Trapped-vortex approach for syngas combustion in gas turbines

The so-called trapped vortex technology can potentially offer several advantages for gas turbine burners. In the systems experimented with so far, this technology is mainly limited to the pilot part of the whole burner. The aim of the work we present here, is to design a combustion chamber completely based on the trapped vortex principle, investigating the possibility to establish a diluted combustion regime, in case of syngas as fuel. This article presents some results obtained by a 3D CFD analysis, using both RANS and LES approaches.

Introduction

A key issue in combustion research is the improvement of combustion efficiency to reduce fossil fuel consumption and carbon dioxide emission. Researchers are involved in the development of a combustion technology able to accomplish energy savings with low pollutant emissions.

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 used methods for reducing NO_x emissions, by maintaining a sufficiently low flame temperature. This technique poses some problems with syngas because of a significant presence of hydrogen and the consequent danger of flashback in the fuel injection systems. In the case of a non-premixed diffusion flame, diluents such as nitrogen, carbon dioxide and water, or other techniques, such as MILD combustion, can be employed to lower flame temperatures and hence NO_x.

The systems developed so far use combustion in cavities as pilot flames for premixed high speed flows. The goal is to design a device operating entirely on the principle of trapped vortices, which is able, based on its intrinsic nature of improving mixing of hot combustion gases and fresh mixture, that represents a prerequisite for a diluted combustion and at the most a MILD combustion regime. The trapped vortex technology offers several advantages for a gas turbine burner:

1. It is possible to burn a variety of fuels with medium and low calorific values.
2. NO_x emissions reach extremely low levels without dilution or post-combustion treatments.
3. It provides extended flammability limits and improves flame stability.

MILD combustion is one of the promising techniques proposed to control pollutant emissions from combustion plants. It is characterized by high preheating of combustion air and massive recycle of burned gases before reaction. These factors lead to high combustion efficiency and good control of thermal peaks and hot spots, lowering NO_x thermal emissions. Two important aspects are crucial for MILD combustion. First of all, the reactants have to be preheated above the self-ignition temperature. Secondly, the reaction region has to be entrained by a sufficient amount of combustion products. The first requirement ensures high thermal efficiency, whereas the latter allows flame dilution, reducing the final temperature well below the adiabatic flame temperature. In this way, reactions take place in a larger portion of the domain in absence of ignition and extinction phenomena, due to the small temperature difference between burnt and unburnt gases and as a result a flame front is no longer identifiable; this is why MILD combustion is often denoted as flameless combustion.

Another advantage is represented by the fact that the temperature homogeneity reduces materials deterioration. Because of the limited temperature, NO_x emissions are greatly reduced and soot formation is also suppressed, thanks to the lean conditions in the combustion chamber,

due to the large dilution level and the large CO_2 concentration.
The introduction of MILD technology in gas turbines is of great interest because it is potentially able to answer two main requirements:
1. A very low level of emissions.
2. An intrinsic thermo acoustic stability (humming).

CFD models
The simulations, performed with the ANSYS-FLUENT code, have been carried out according to steady RANS and LES approaches. The models adopted for chemical reactions and radiation are the EDC, in conjunction with a reduced $CO/H_2/O_2$ mechanism made up of 32 reactions and 9 species, and the P1, respectively. NO_x have been calculated

Air tangential mass flow [kg/s]	Air tangential flow velocity [m/s]	Air vertical mass flow [kg/s]	Air vertical flow velocity [m/s]	Fuel mass flow [kg/s]	Fuel mass flow velocity [m/s]	Air/Fuel global	Air/Fuel primary
0.01238	75	0.00592	62	0.00462	61	3.96	1.28

Table 1 - Boundary conditions for the reference case.

Prototype description
The TVC project concerns gas turbines which use annular combustion chambers. The prototype to be realized, for simplicity of design and measurement, consists in a linearized sector of the annular chamber having a square section of 190x190mm (fig. 1).
The power density is about 15 MW/m³ bar. The most obvious technique to create a vortex in a combustion chamber volume is to set one or more tangential flows. In this case 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 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 (Fuel/Air/(Fuel/Air)stoic) 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, but the combustion air will be at a temperature of 700 K, corresponding to a compression ratio of about 20 bar, in order to better simulate the real operating conditions. The syngas will have the following composition: 19% H_2 - 31% CO - 50% N_2 LHV 6 MJ/kg. The reference case boundary conditions are reported in table 1.

in post-processing. In order to save computational resources, the simulations have been conducted only on one sector (1/3) of the whole prototype reported in the figure 1, imposing a periodicity condition on side walls. A structured hexahedral grid, with a total number of about 2 million cells has been generated.

