High performance Ultra-low NOx burner for industrial boilers

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Abstract

Following the more and more stringent requirements on the Greenhouse Gases (GHG) and harmful emissions, NOx reduction from the combustion processes is still a challenging purpose for industrial boiler manufacturers. In the frame of the R&D project named "BE4GreenS" supported by *Regione Puglia*, Macchi, the boiler brand of the SOFINTER Group, in cooperation with CCA (Combustion and Environment Research Center), designed, engineered and tested an innovative ultra-low NOx gas burner for industrial boiler application. The present paper describes the results obtained by a full scale testing at different size up to 45 MW_{th}. An innovative burner design developed by means of a massive use of CFD analysis, gave to the MARS-II burner architecture an unconventional reactants mixing. The comburent (Air) and the fuel (Natural Gas) are decoupled to aerodynamically trigger an *internal* Flue Gas Recirculation (FGR) diluting the oxygen concentration. Because of the diluted conditions, the main fuel injection produces a delocalized volumetric combustion with a low emission flame (MILD) along with significantly reduced temperature levels. A drastic NOx emission reduction is recorded as a consequence. A reduced amount of natural gas is conversely injected along the burner axis in order to produce in diffusion mode a pilot flame for stabilization purposes during ignition, warm-up and full-firing stages useful to give the burner both the required flame stability and a visible detectable flame. Full scale test at CCA experimental plant shed light into "one digit" ppm NOx emission recorded. Insights into the gas burner performance are herein described. Furthermore the effect of additional "external" FGR and steam injection on the burner performance are provided.

Keywords: Low-NOx industrial gas burner; CFD simulation, natural gas MILD combustion

Introduction: the context and the challenge

The growing attention to air pollution and climate change on a global scale, confirmed by the COP21 protocols, requires, together with an accelerating energy transition towards renewable energy sources, also an improvement in the use of fossil fuels. Global emissions of nitrogen oxides are projected to fall by 10% over the period to 2040 [1], such that both a significant reduction in emissions and high efficiency are crucial to meet market demands in terms of – tightly connected – cost and sustainability.

Figure 1. MARS-II 35 MW burner (left), and CCA 48 MW_{th} test-rig in Gioia del Colle (right).

Moreover, along the transition period towards the decarbonization, natural gas will gain more and more relevance in the fossil fuel market, since it combines higher availability with the lowest environmental impact.
In order to strongly decrease the NOx emissions, new generation of Low-NOx burners (LNBs) needs to be developed [2]. The LNBs technology includes strategies such as air/fuel staging and flue gas recirculation, not necessarily as an alternative but often in synergy [3]. A particular mention deserves the MILD combustion technology [4-8] where a dilution of the comburent air together with an increase of its temperature above the fuel self-ignition temperatures allows the delocalization of the oxidation reaction avoiding temperature peaks and NOx formation.
In this frame, and in particular regarding the industrial combustion applications, Macchi, an historical Italian brand active since 1959 in industrial boiler design and production, plays a leadership role in the world-wide market for cogeneration, oil&gas and petrochemical applications. In the framework of the BE4GreenS research project, CCA together with Macchi has developed the new MARS-II Ultra-low NOx burner, in the 35 and 45 MW_{th} scale, which have been studied and optimized by means of CFD analysis, and tested in full scale at the CCA facility in Gioia del Colle (Italy). CCA is indicated as one of the most important European combustion research centers for the testing and development of innovative combustion systems. Over the years extensive specialized experience has been acquired in combustion processes for both utility boilers and gas turbines, continuously developing the test-rigs. Both Macchi and CCA belongs to the SOFINTER group, which is a leader in the international energy market, providing plants and parts for steam generation.
The above mentioned improvement of the sustainability (and cost) of energy production from fossil and waste fuels gases requires the development of advanced investigation tools. In particular, computational fluid dynamics (CFD) simulations are needed in order to support the design process of low emission burners [9-10]. Under this frame work, CCA and Polytechnic University of Bari decided to settle a public/private Lab, called ETF (Energy Transition to the Future), in order to prepare a new generation of experts capable to deal with the development of the burner from the CFD up to the tests.

Burner design principles and CFD optimization analysis

The MARS-II burner was designed in order to create an heavy duty industrial combustor for the combustion of gaseous streams, having power up to 65 MW_{th}, capable of achieving high performance in terms of very low NOx emissions and high thermal efficiency.
The MARS-II burner is characterized by a steel comburent adduction jacket ending with a lobed air-ejector, clearly visible in figure 2, in which the shop-model of the entire burner is shown. The air is eventually mixed with combustion products (FGR) and/or steam into the jacket upstream to the ejector. The lobed ejector is made of stainless steel sheet metal, and extends into the combustion chamber, so it separates the comburent from the combustion gases present around.
The injection of fuel takes place mainly through the external spuds, positioned between the lobes of the ejector, and therefore in a number equal to that of the lobes (6 in 35 MW_{th}, 8 in 45 MW_{th}).
A minor part of the fuel is introduced by the central lance, also called stabilizer. In the front near the comburent outlet section a swirler (the “impeller”) is placed in order to generate a low axial speed area downstream for stabilizing the diffusion flame created by the central lance.

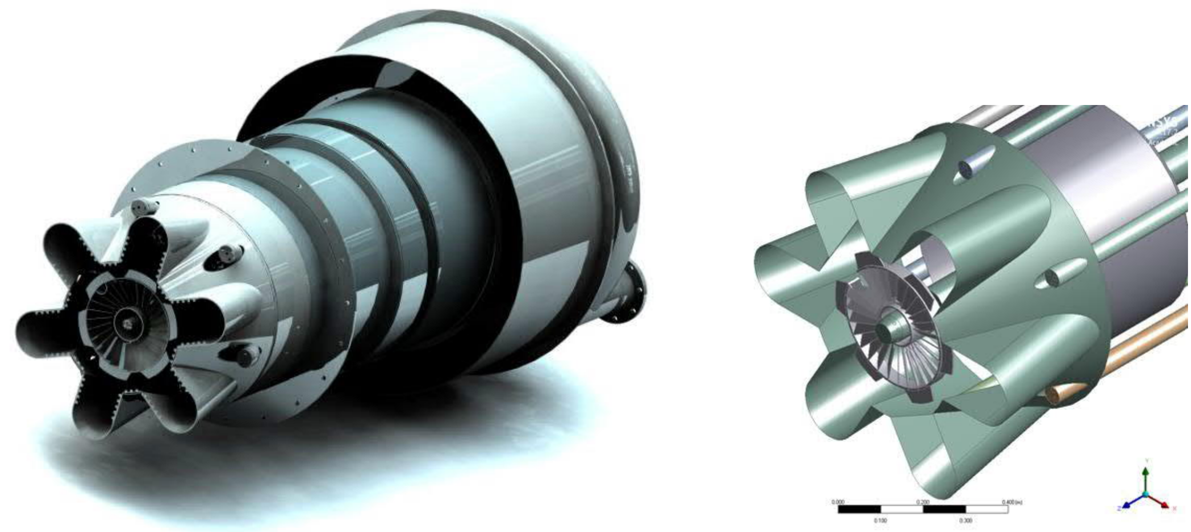

Figure 2. MARS-II 35 MW burner: shop model versus 3D model for CFD analysis.

