DESIGN AND SIMULATION OF A TRAPPED-VORTEX COMBUSTION CHAMBER FOR GAS TURBINE FED BY SYNGAS

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Abstract
The trapped vortex technology offers several advantages as gas turbines burner and the systems experimented so far have limited mainly this technology at the pilot part of the whole burner. Aim of the work was to design a combustion chamber completely based on that principle, investigating the possibility to establish a MILD combustion regime, in case of syngas as fuel. The results of steady RANS simulation and PSR network analysis are presented in the following sections.

Introduction
The differences between syngas and natural gas combustion are mainly two:

- For the same power, fuel mass flow should be 4-8 times higher than natural gas, due to the lower calorific value.
- Premixed combustion of natural gas and air is one of the most commonly methods used for reducing NO_x emissions, by maintaining a sufficiently low flame temperature. This technique can not be used with the syngas because of a significant presence of hydrogen and the consequent danger of flashback in fuel injection systems. For this reason it is necessary to use non-premixed diffusion flame, using diluents such as nitrogen, carbon dioxide and water, to lower flame temperatures and hence NO_x.

The trapped vortex technology offers several advantages as gas turbines burner:

1. It is possible to burn a variety of fuels with medium and low calorific value.
2. It is possible to operate at high excess air premixed regime, given the ability to support high-speed injections, which avoids flashback.
3. NO_x emissions reach extremely low levels without dilution or post-combustion treatments.
4. Produces the extension of the flammability limits and improves flame stability.

The systems developed so far use combustion in cavities as pilot flames for premixed high speed flows [1-6]. The goal is to design a device operating entirely with the principle of trapped vortices, improving mixing of hot combustion gases and fresh mixture, which is a prerequisite for a diluted combustion and at the most a MILD [7] combustion regime. The study was carried out by means of CFD analysis and by means of reactor networks analysis, using commercial codes. The prerequisite for a MILD combustion regime are: high temperature of the oxidant

(above the auto-ignition temperature), a high turbulence level, a rapid and uniform mixing of fuel and oxidizer, a lean mixture, a low concentration of oxygen in the reaction zone and the recirculation of hot combustion products. It is clear that all these factors are closely interconnected. In fact, the internal exhaust gas recirculation requires the creation of a flows with characteristics that increase the levels of turbulence, thus producing a better and faster mixing. The gas recirculation clearly brings an increase in pre-combustion temperature and reduces the concentration of oxygen.
The introduction of MILD technologies in pressurized combustion is of great interest because it is potentially able to answer two main requirements:
1) a very low level of emissions and
2) an intrinsic thermo acoustic stability (humming).
The difficulty in designing a prototype, arises from the fact that there are no standard design tools for this type of activity.
In spite of the highly innovative concept, its design and implementation involves the traditional issues of a gas turbine burner:
1. design a component with a suitable geometry taking into account the operating conditions;
2. ensure the absence of thermo acoustic oscillations;
3. ensure the stability of the burner;
4. ensure the absence of flashback phenomena.

Possible configurations of the system fall basically into two categories:
a) MILD systems with external control (outer recirculation, independent source of inert, sequential burning)
b) MILD systems with internal recirculation.

The type of application on the point a) is theoretically very promising from the point of view of both reducing pollutants and increasing the overall efficiency of the system, but it is associated with a higher complexity.

Description
The TVC project concerns gas turbines using annular combustion chambers. The prototype to be realized, for simplicity of design and measurement, consists in a linearized sector of the annular chamber with a square section of size 190x190mm (fig. 1). The power density is about 15 MW/m^3 bar. The most obvious technique to create a vortex in a combustion chamber volume is to set one or more tangential flows. Two flows promote the formation of the vortex, while other streams of air and fuel, distributed among the tangential ones, feed the "vortex heart". The air flows placed in the middle provide primary oxidant to the combustion reaction, while the tangential ones provide the air excess, cool the walls and the combustion products, in analogy to what happens in the traditional combustion chambers, in which this process occurs in the axial direction. The primary and the global equivalence ratio were equal to 1.2 and 0.4, respectively.