Results
A big effort has been made to properly modulate flow rates, velocities, momentum and minimum size of the combustion chamber. It's clear that inlets placement plays a key role in the formation of a energetic vortex which can be able to properly dilute the reactants and create sufficient residence time that favorites complete combustion. The resulting configuration establishes a perfect balance between the action of the tangential flows, which tend to generate the vortex and the action of the vertical flows that tend to destroy it (fig. 2).

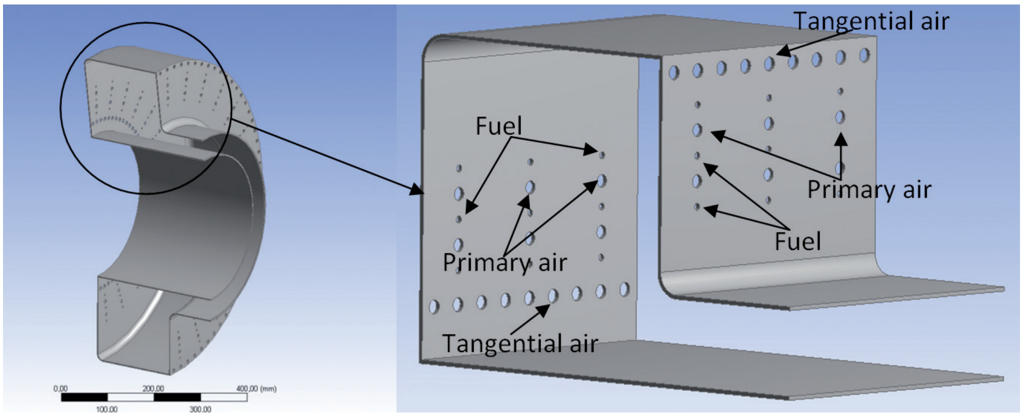

Fig. 1 - Burner geometry.

In this sense, it is worth pointing out that it is especially the tangential flow further from the outlet which is the most effective. The negative effects on vortex location and size resulting from a reduction of its strength, compared with the other inlets, have been evident. Even the distance between the two vertical hole rows has been properly adjusted. In fact, the upper tangential stream flows between the two vertical rows on the opposed side and, if the available space is insufficient, it doesn't remain adherent to the wall and the vortex is destroyed. In principle, a significant presence a very reactive hydrogen, 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

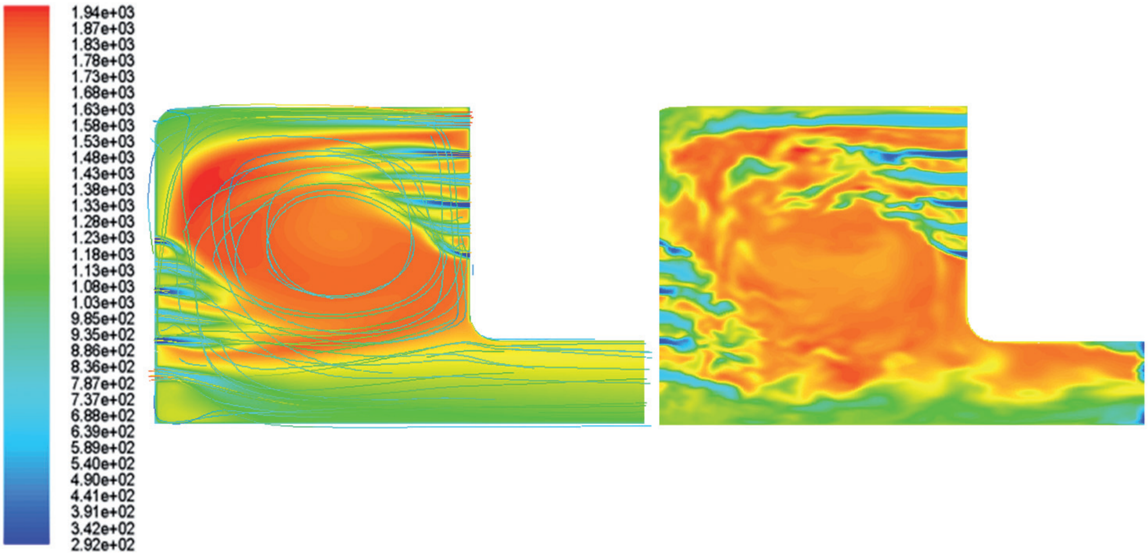

Fig. 2 - Temperature (K) field on central section plane. (left) RANS (right) instantaneous LES.

