion temperatures and combustion technologies used across different classes. The pursuit of a combustion strategy for high-H_2 content blends with low NO_x emissions is a focal point for gas turbine manufacturers [3]. Currently, NO_x emissions are often controlled by derating the machine, meaning reducing its power output. It's also observed that adding H_2 to natural gas affects the start-up and shutdown procedures of the machines. Additionally, the machines will need to maintain a suitable degree of operational flexibility, meaning they must reliably and safely vary power output quickly to meet changes in energy demand.

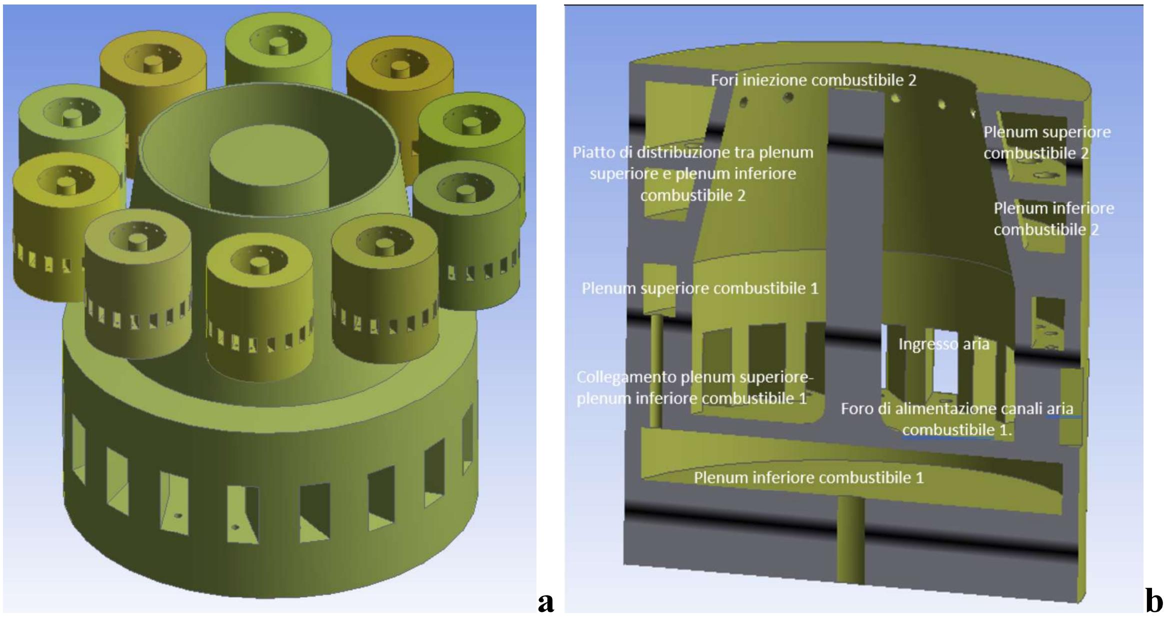

Figure 1. Complete burner (a); section of a crown system burner (b).

The developed burner configuration

Present results come from a project aiming to identify a low-emission fuel-flexible burner technology, build a prototype, and test it in an off-machine test facility. The design target machine is the TURBEC T100 microturbine.

An entirely original construction and operating strategy was devised. This involves two independent lean-premixed swirl burners (Fig. 1a) with flame aerodynamic stabilization: one central (330 kW_t) for low hydrogen content mixtures and one coaxial (crown burner system, consisting of 10 burners of 33 kW_t) for high hydrogen content mixtures. To independently operate the two burners, two separate air plenums have been provided, one for the central burner and one for the crown system, fed from a common source. By controlling their flow rates through an active control system, the operation of the gas turbine can be adjusted based on the hydrogen content in the incoming HENG mixture and the machine load.

This article deals with the development and first characterizations of one of the burners in the coaxial crown system, operating with high hydrogen content, i.e., higher than 50% by volume. To mitigate flashback risks the burner must be sized to ensure sufficiently high efflux velocities and low residence times in the mixer. To achieve these characteristics, the crown system burners were designed by hybridizing a typical swirl configuration (providing flame aerodynamic stabilization via central recirculation or vortex breakdown) with micro-mixing concepts.

The even number of burners in the crown system has alternating swirl flow directions, clockwise/counterclockwise, so that in the contact zone between the flows of two adjacent burners, the velocity vectors have the same direction.

