Conversion to Natural Gas Operation of a Formerly Liquid-Fuelled Rapid-Mix Ultra-Low NOx Burner

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ABSTRACT

The paper deals with the strategy conceived by the authors in order to convert a formerly liquid-fuelled burner technology, of fuel-air (ultra-lean) rapid-mix type, on to a gas-fuelled design, possibly preserving its excellent characteristics of ultra-low emissions and high flame-process stability. To this end, a combined theoretical-numerical and experimental effort has been pursued, typically in parametric mode, in order to find an optimised set of geometrical, fuel injection and functional provisions capable of taking advantage both of the previous experience in connection with liquid-fuel operation and of the necessary design changes required by the new gas-fuel application. The paper discusses, for these new operational conditions, the parametric numerical analysis so far performed, as well as the philosophy underlying the conversion of the burner design criteria from liquid to gaseous fuel operation. For each design variation or adjustment progressively conceived, the corresponding technological implementation has been realized, mounted on the burner test-rig and experimentally tested. Though preliminary, the experimental data presented in the paper confirm, in terms of combustion efficiency, stability and emissions, the attainment of a significant milestone toward the successful conversion of the burner to gas-fuel operation.

INTRODUCTION

In order to attain the highly difficult target, for a gasoil-fuelled gas-turbine burner, of containing NO_x emissions within one-digit-ppmv limit (at atmospheric pressure) without resorting to steam injection, a rather innovative, sophisticated burner-design strategy was conceived and transferred into technological provisions. As a matter of fact, whilst the target of reducing thermal NO_x would require the lowest possible equivalence ratios in the primary zones, such a provision is going to be largely ineffective if the premixing process is not adequate. Notice that in presence of a liquid fuel such as gasoil, a high degree of premixing would of course pre-require attainment of a prompt and thorough vaporisation of the fuel droplets, immediately followed by an extremely efficient premixing, at a molecular level, of the oxidant with the fuel vapour. On the other hand, in the very case when the latter situation takes place, quite frequently a series of other unsustainable conditions occur, such as possible ignition and flame flashback problems, poor combustion efficiency, weak extinction and/or serious instability. Notice that when the premixed-combustion process becomes unstable due the presence of thermo-acoustical waves travelling the combustor, a series of dangerous effects take place, inducing negative consequences not just on power plant performance, but directly on its structural safety. In many systems, low NO_x regime is achieved right at the edge of weak extinction, i.e. with an extremely narrow stability margin.

The conceptual cornerstones, which the LRPM burner-design strategy, here in object, is based on, do not belong mainly to the chemistry realm; rather they involve clear physical principles of basic fluid-dynamical nature, in close connection with turbulence theory. The sequential reasoning, which motivates the LRPM strategy (Liquid-fuel Rapid Pre-Mix), can be here synthesised as follows. In order to achieve a strong containment of NO_x emissions, flame temperatures must be kept as low as possible, compatible with flammability limits, whilst oxygen concentration must be provided at high levels and at a well-mixed condition (molecularly with fuel) in order to prevent CO production. Whilst the flame temperature constraint can be satisfied by adoption of ultra-lean equivalence ratios, the core problem is the attainment of an adequate level of fuel and air molecular mixing: notice that when thermal NO_x is contrasted thanks to a proper achievement of well-mixed lean primary zones, also prompt NO_x is suitably minimised.

In order to attain the above objectives in terms of ultra-low emissions while keeping a wide, safe margin of combustion stability, the LRPM technology resorts to the intrinsic capacity of the turbulence kinetic energy, for the larger scales, and, more specifically for the smaller scales, of its dissipation rate, to rapidly disaggregate the flow eddies into ever smaller structures and then to "molecularly diffuse" their residual dynamics into heat. If the burner design can impose that, from a physical/fluid-dynamical point of view, the turbulent kinetic energy and its dissipation rate would be maintained, in specific locations, at their peaks, then these regions (typically represented by the jet-air high-shear layers) could be selected as most suitable for localised injections of the fuel, thus providing a strong "drive" to its turbulent mixing.