The above described configuration of the MARS-II burner comes from the implementation of the operational needs described in the following.

- Ability to generate a self-recirculating field through the ejector (protruded inside the combustion chamber) due to the acceleration of the comburent stream inside, a surrounding low pressure zone is created, which is able to recall a great amount of hot gases (poor in oxygen) from the furnace. Indeed the shape of the ejector is designed to maximize his wet perimeter: this is therefore the reason for the characteristic “multi-lobed” shape which distinguishes this burner. As a consequence, a reduction in the excess air needed during burner operation is obtained (values of oxygen in the flue-gases even lower than 1% in common applications).
- Major part (approx. 96%) of fuel injected externally to the burner, is done through some appropriately oriented nozzles, positioned between the lobes. This solution allows the mixing of the fuel with the internal furnace recirculation flue gases in order to produce a mixture having a lower calorific value compared to the original fuel, realizing near-field prevalent MILD condition.
- Injection of a very small portion of fuel (about 4%) in the central part of the burner just downstream the impeller in order to stabilize the flame, creating a conventional diffusive combustion zone, such avoiding the transition of the burner flame toward to a complete "MILD" condition. This arrangement also allows the flame scanners to correctly detect the flame, being an essential indication that the burner is in safe operation.

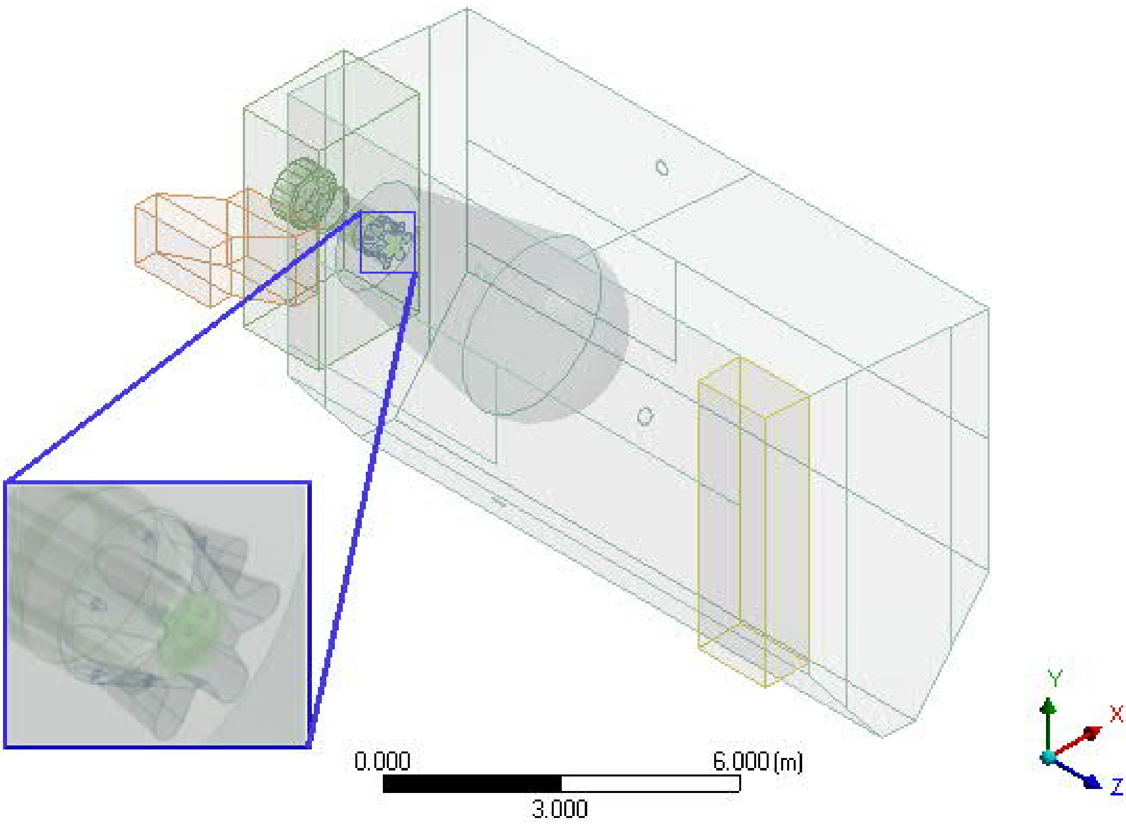

Figure 3. MARS-II 35 MW burner in the CCA furnace: 3D model for CFD analysis.

MARS-II burner has been designed and optimized by massive use of CFD analysis, so gaining more insight on both the cold and even more on the hot reactive flow characteristics. In this paper we show the results of thermo-fluid-dynamics simulations on the 35 MW_{th} burner under baseline testing conditions, *i.e.* without neither EXTERNAL FGR nor steam injection. The computational domain includes, upstream the burner, the entire wind-box supplying the oxidizer, and downstream the complete CCA furnace volume, as shown in figure 3. The combustion chamber walls have been “split” geometrically and heat-transfer properties of each surface modeled, in order to take accurately into account its influence on gas temperature which significantly affects both exit exhaust temperature and local NOx formation phenomena. Infact the furnace walls are made by membrane wall tubes, partially insulated by refractory pouring or ceramic tiles in order to get the desired outlet temperature under testing conditions, in order to correctly reproduce real-boiler running conditions. The geometrical model includes the thickness of all sheets except that of the ejector.