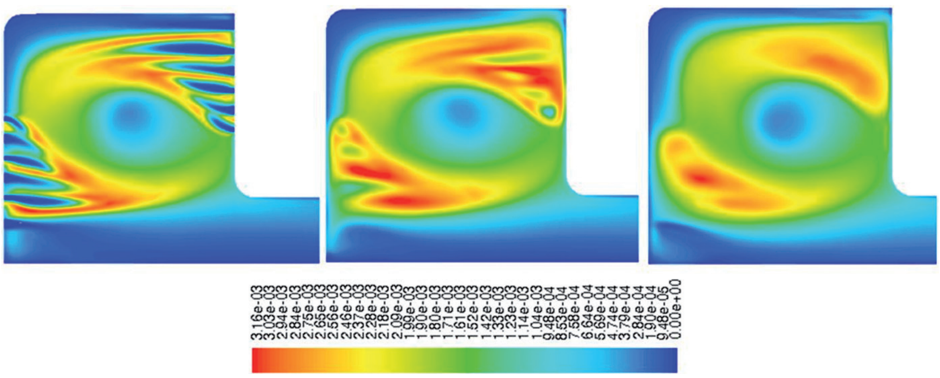

Fig. 3 - OH mass fraction on different planes.

shape and position, without slowing reaction and reducing temperature peaks.

The aim of the LES simulation has been to analyze the unsteadiness of the system. The vortex appears very stable in the cavity, i.e. trapped. No vortex shedding has been noted.

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 and a bigger volume.

It can be observed that high temperature zones (fig. 2) are concentrated in the vortex heart. If the hydrogen content is rapidly consumed, the carbon monoxide lasts longer and accumulates given that the amount of primary air is less than the stoichiometric value. The mean LES and the steady RANS fields have provided very similar results.

It is interesting to evaluate the residence time inside the chamber. In the central part of the chamber, the residence time ranges from 0.02 to 0.04 sec.

The establishment of a MILD combustion regime depends especially on a sufficient internal exhaust gas recirculation, which associated to a good degree of mixing with reactants, represents a necessary condition for MILD combustion. In order to quantify the degree of mixing, the following variable has been mapped:

$$MIX=|H_2-H_{2mean}|+|H_2O-H_2O_{mean}|+|CO_2-CO_{2mean}|+|O_2-O_{2mean}|+|CO-CO_{mean}|+|N_2-N_{2mean}|$$

If all the species involved were perfectly mixed, MIX should be zero everywhere. In practice, the more MIX tends to zero, the more reactants and products are well mixed. If the zones immediately downstream the inlets are neglected, MIX assumes very low values in the chamber. This supports the fact that the vortex is able to produce the expected results.

The recirculation factor, i.e. the ratio between exhaust recirculated and fresh mixture introduced, is about 0.87, while exhaust composition is: 0.19% CO_2, 0.05% H_2O, 0.005% CO, 0.039% O2, 0.713% N_2.

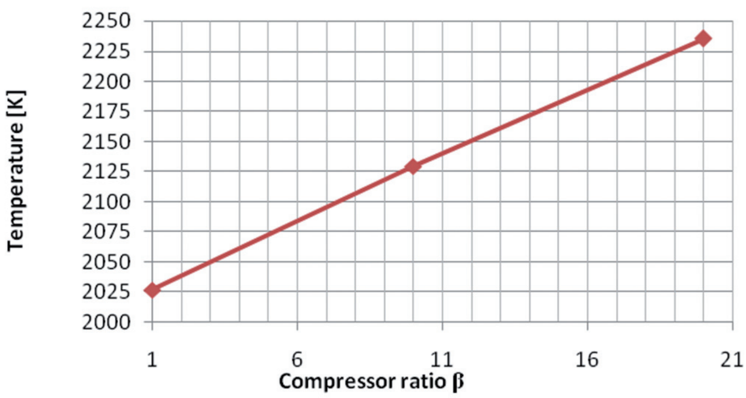

Fig. 4 - Maximum temperature vs compressor ratio.

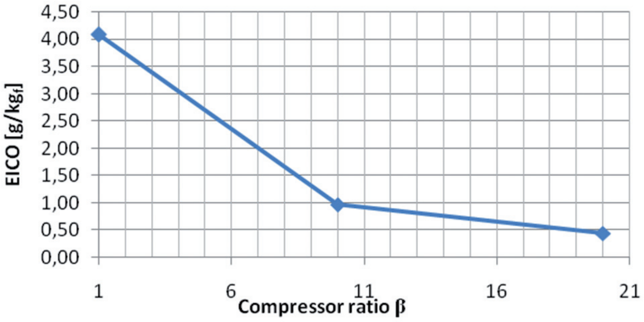

Fig. 5 - EICO (CO emission index) vs compressor ratio.