In addition, if, in these regions, any recirculation of the flow is avoided by design, so to limit at a minimum the residence times, then the overall process could, expectedly, enter the "ultra low emissions" regime. Finally, if the fuel-injection modality could maintain a well-defined, directional, fuel-concentration gradient in the jet-air shear-layers immediately ahead of the flame front, then the combustion process will be free of ignition problems and flame flash-back danger, as well as of combustion process instabilities, including the detrimental thermo-acoustical wave pulsations. As well known, these latter typically correlate with the presence of uniform, i.e. non-directional, premixing processes taking place within ducts of adequate length extension so to achieve a well-mixed, evenly distributed, lean condition ahead of flame front, but at the same time quite frequently inducing wave resonance and pulsations' amplification.

Fig. 1 LRPM radially-inward swirler and burner test-rig

The LRPM concept is basically a dry, rapid fuel-air mixing system, which takes advantage of a radial swirler (the "stabiliser"), equipped with eight curved, radially inward, vane passages. For liquid-fuel, one single-hole fuel injector is provided within each passage, located near the outer, peripheral, swirler inlet. The vane design, characterised by high turning angles so to avoid any "see-through", in radially inward direction along the channels, was pursued with the combined aims of preventing, or anyhow minimising, flow separation within the passages, as well as of avoiding significant wake effects at the outlet. To this latter end, the vanes are properly contoured and provided with sharp trailing edges.

Due to some pending industrial confidentiality, the detailed, optimised-design, geometric and functional features of the rapid mixer are not discussed here. Fig.1 presents its configuration from an overall point of view only. Additional details can be found in [1, 2] as well as in [3].

CONVERSION TO NATURAL GAS OPERATION

In order to convert from liquid to gaseous fuel operation the excellent performance and ultra-low emissions characteristics attained by LRPM technology, a joint conceptual, numerical and experimental strategy has been set up and technologically pursued. Of course, one main target of the research was that of preserving, also with gaseous fuels, the high flame-process stability afforded by the air-fuel directional premixing modality, while keeping the ultra-lean equivalence ratios required so to confine within a few ppm the NOx and CO emissions. To this end, the starting point for the development of the new GRPM (Gas-fuel Rapid Pre-Mix) design philosophy was rooted, almost completely, into the previous LRPM technology, in order to progressively test which, among its features, should be kept, and which should be changed or updated, toward an optimised design of a natural-gas fuelled premixed burner. An additional advantage of this strategy has been the possibility of immediately installing, after a few necessary conversions and adjustments, the GRPM prototype on to the already available and operational burner test-rig previously dedicated to LRPM burner performance testing.
The final, updated, characteristics of the natural-gas fuelled burner test-rig are summarised as follows:

- Air mass flow: up to 500 kg/h
- Radial fan absorbed power: 2.65 kW
- Air pre-heating temperature: 300 ÷ 500 °C
- Electrical pre-heating power: 115 kW
- Thermo-chemical power: up to 250 kW (from fuel)
- Equivalence ratio range: 0.36 ÷ 0.48
- Combustor pressure: 1.15 bar

The test rig is instrumented in order to make possible, via PLC, the following operations:

- Control of air and fuel flow rates
- Control of air pre-heating temperature
- Characterisation of the burner-combustor temperature field (5-sensor thermo-couple)
- Measurement of burner pressure losses (pressure sensors)
- Gas exhaust analysis (Chemical Ionization Mass Spectrometer, Airsense 500; Fourier Transformed Infrared Spectroscope, FTIR)
- Optically-based detection of flame-process stability (digital video camera)

The LRPM-technology emissions-related experimental characterisation, as well as its numerical prediction, with gasoil fuel, is synthetically shown in Fig.2 and 3.