A *patch-conforming* tetrahedral mesh has been used, with a maximum cell size equal to 100 mm inside the furnace, and a minimum cell size equal to 1 mm in the zone of the impeller, and gas injection nozzles. The abundance of such detailed geometries led to a final mesh of more than 16 million cells. In the near-field flame zone the maximum cell size was limited to 50 mm, in order to accurately simulate higher gradient zones. The growth ratio was limited to 1.10 on nozzles and ejector surfaces, against an overall 1.20 value elsewhere. On curved edges the maximum curvature-angle allowed was limited to 10°.

The physical modelling was based on the solution of the steady RANS together with the continuity and the energy conservation equations, while the 2 equation κ-ε *realizable* model was used for turbulent closure and the wall treatment was based on *non-equilibrium* wall functions. The gas combustion was modelled by a pdf-approach (table with 20 species) together with a non-premixed mixture fraction model, employing an *incompressible* approach, in which the density depends only on local temperature and bulk pressure, while it is independent of local gauge pressure. Heat transfer includes convection and radiation on chamber and burner walls. Heat exchange by radiation in gas (continuous phase) was taken into account by a Discrete Ordinate method, with the domain-based WSGGM (Weighted Sum of Grey Gas Model) to compute the local absorption coefficient. Finally, NOx modelling was carried out by *post-processing* on CFD solution, employing a combined *thermal* and *prompt* mechanism.

We show in the following the results of the CFD simulation under baseline condition, *i.e.*:

- 35 MW_{th} of thermal input, obtained injecting 0.8189 kg/s of an Algerian natural gas, modeled with CH_4 85$\%_{vol}$, C_2H_6 6$\%_{vol}$, N_2 9$\%_{vol}$, LHV=42.74 MJ/kg and stoichiometric ratio 14.60;
- 95% of fuel fed to spuds, and 5% to the central lance;
- neither external Flue-Gas-Recirculation, nor steam injection;
- overall 10% excess air, leading to 13.15 kg/s of mass flow rate, and an exit O_2 concentration of about 2% in volume on dry basis.

Figure 4. shows the path-lines exiting the spuds and central lance nozzles: it clearly illustrates how the fuel jets of the spuds approach almost tangentially to the ejector external surface, thus recalling the flue gases, strengthening the internal recirculating effect driven from oxidizer entering into the furnace internally to the ejector.

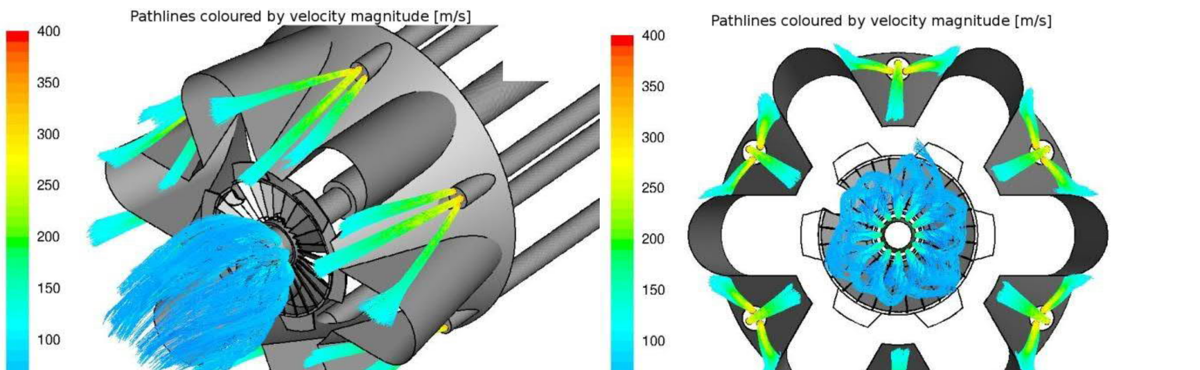

Figure 4. CFD analysis for 35 MW MARS-II in baseline cond.: path-lines exiting fuel-nozzles.

Figure 5 draws attention to the velocity field into the jacket and at the burner exit. The first plane shown, on the left, is the vertical plane cutting the ejector between two lobes, such that the spud and in particular the central nozzle is put in evidence. On the other hand the contour-plot on the right is taken on the horizontal plane, which cuts two opposite lobes, showing the oxidizer flow entering the combustion chamber. In both pictures is clearly visible the central fuel injection, and the recirculation zone downstream the impeller, realizing a stable and visible diffusion flame.

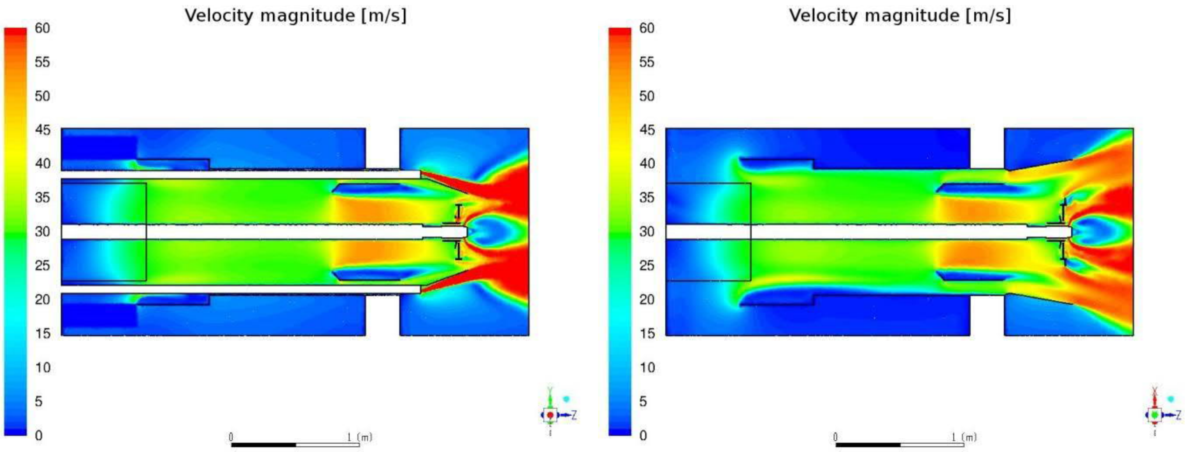

Figure 5. Velocity magnitude inside the burner up to furnace inlet: vertical plane (left) cutting gas-spud, and horizontal plane (right) corresponding to mid-plane of an ejector lobe.