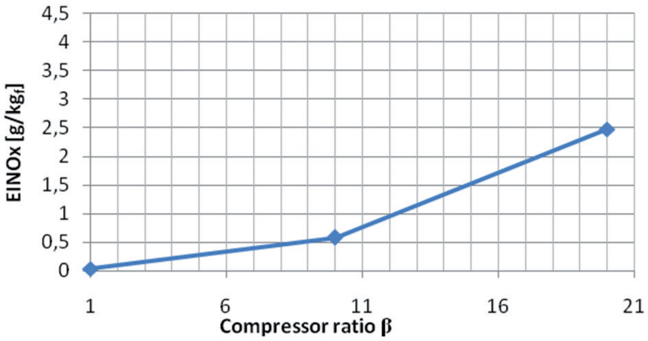

Fig. 6 - EINOx (NOx emission index) vs compressor ratio.

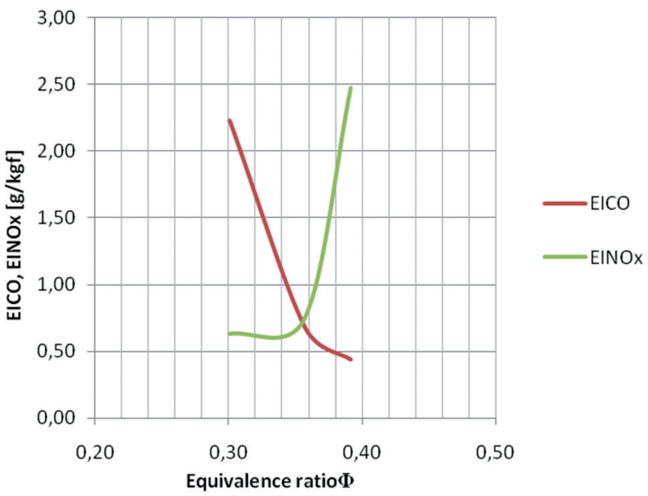

Fig. 7 - EICO and EINOx vs equivalence ratio, operating pressure 20 bar.

In order to determine where reactions are concentrated, it is useful to analyze radical species distribution, such as OH. The fact that radicals are not concentrated in a thin flame front, but well distributed in the volume (fig. 3), represents an evidence of a volumetric reaction regime.

A sensitivity analysis has been conducted varying the boundary conditions around the references previously reported in table 1. The quality of the different cases was judged in terms of pollutants emission indices (g pollutant/kg fuel), in particular for CO and NO_x. CO is an indicator for incomplete combustion. Its presence in the exhaust is favored by low temperature and lack of oxygen. On the contrary, NO_x are favored by high temperature and oxygen abundance. A 30% increment of the tangential flow velocity causes a faster rotation of the vortex, but the recirculation ratio increases only to 0.92. A 30% decrement of the equivalence ratio (leaner combustion) causes a reduction in temperature and a subsequent increment in unburnt species, especially CO. NO_x emissions are in general unimportant for all the cases mentioned.

If the operating pressure is augmented from 1 bar to 10-20 bar at constant geometry and inlet velocities, the mass flow rates and then the burner power increases by about 10-20 times, even if the specific power density (MW/m^3 bar) remains constant. The temperature and pollutants trends for those cases are reported in figures 4-6. The maximum and average temperatures in the chamber increase almost linearly, while EICO increases and EINOx decreases as pressure increases. For each operating pressure, it is then possible to identify an optimal equivalence ratio condition, at the intersection of the two curves in figure 7, where the major pollutants are kept down at the same time.

Scaling

One of the aims of this work has been to verify if when varying the prototype dimensions, their behavior would remain unchanged or not, in terms of fluid dynamics and chemistry. The scaling method based on constant velocities has been chosen for this purpose, because all the physics of the system are based on a fluid dynamic equilibrium, if one refers to the above discussion.
If one imagines to halve all sizes, the volume will be reduced by a factor of 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 behavior of the burner remains unchanged, in terms of velocity, temperature, species, etc. fields. It can be concluded that, if the overall size of the burner is reduced, the power density increases accordingly to $Power^{0.5}$.

Conclusions

A gas turbine combustion chamber prototype has been designed based on the trapped vortex technique.
A preliminary optimization of the geometry has led to a prototype in which the actions of the different flows are in perfect balance, and a vortex filling the entire volume has been established. The large exhaust recirculation and the good mixing determine a diluted combustion regime, which helps to keep down flame temperature. A sensitivity analysis has allowed to determine the optimal operating conditions for which the contemporary lowering of the major pollutants species was achieved. In addition, a scaling study has been conducted which demonstrated how the prototype keeps its characteristics unaltered if halved or doubled in dimensions.

A. Di Nardo, G. Calchetti, C. Mongiello
ENEA-Italian National Agency for New Technologies
Energy and Economic Development