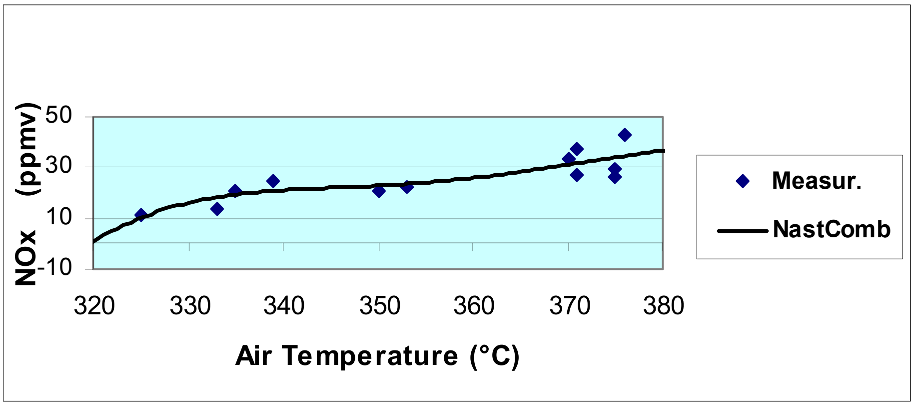

Fig. 2 NOx emissions trends (measured and predicted) as functions of preheating level

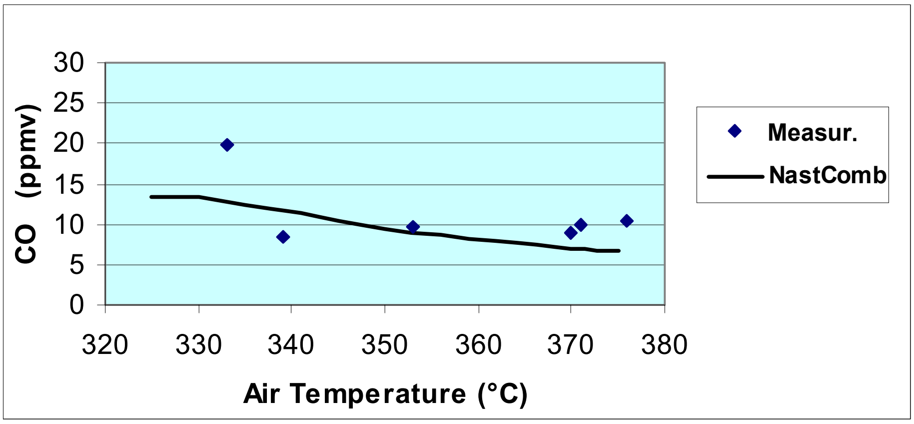

Fig. 3 CO emissions trends (measured and predicted) as functions of preheating level

The conversion from liquid fuel to natural-gas of the burner design-philosophy is still in progress, and is being pursued by means of both numerical and experimental investigations. From this latter point of view, the first step has been the implementation, on the existing burner test-rig, of a flexible gas-injection system, so to make it possible to parametrically test the performance behaviour of the burner, of unmodified geometry, when injecting gaseous fuel in different locations. The choice of the fuel has been propane, with injection over-pressure of 10 kPa, in order to obtain results cross-comparable with the numerical predictions presented in [4]. The injection modalities taken into consideration are herewith summarized:

- Premixing zone, 8 wall injection-holes, 35° downstream oriented (Case A, Fig.4 a)
- Premixing zone, 4 wall injection-holes, 35° upstream oriented (Case B, Fig.4 b)
- Swirler channels, 8 injectors, perpendicular to mean flow velocity (Case C, Fig.4 c)