Given the characteristics of the available test rig, the prototype will be tested under atmospheric pressure conditions. The combustion will be at a temperature of 700 K, corresponding to a compression ratio of about 20 bar, to simulate the real operating conditions. The syngas used will have the following composition: 19% H_2 - 31% CO - 50% N_2 LHV 6 MJ/kg.

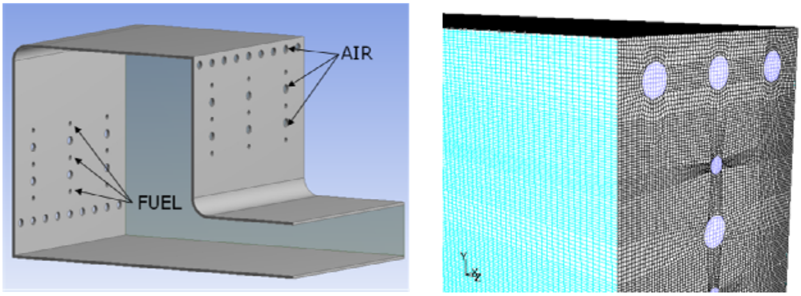

Figure 1. Burner geometry and computational grid.

CFD simulations

The simulations, performed with the ANSYS-FLUENT code, were carried out according to a steady RANS approach. The models adopted for chemical reactions and radiation are the EDC [8], in conjunction with a reduced mechanism [9] and the P1, respectively. NO_x were calculated in post-processing. In order to save computational resources, the simulations were conducted only on one sector of the whole prototype reported in the figure above, imposing a periodicity condition on side walls. A structured hexahedral grid, with a total number of about 2 million cells, was generated (fig. 1).

A big effort was made to properly modulate flow rates, velocities, momentum and minimum size of the combustion chamber. The resulting configuration establishes a perfect balance between the action of tangential flows, which tend to generate the vortex and the action of vertical flows that tend to destroy it (fig. 2). In this sense it is worth pointing out that it is especially the tangential flow, further from the outlet, the most effective. The negative effects on vortex location and size resulting from a reduction of its strength, compared with the other inlets, were evident. In principle, a significant presence of hydrogen, very reactive, can produce elevated temperatures and fast reaction, especially near fuel inlets. For this reason inlet velocities are sufficiently high to generate a fast rotating vortex and then a rapid mixing. Further increase in fuel injection velocity has a negative influence on vortex shape and position, without slowing reaction and reducing temperature peaks.

Compared to axial combustors, the minimum space required for the vortex, results in an increase in volume and a reduction in power density. On the other hand, carbon monoxide content, with its slow chemical kinetic rate compared to natural gas, requires longer residence time.

As can be seen from the figures (3, 4), high temperature zones are concentrated in the vortex heart and the radical species are sufficiently distributed. This means that reactions take place within a larger volume than a conventional flame front. Experimental insights are necessary to asses if it is a MILD or a “flameless” regime. The emission indexes are EICO=3.59 g/kg$_{fuel}$ and EINO$_x$≈ 0 g/kg$_{fuel}$.

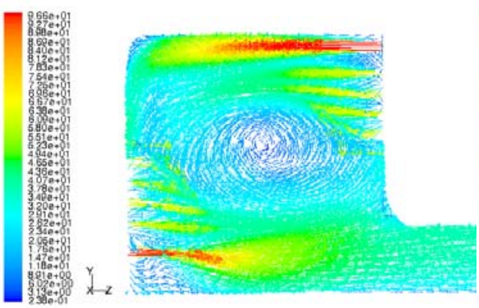

Figure 2. Flow field (m/s).

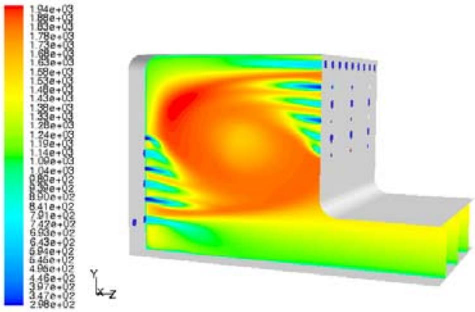

Figure 3. Temperature field (K).