In figure 6 the results are compared in terms of gas temperature distributions into the furnace, obtained on the "baseline" testing conditions with a 10% of fuel fed to the central stabilizer lance (pictures on the left) with those with just 3.3% (pictures on the right) of fuel injected through the stabilizer. It is worth noting how the thermal field changes significantly, leading to an increase of the gas volume involved in combustion, further decreasing temperature peaks, when the fuel fed to the central lance decreases.

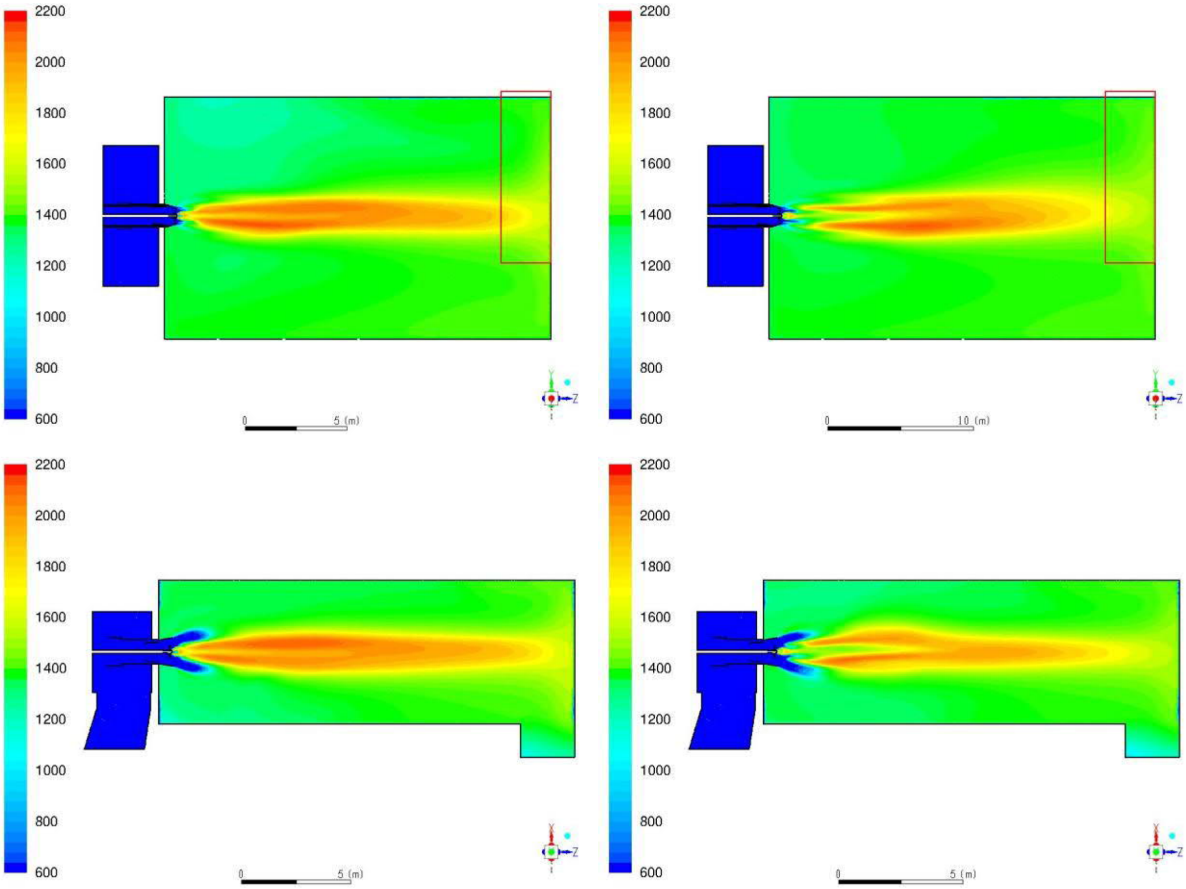

Figure 6. Temperature contour plot in two different operating conditions: with 10% (left) and 3.3% (right) of total fuel (NG) mass-flow-rate to the central stabilization diffusion flame. Top pictures are taken on vertical symmetry plane, bottom ones on horizontal symmetry plane.

Finally in figure 7 a significant visualization of the flame shape is shown, obtained coloring with static temperature contorus the surface at constant value of mixture fraction, equal to its stoichiometric value

($f_{stech.}$ = 0.0641). In Table 1 are summarized the results obtained by the CFD simulation under baseline operating conditions in terms of outlet temperatures in the two points where the thermocouples probes are placed, and the computed NOx and oxygen levels in the flue gases (mass averaged means on outlet).

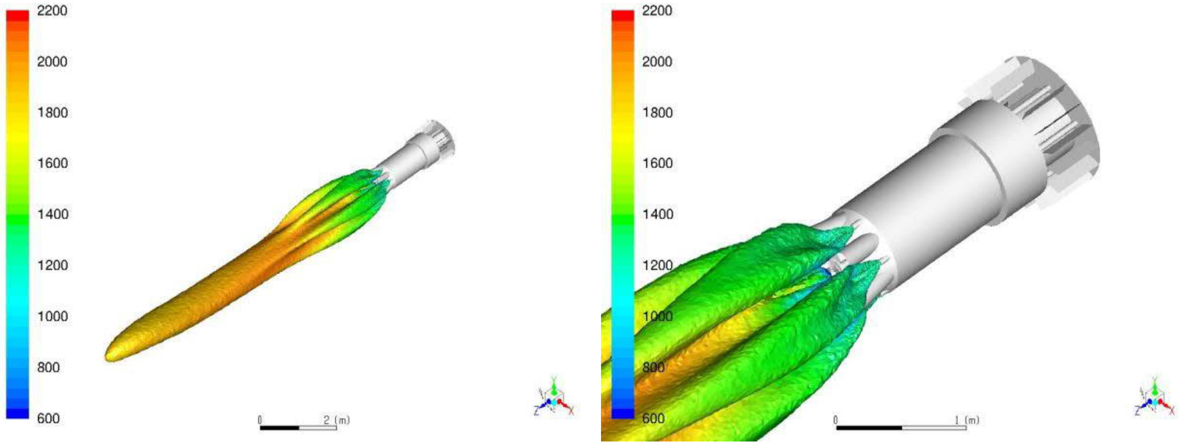

Figure 7. CFD visualization of flame front.

Table 1. CFD results at furnace outlet: 35 MW MARS-II, baseline testing conditions.