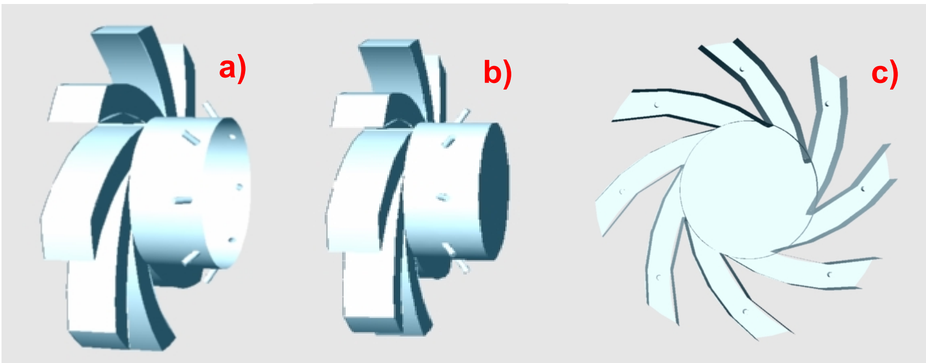

Fig. 4 GRPM burner design: gaseous fuel injection modalities

The 3 different injection modalities have been transposed as boundary conditions into the CRFD (Computational Reactive Fluid Dynamics) solver NastComb [2,6] and numerically investigated in parametric mode. Exactly for this latter reason, the study was addressed toward capturing burner's performance trends rather than absolute design values, and thus the configuration of NastComb utilised was simplified, with a quasi-global reaction mechanism, a few elementary reactions and no radiation model [7]. No refined grids were adopted.
Numerical simulations have been performed, at first, in non-reactive mode, so to assess the internal fluid-dynamics of the burner-combustor assembly, particularly the pressure losses and the distributions of turbulent kinetic energy and of its dissipation rate. Then, NastComb has been applied in reactive mode, in order to investigate the cross-influences between fluid-dynamics and flame process, notably the flame front locations and the temperature distribution fields. Inspection of the results coming from the non-reactive flow calculations

shows no important differences in the flow fields among the different cases. Fig.5 shows an example of the velocity field and Fig.6 the corresponding turbulent kinetic energy distribution, both relative to case B (upstream oriented injection).

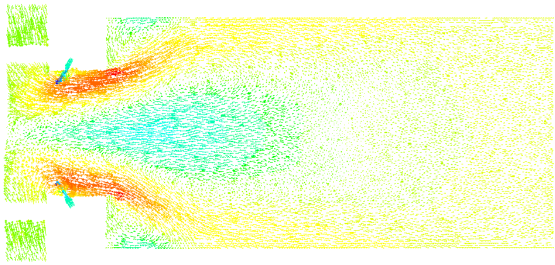

Fig. 5 Velocity field (NastComb)

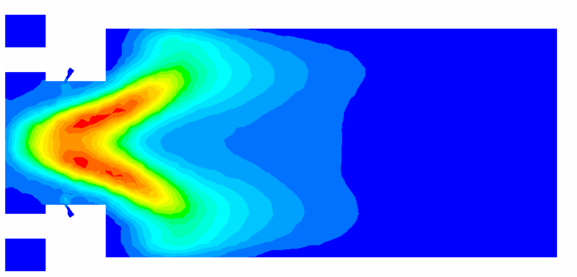

Fig.6 Turbulent kinetic energy (NastComb)

On the other hand, the analysis of the quite different temperature distributions obtained from the reactive simulations, respectively for each one of the three above Cases A, B and C, allows to draw clear indications about the location and the shape of the flame fronts.

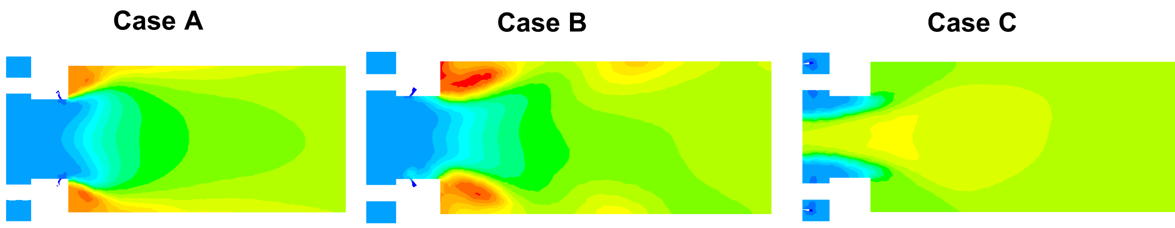

Fig. 7 Temperature distributions corresponding to the 3 different injection modalities