In its final configuration, the burner (Fig. 2b) consists of 18 inclined channels through which air flows. Fuel is injected into each channel in crossflow at two opposing points (holes' diameter, 0.75 mm), facilitating fuel penetration into a significant portion of the air flow, although it does not diffuse throughout the entire channel height. The dual injection necessitates two fuel plenums: the main fuel inlet feeds the lower plenum, which is then connected to the upper plenum through channels between the air conduits. The high number of channels and injection holes accelerates mixing through distributed fuel injection. Fuel and oxidizer complete mixing inside a premixing chamber of sufficient axial length (20 mm) to uniformize fuel concentration. The initially cylindrical chamber narrows towards the outlet to accelerate flow (exit diameter, 15 mm). The tangential velocity component imparts the initial rotation to the flow, necessary to achieve a swirl flow number SN = 1 at the burner outlets. Simultaneously, this rotation facilitates effective and rapid mixing between air and fuel in the premixing chambers.

For the first prototype of the crown system burner, it was equipped with an additional, independent diffusive fuel injection system (holes' diameter, 0.6 mm), located just before the outlet section, to experimentally evaluate its potential for very high concentrations of hydrogen in the fuel mixture.

The RANS development strategy

The sizing and optimization of the burners were conducted using RANS (Reynolds-Averaged Navier-Stokes) simulations with Ansys-Fluent 2019R1 software, focusing on mixing (non-reactive simulations). The computational grid has approximately five million cells. The "k-ε realizable" turbulence model was adopted, coupled to the Eddy Dissipation Concept (EDC) model with 46 chemical reactions and 17 species in reactive simulations. Transport properties were computed using kinetic gas theory. Simulations were performed at an operating pressure of 4.5 bar.

The representative burner of the crown system was studied for mixtures 50% and 100% H_2 at the nominal power level of 33 kW_t and maintaining constant air flow rate. It is observed that, the average nominal equivalence ratio ϕ decreases with increasing H_2 content: 0.5 and 0.43, for 50 and 100% H_2 respectively (ϕ used here are preliminary).

The objective was to design a burner that optimally mixes the reactants, reduces the risk of flashback, and is characterized by low NO_x emissions. After identifying the optimal configuration, the fuel supply system was also simulated to assess pressure losses and flow distribution through various channels and injection ports. Additionally, heat transfer through the burner material was simulated to estimate the preheating effect of the fuel due to the incoming air at 560°C.

A simple swirling configuration was initially chosen. Upon initial assessment of the dimensions and footprint of the central burner, it became apparent that the length of the lateral burners needed to be very short. Reducing this length created a dangerous central depression, potentially leading to the return of hot gases throughout the premixing chamber. Therefore, it became necessary to add a central body whose width was optimized to achieve a sufficiently high axial velocity profile at the outlet, particularly in the area adjacent to it. With this configuration, however, the length of the premixing chamber proved insufficient to ensure uniform mixing between fuel and air. For this reason, additional and properly located fuel injections were added in the air channels, imposing a geometric configuration with an additional fuel plenum. An example of the obtained equivalence ratio distribution is in Fig. 2 (left): ϕ at the outlet section generally exhibits a radial distribution, with two inner and/or outer rings richer in fuel and a central ring poorer in fuel. The flow is highly swirled at the exit plane of the burner, exhibiting velocities of approximately 115 m/s, as shown in Fig. 2 (right).

The reactive simulations show that as the H_2content increases, the flame shortens. Such reduction is very noticeable when it is fueled with 100% H_2. Moreover, the flow velocities of the reactive mixture for which the burner was designed seem sufficient to prevent flame flashback in the premixing chamber. In the opposite case, i.e., with 50% H_2, the flame appears quite elongated and stretched.