Outlet temperature at probes		Outlet flue gas composition	
Upper temperature probe	1207°C	NOx [mg/Nm^3 @ 3%$O_2^{dry, OUT}$]	27.4
Lower temperature probe	1188°C	$O_2^{dry, OUT}$ [%vol]	2.03

Full scale testing and validation of 35 and 45 MW MARS-II burners

Description of test-rig

The CCA experimental equipment includes a boiler test rig able to allow burners in multiple or single set arrangement up to 48 MW_{th} in power. On this experimental facility it is possible to test burners fed by different fuels as solids (as pulverized coal, also in co-firing with grinded biomass), liquids (as HFO, orimulsion, etc.) and gaseous (natural gas, syngas, also with addition of H2, N2, etc.). The boiler is an horizontally shaped having an hopper in the bottom. The main dimensions are 12 m in length, 4.5 m of width and 6.0 m of height (without hopper). In order to simulate as better as possible the real boiler flame boundary condition, the combustion chamber is partially refractory lined in the aim to reproduce the right heat extraction and in consequence the proper flame temperature. Downstream the combustion chamber, the flue gas passes through a convective pass located along the right hand side of the boiler where a part of the total steam produced is superheated. On the left side of the combustion chamber, several windows for the flame view and instrumental access are available. On the top of the burner front an air cooled probe with a boroscope inside gives an overall top view of the flame. The test rig is complete in auxiliaries and instrument for a very wide range of experimental applications. The combustion chamber is pressure balanced by forced and induced fans; a tubular air heater can control air temperature up to 300 °C, a flue gas recirculation can be operated by a recirculating gas fan. Flue gas can be analyzed in gas composition. The standard gas analysis can includes O2 concentrations % both on a wet (ZrO cell) and on a dry basis (paramagnetic analyzer); by means of an Infrared analyzer CO2, SOx and CO concentrations are measured on a dry base; NOx concentration measurements on a dry base is given both by an Infrared analyzer with NO2 converter, and by Chemiluminescent analyzer with NO2 converter.

Results of 35 MW_{th} testing

The test of the 35 MW prototype confirmed the aerodynamic behavior of the innovative design. The MILD combustion regime reached in the main part of the flame – which is an important characteristic of this burner – allows to achieve very low NOx emission levels.

In the pictures below (figure 8) is possible to see the Mars-II burner at 100% load under different conditions: on the left the baseline condition (neither external FGR nor steam injection), on the center steam injection only and, on the right, both steam injection and FGR activated. Note the stabilizing flame in the center section of the burner that ensures the maximum stability in any operating condition. From these pictures it is also possible to observe the *flameless* (MILD) combustion condition relative to the main fuel gas injection system (placed outside the ejector, in the external section of the burner).

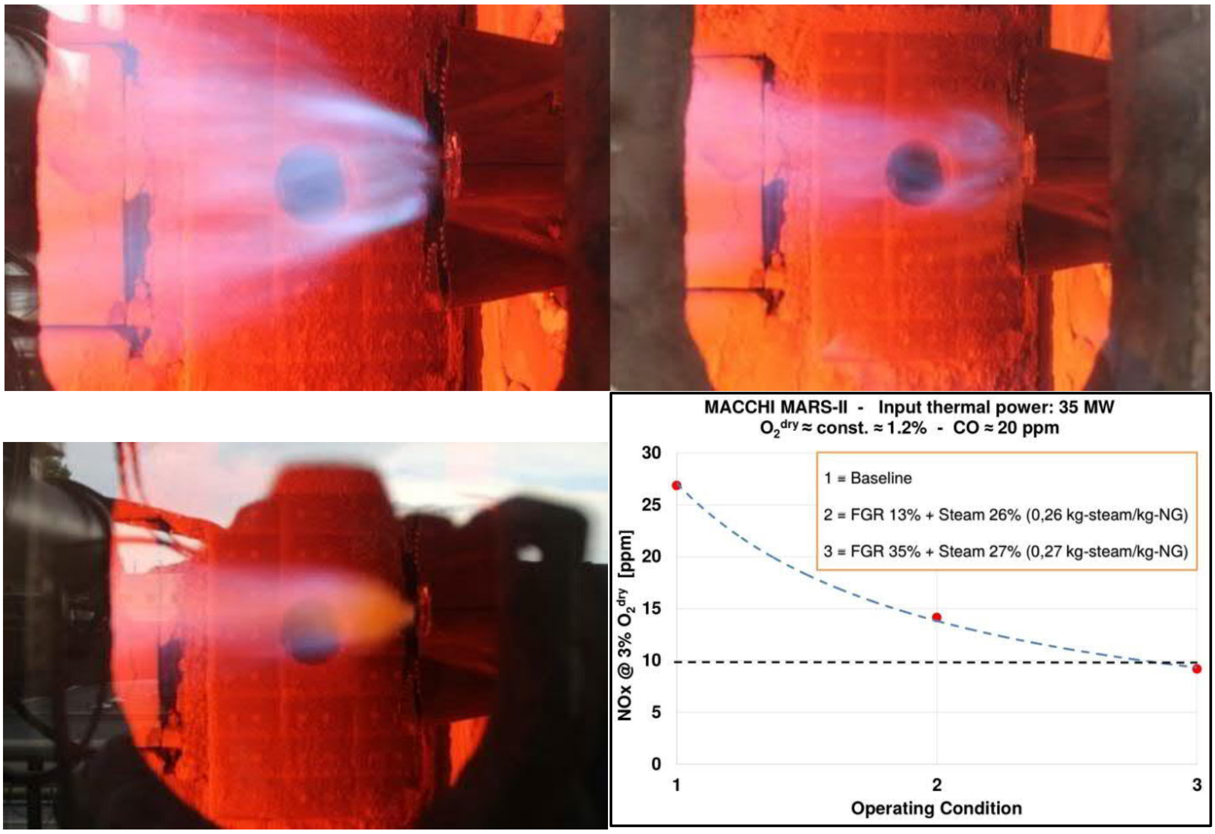

Figure 8. MARS-II testing at 35 MW_{th}: pictures of furnace in the 3 main operating conditions, namely **#1** – baseline (top left), **#2** – steam injection and low FGR mass flow rate (top right) **#3** – steam injection and higher FGR (bottom left), and relative NOx output (bottom right).