Indeed, from Fig.7, in Cases A and B the flame, almost unpremixed, appears anchored in the recirculating corner zones immediately downstream of the combustor section enlargement, where temperatures attain their peaks. This suggests that the air-fuel mixing process, expected to take place in the high turbulent kinetic energy regions shown in Fig.6, does not succeed in achieving a sufficiently homogeneous mixture, due to ill-locations of the injection points, which do not provide enough space-time allowance in order to attain adequate premixing levels. Furthermore, the high residence times induced by the recirculation of the reacting flow in the peak temperature regions above seen, cannot but increase the thermal NO_x formation.

Whilst the numerical analysis was in progress, the different injection modalities have been technologically implemented on the burner test-rig and, in sequence, experimentally tested. The tests on the burner configurations, corresponding to Cases A and B, confirmed the numerical predictions. Fig.8 shows rather high NO_x emission levels (for propane fuel in atmospheric combustion), especially for Case A, possibly due to the shortest mixing times made available by this solution.

On the other hand, excellent combustion stability has been observed for Cases A and B for varying equivalence ratios in the range 0.3 through 0.5 , typical outcome for diffusion flames.

Experimental testing is presently in progress for Case C, for which quite lower emission levels, in terms of NO_x production, are expected, in dependence of the far lower and more uniform temperatures, in the combustor, that can be observed, for this Case, in Fig.7, symptom of a more efficient air-fuel premixing process.

In parallel with the above parametric investigation, centred on the fuel injection modalities, and taking advantage of indications available in [4,5], additional design provisions, deemed

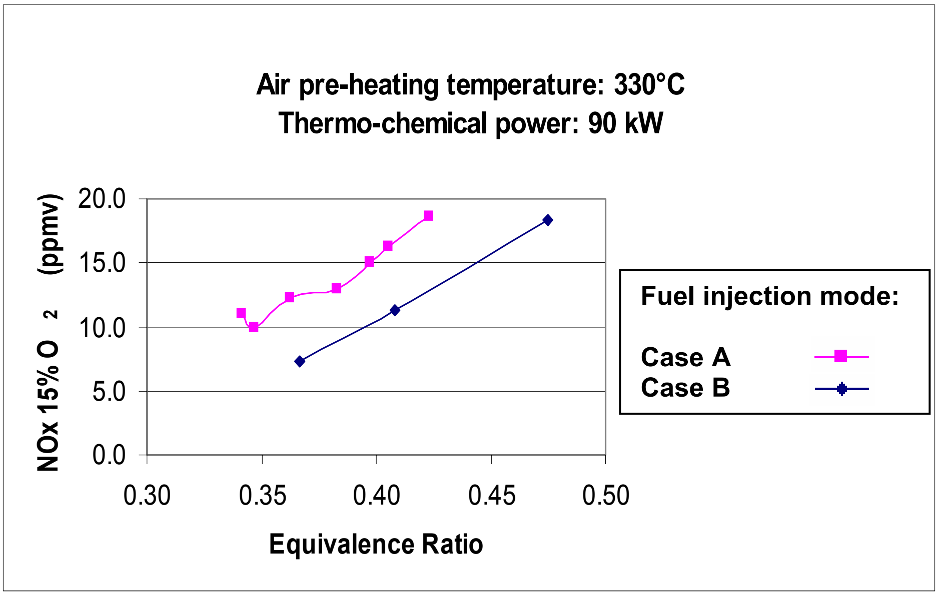

Fig. 8 NO_x emissions: experimental data for Case A and Case B

useful for gaseous fuel operation, have been conceived in order to attain the final, optimised configuration for the GRPM burner. These provisions are mainly addressed toward increasing the spatial extension and the levels of the turbulence kinetic energy by means of a fluid dynamic optimisation of the air velocity gradients, i.e. the shear layers' "strength", as induced by the swirler vanes inside the reduced-diameter pre-combustor section. In addition, always according to [5], the reactants' residence times, in primary zone, should be restricted to below 6 ms, whilst the flow recirculations should be more limited within the combustion chamber. Finally, it can be shown that an adequate level for the flow Mach number in combustion chamber should be about 0.02, in connection with a pressure drop $\Delta p/p$ lower than 0.04.