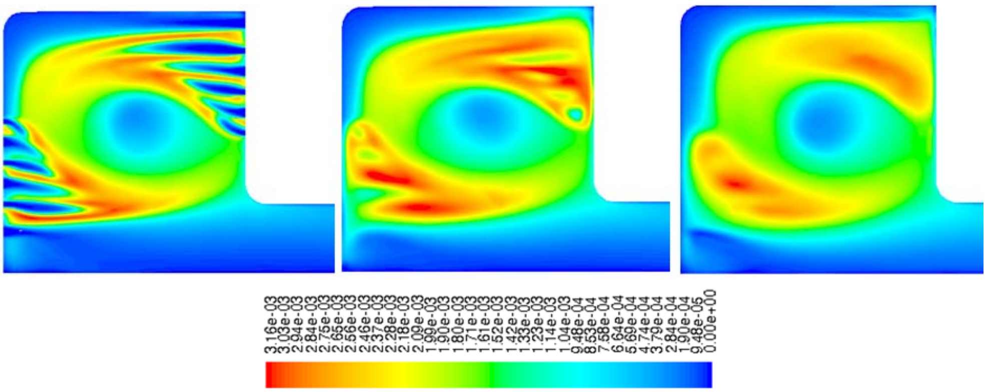

Figure 4. OH mass fraction on different planes.

PSR network analysis

A useful tool is represented by models based on network of ideal reactors, such as PSR (perfectly stirred reactor) and PFR (plug flow reactor). With this approach it is possible to study the behavior of the combustor with a more sophisticated chemistry, sacrificing fluid dynamics. The advantage is that the simulations are considerably faster and it is possible to obtain complementary information respect a CFD analysis. The construction of this network can be empirical, in case the system is modeled with a limited number of reactors, or more rigorous using a large number of reactors. The configuration of the network and its interconnection can be deduced from the CFD analysis and depends, even for the same burner, on the operating conditions. In this case, the network is shown in figure 5 The model is based on the GRI-Mech 3.0 kinetic mechanism and includes 53 species and 325 reactions. The results shown in the figure 6 are generally in agreement with those of the CFD simulation. Temperatures and species concentration in different combustion chamber zones match those obtained by CFD.

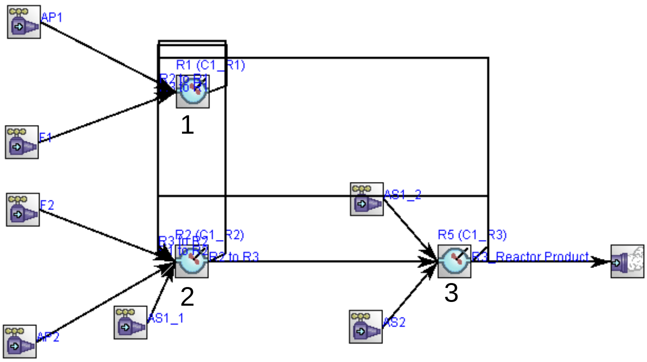

Figure 5. Reactor network.

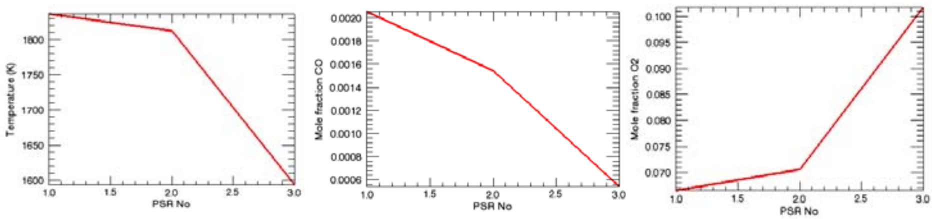

Figure 6. Reactor network results.

Further comments

The effects of burner scaling was also analysed. In particular, the system was scaled maintaining constant inlet velocities. If one imagines to halve all sizes, the volume will be reduced by a factor 0.5x0.5x0.5=0.125, while the areas will be reduced by a factor of 0.5x0.5=0.25. Then mass flow-rates will be scaled by a factor of 0.25. Therefore, the power density (power/volume) will increase by a factor of 0.25/0.125=2. The simulations show that the behaviour of the burner remains unchanged, in terms of velocity, temperature, species, etc. fields. One can conclude that, if the overall size of the burner decrease, the power density increases according to the formula Power $^{0.5}$.

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