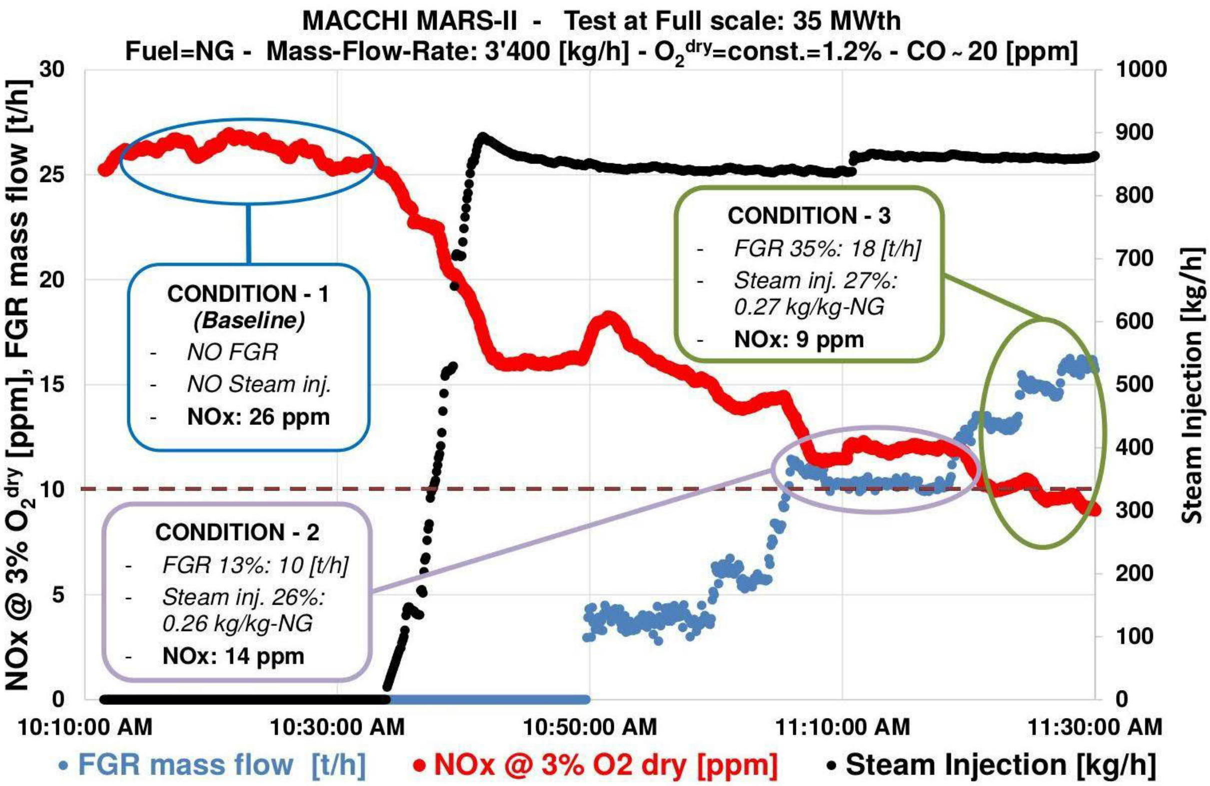

Figure 9. MARS-II 35 MW (6 lobes) testing at full power: experimental results (DCS data) for the 3 main operating conditions (the same already referred to in Figure 8).

In the graph above (figure 9) the results coming from testing are summarized, reporting the performance behavior at three different operating conditions (the same running conditions shown in figure 8):

- Baseline (without FGR and steam injection);
- Adding $20\%_{weight}$ of FGR with respect to combustion air flow rate and $26\%_{weight}$ of steam injection with respect the fuel gas mass flow;
- Adding $35\%_{weight}$ of FGR with respect to combustion air flow rate and $27\%_{weight}$ of steam injection with respect the fuel gas mass flow;

It is possible to underline the strong effect of FGR that, at high value gave the opportunity to reach the “one digit” ppm NOx performance (NOx lower than 10 ppm @ 3% O2 on dry base).

Results of 45 MW_{th} testing

In the following, some results of the 45 MW prototype test campaign are reported.
The different geometry of the burner ejector (with 8 lobes instead of 6) replicates the optimal burner aerodynamic characteristic of the burner design and the high level in performance.
In consequence of the first testing experience at 35 MW_{th}, in the aim to maximize the burner performance, the 45 MW prototype was designed to be operated with higher flow rate of FGR and steam injection. In order to match the higher design characteristic of the prototype to be tested at the CCA experimental facility, the utility lines, regarding steam injection and FGR has been improved in order to reach the higher flow rates.
In figures 10 and 11 the image pyrometer (Durag two color based technology) put in evidence the flame temperature variation at two different FGR operative condition. In figure 11 the increasing of FGR is evident in a lower temperature flame. In the following, the more significant behavior of the burner under the most significant operating condition are reported in figure 12 by DCS data. The experimental test gave the possibility to confirm the numerical hypothesis regarding the benefit of FGR and steam injection on the NOx performance.