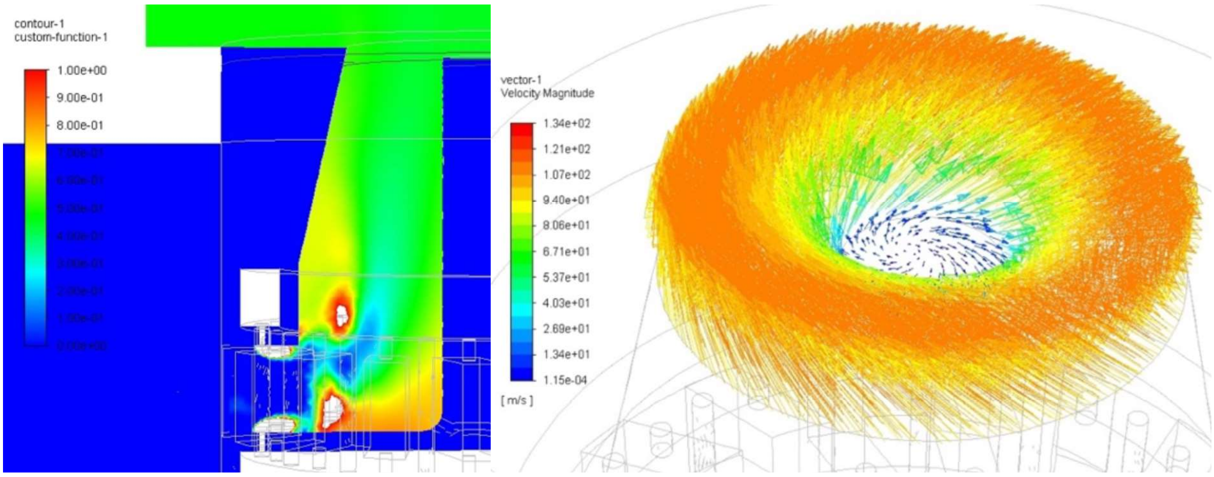

Figure 2. Equivalence ratio distribution for the 50%CH_4-50%H_2 fuel mixture (exit average value 0.5) (left). Velocity vectors at the exit (right).

LES and combustion dynamics

The LES simulations use the in-house parallel code HeaRT and ENEA's CRESCO supercomputing facility. The code solves the compressible Navier–Stokes equations with staggered finite-difference schemes, employing the dynamic Smagorinsky and LTSM models for subgrid terms. Convective terms are handled with the AUSM+-up method and WENO interpolation, while diffusive fluxes use a second-order central difference scheme.

The computational domain is a 60° cylindrical sector, 0.10 m in length, and 0.05 m in radius. The chamber starts with a quiescent flow at 874 K, and the fuel jet is injected through an annular section using a boundary condition from RANS simulations. The mesh has 400 × 300 × 64 grid points, totaling about 7.68 million cells. Chemical reactions follow the Glarborg et al. mechanism [4] for H_2, with 21 species and 109 reactions. Wilke's formula and Mathur's expression are used for viscosity and thermal conductivity, respectively, with preferential diffusion based on Hirschfelder and Curtiss law.

Figure 3 displays (left) snapshots of temperature fields of two 100% H_2 premixed flames with different equivalence ratios. At ϕ=0.43, temperatures exceed 2000 K near the jet entrance, indicating the ignition zone with intense turbulence fostering efficient combustion. A strong recirculation bubble is observed near the jet axis, sustaining continuous ignition of fuel. At ϕ=0.30, temperatures peak below 1700 K with a longer flame length, showing less intense turbulence and quicker dissipation of high-temperature areas.

In both flames, the combustion region is confined to the internal shear layer, with intermittent combustion occurring in the external shear layer due to strong vortices detached from the flame tip flapping motion (not visible). Flame front topology is clear looking at the heat release rate (HRR) distribution on the right of Fig. 3. The flame at ϕ=0.43 exhibits more intense combustion and greater heat release rate. In contrast, at ϕ=0.30, the HRR is significantly reduced, indicating weaker combustion, and the flame length increases. Additionally, at ϕ=0.43, the flame front appears corrugated but not fragmented, unlike the other case where the flame front appears discontinuous in certain regions.