According to above guidelines, a modified geometry has been conceived: notice in particular the presence of a flare section at the outer periphery of the combustor inlet, instead of the previous sharp corners where recirculating flows were taking place. The geometry is presented in Fig.9 and is now undergoing preliminary numerical investigation.

The first results, in connection only with the basic fluid-dynamics features (no fuel injection) of the burner-combustor assembly are also shown in Fig.9. The peaks of the turbulent kinetic energy appear thicker and more aligned with the expected path-lines followed by the injected fuel. Recirculation zones in the combustor appear of limited extension. Pressure drop is predicted in no more than 0.03. For all the above, there is confidence that the new GRPM system, fed with gaseous fuel, could properly meet the design constraints suitable to achieve the expected targets in terms of performance, stability and emissions level.

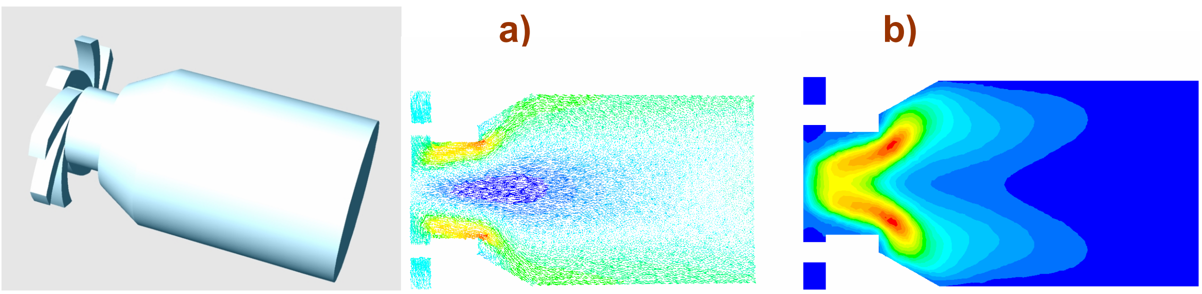

Fig. 9 New GRPM geometry, velocity field (a) and turbulent kinetic energy (b) (NastComb)

CONCLUSIONS

The redesign strategy, above conceived and discussed, suitable to convert to gaseous fuel operation a formerly liquid-fuelled burner, appears positively in progress. The already attained theoretical results as well the experimental ones, though preliminary, appear anyhow significant and encouraging. In particular, the numerical calculations performed on the new GRPM design show both a proper redistribution of the turbulence kinetic energy along the expected path-lines of the fuel-air mixture, to the advantage of its rapid mix process, as well as lower and more uniform temperatures in the combustor chamber which, together with the better controlled re-circulating flow regions, should greatly help toward containment of NOx emissions.

The attained results will now drive the conclusive development of the GRPM design together with its technological realisation, starting from the new fuel-injection modalities directly within the swirler passages: to this end, whilst the numerical analysis will, from now on, take advantage of a very recent, detailed chemistry, version of solver NastComb, the experimental investigations will rely on a new burner test facility, ready to enter into operation, with increased thermo-chemical power and most advanced instrumentation.

The combined effort is expected to be up to succeeding in readily assessing the final burner-combustor configuration, optimised for gas-fuel operation. In this endeavour, the authors wish to acknowledge herewith the strong, at all fundamental, support, both technical and financial, being granted by Ansaldo Energia to the research here presented.

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