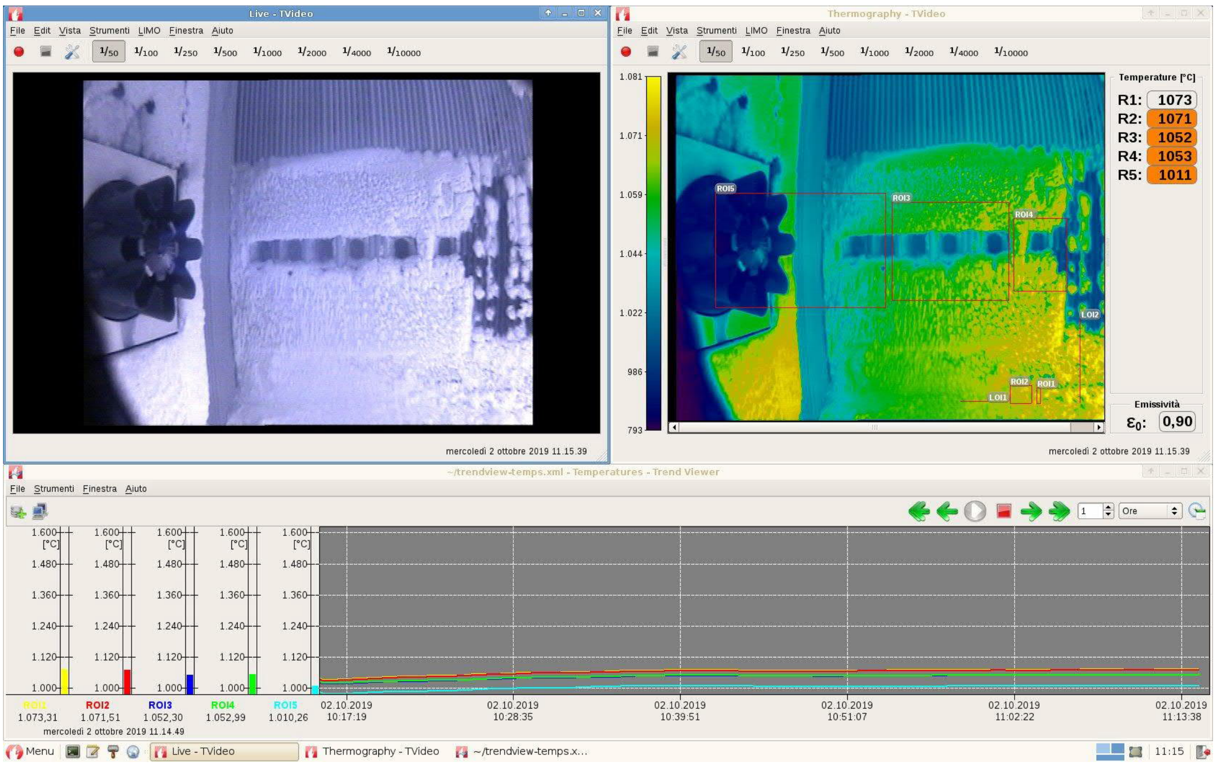

Figure 10. 8-lobes MARS-II 45 MW_{th} testing: furnace pictures by Durag pyrometer; operating condition: steam injection ≈ 3.5 [t/h], FGR ≈ 23 [t/h], leading to NOx ≈ 18 [ppm].

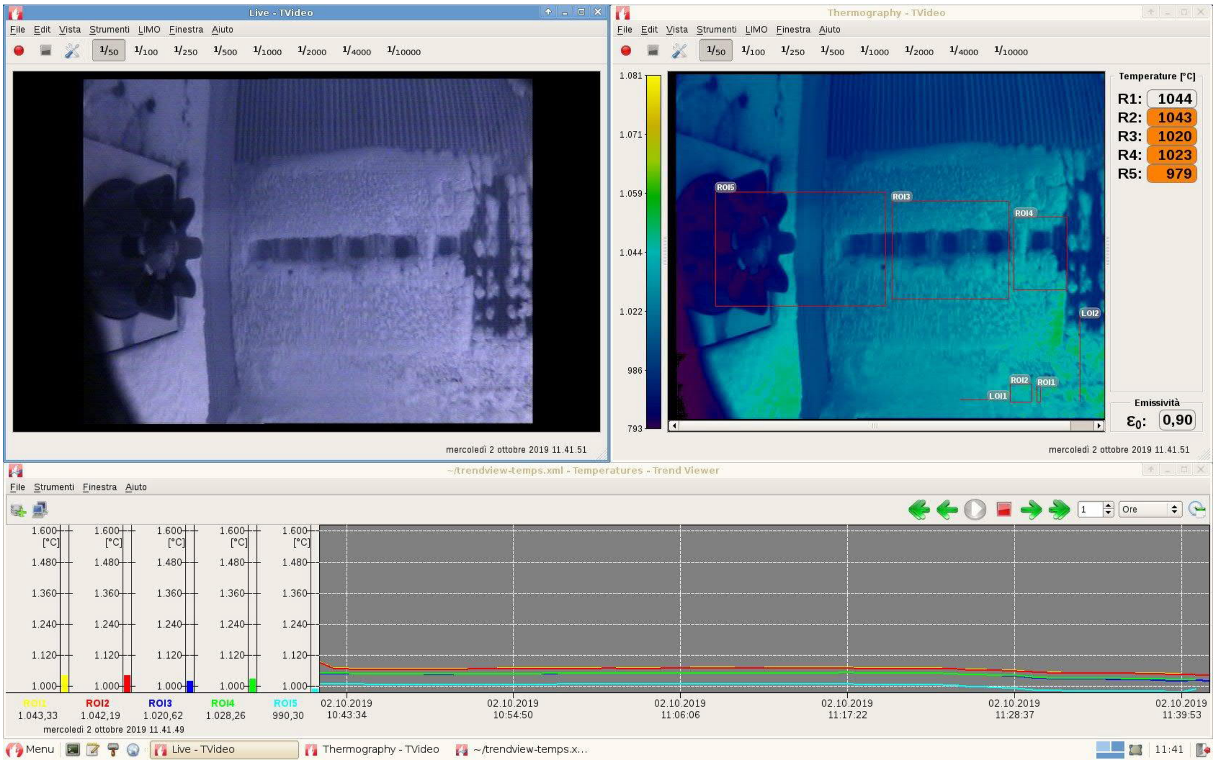

Figure 11. 8-lobes MARS-II 45 MW_{th} testing: furnace pictures by Durag pyrometer; operating condition: steam injection ≈ 3.5 [t/h], FGR ≈ 30 [t/h], leading to NOx ≈ 8 [ppm].