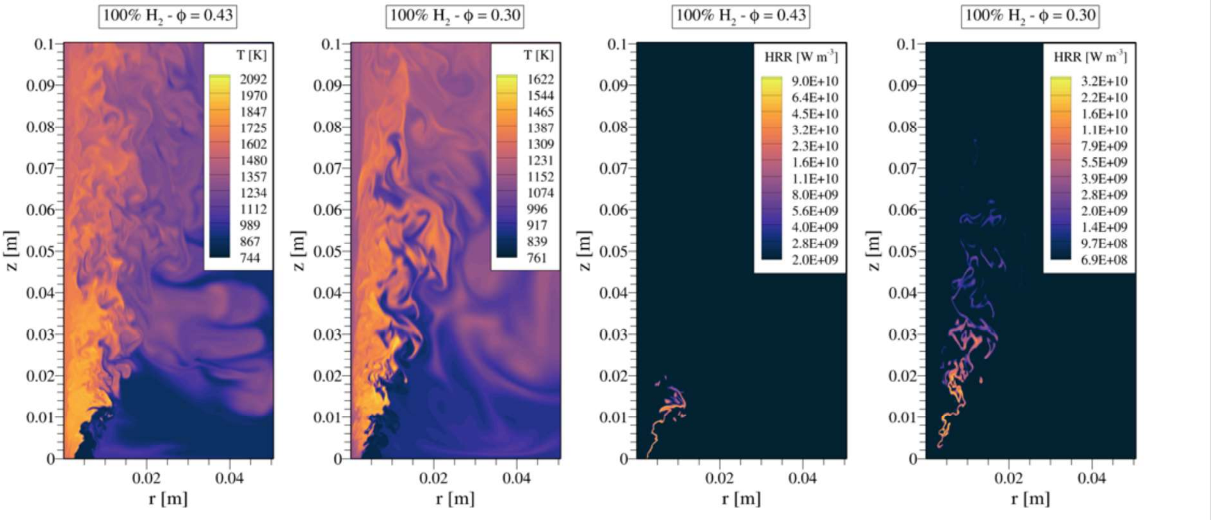

Figure 3. Snapshots of temperature field for 100% H_2 at different equivalence ratios.

Experimental tests

The conceptual burner for the crown system, designed for high-H_2 content fuel mixtures, has been mechanically designed and constructed. The prototype is shown in Fig. 4: the burner is on the left (about the diameter of a €1 coin), while it is assembled in its feeding system on the right.

The initial experimental tests aim to identify the stable ignition range of the burner at 1 and 4.5 bar, with various nominal powers and different hydrogen percentages in the HENG blend, while altering the nominal equivalence ratio. Figure 4, on the right, shows some initial results at 1 bar; further tests are planned, also aimed at quantifying NOx emissions. The initial results in Fig. 4 highlight critical flashback issues due to the central body for high hydrogen content: the central recirculation zone causes a strong impingement of hot gas products on its surface, making it incandescent.

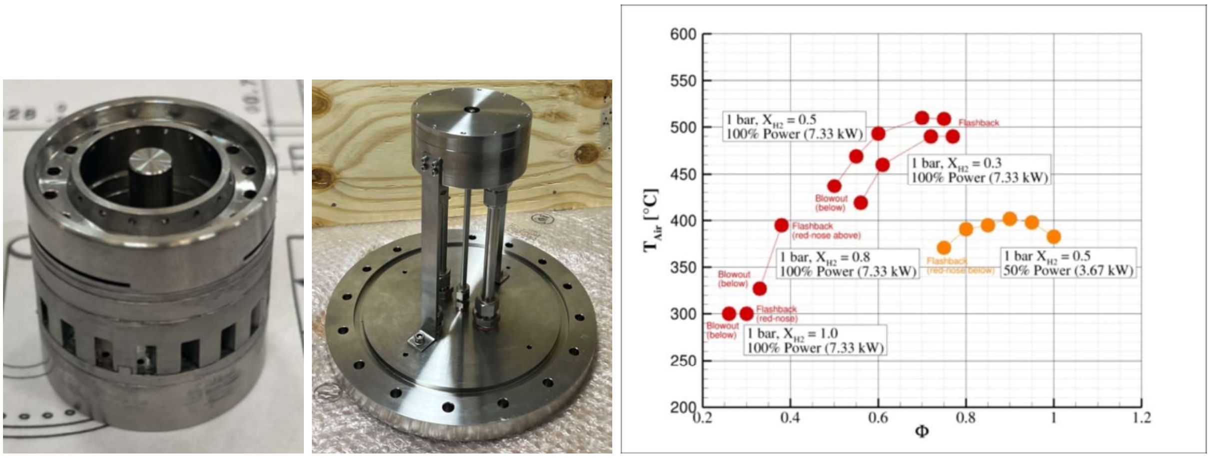

Figure 4. First prototype of the micro-mixing burner alone (left) and assembled in its feeding system (center); initial flame stability results from experimental tests at 1 bar (right).

Conclusions and future work

A combustion strategy capable of potentially operating over a wide range of natural gas/hydrogen mixtures has been identified through RANS simulations, focusing on the defined crown system burner for high-H_2 content blends. Some LES simulations were performed to examine combustion dynamics issues before constructing a representative prototype. Ongoing experimental tests will validate the adopted combustion strategy and suggest appropriate modifications. Consequently, the device may undergo improvements, and numerical studies will be conducted on integration with the feed system and liner for future implementation on the TURBEC T100 microturbine.

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