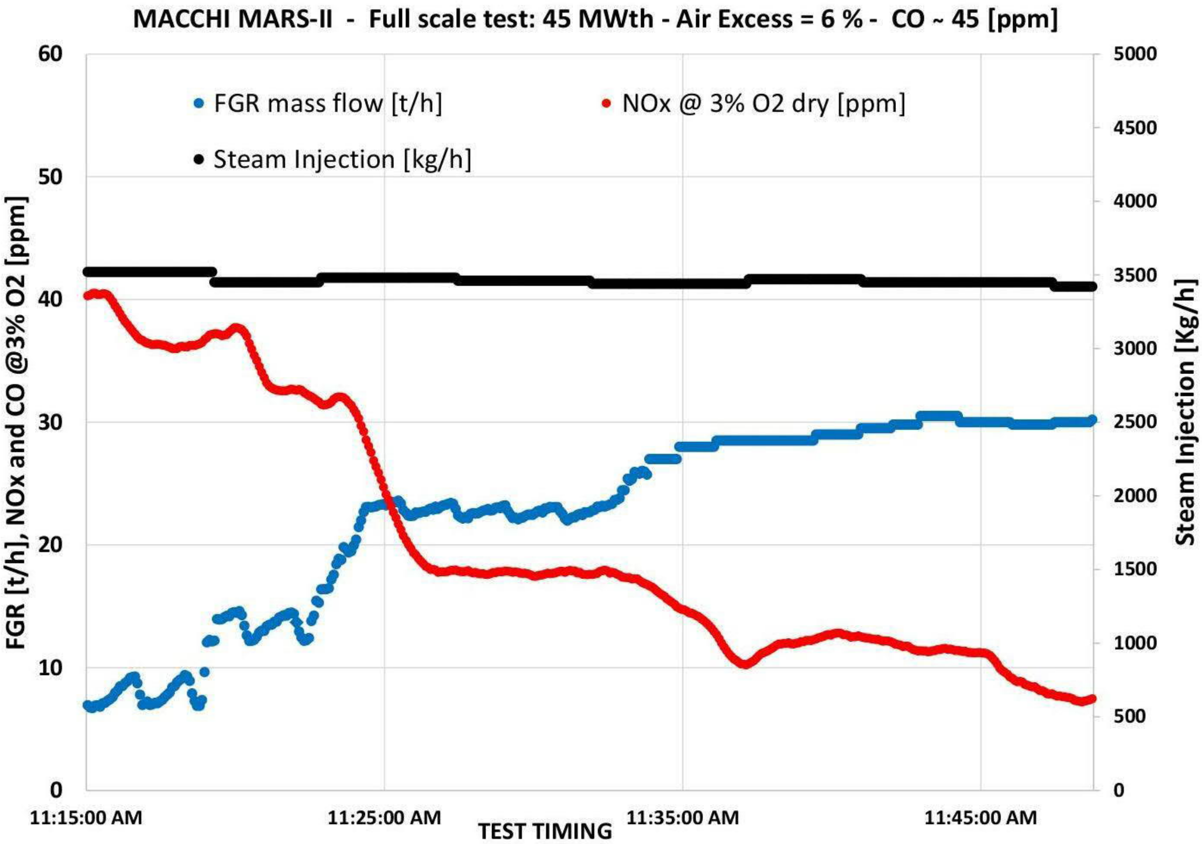

Figure 12. MARS-II 45 MW_{th} testing: experimental results in 2 main operating conditions.

Conclusions

The development of an high performance gas burner for industrial application was successfully obtained. A scientific approach was applied. A MILD mode combustion condition was pursued; the use of CFD, to optimize the burner architecture and the combustion process was adopted; then, extensive full scale experimental testing on two different design architecture and duty took place to confirm the design hypothesis.

The self-recirculating mechanism triggered by the MARS-II ejector has proved to be extremely effective in diluting the main fuel stream injected by the main spuds surrounding the burner.

This effectiveness has been proven both by CFD simulations and full scale tests, carried out at 35 MW_{th} where, operating at the baseline conditions (without neither external recirculation nor steam injection), the NOx emission levels have been reached the level of 50 mg/Nm^3 at 3% O_2 on a dry base and, in the same condition, the CO levels was around 20 mg/Nm^3.

These features also allow us to highlight all the economic advantages that the adoption of a MARS-II Very Low NOx burner entails, especially if we consider the possibility of NOT to install an expensive NOx abatement systems, such as, for example, an SCR reactor.

The multi-lobed design has also proved to be particularly effective in improving the global burner mixing capabilities, which has allowed to operate it with an excess air of about 5%. The benefit of this situation involves both combustion efficiency and overall efficiency of plant (which has an immediate economic impact on the auxiliaries consumption).

In addition, the fuel dilution mechanism obtained from the multi-lobed ejector makes the MARS-II particularly suitable for the combustion of very heterogeneous gases, including those containing high H_2 fractions (in dedicated test campaigns, excellent results were obtained by burning fuel streams containing up to at $70\%_{vol}$ of hydrogen).

Last (but not least) feature of this design is related to its robustness in terms of flame stability. This burner is in fact able to reach very high flow rates of external flue gas recirculation (up to 40%), which, in addition with the adoption of a steam injection system, allows Macchi to achieve NOx emission levels lower than 10 ppm. It should be noted that these performances were achieved both at 35 and at 45 MW_{th} with the two design air injectors.

In short, the MARS-II burner has demonstrated possible to achieve at the same time both the highest level of flexibility and operational robustness, together with the ability to achieve extreme performance in terms of pollutant emissions and CO control.

References

[1] *WEO-2016 Special Report: Energy and Air Pollution*, International Energy Agency: Paris, France, 2016.

[2] J.M. Ballester, C. Dopazo, N. Fueyo, M. Hernández, P.J. Vidal, "Investigation of low-NOx strategies for natural gas combustion", *Fuel, 76, 1997*, 435-446.

[3] E.C. Zabetta, M. Hupa, K. Saviharju, "Reducing NOx emissions using fuel staging, air staging, and selective noncatalytic reduction in synergy", *Ind. Eng. Chem. Res., 44, 2005*, 4552-4561.

[4] M. De Joannon, G. Langella, F. Beretta, A. Cavaliere, C. Noviello, "Mild Combustion: Process Features and Technological Constrains", *Combustion Science and Technology, 153, 2000*, 33-50.

[5] A. Cavaliere, M. De Joannon, R. Ragucci, "Physical and chemical aspects of the MILD combustion. Examples related to gas turbine combustion", *4th International. Symposium on HTACG*, Rome, Italy, 2001, 26-30.

[6] J.A. Wünning, J.G. Wünning, "Flameless Oxidation to reduce thermal NO-formation", *Progress in Energy and Combustion Science, 23, 1997*, 81-94.

[7] B.B. Dally, E. Riesmeier, N. Peters, "Effect of fuel mixture on moderate and intense low oxygen dilution combustion", *Combustion and Flame, 137, 2004*, 418-431.

[8] I.B. Özdemir, N. Peters, "Characteristics of the reaction zone in a combustor operating at mild combustion", *Experiments in Fluids, 30, 2001*, 683-695.

[9] M. Torresi, F. Fornarelli, B. Fortunato, S.M. Camporeale, A. Saponaro, "Assessment against experiments of devolatilization and char burnout models for the simulation of an aerodynamically staged swirled Low-NOx pulverized coal burner." *Energies, 10.3390/en10010066, 10(1), 2017, 66*.

[10] G.D. Rago, G. Rossiello, R. Dadduzio, T. Giani, A. Saponaro, F. Cesareo, M. Lacerenza, F. Fornarelli, G. Caramia, B. Fortunato, S.M. Camporeale, M. Torresi, V. Panebianco, "CFD analysis of a swirl stabilized coal combustion burner", *Energy Procedia, 148, 2018*, 703-711, DOI: 10.1016/j.egypro.2018.08.160.