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Testing a new lignite prototype burner by experiment and numerical modeling

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Abstract

This research is the first step of a complex research program that has the goal to retrofit the lignite burners of a 2×315 MWe units of a thermal power plant, in order to reduce NO_x emission by staggered under-stoichiometric combustion. The straight-flow pulverized-coal burner will be built-on from a set of 16 modules. The experiments were made in a wind tunnel on a single module that was converted for the staggered combustion. The experimental data were compared to those resulted from the numerical modeling flow processes for the jets interaction, in order to achieve the desired aerodynamic.

Keywords: Pulverized lignite burner modernization; Low NO_x emissions; Staggered combustion

Nomenclature

NO_x	–	nitrogen oxides
Re	–	Reynolds number
V	–	dimensionless velocity number
G	–	dimensionless geometrical number
a	–	length of the burner transversal section, m
b	–	height of the burner transversal section, m
d	–	characteristic dimension of the burner exhaust section (equivalent diameter), m
L	–	furnace width, m
H	–	furnace combustion height, m

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I – furnace length, m
w – air velocity at burner exhaust, m/s
u – coal particles velocity at burner exhaust, m/s
$\dot{m}$ – mass-flow rate of the primary air
F – transfer function from secondary to primary air
T – absolute temperature, K.

Greek symbols

υ – dimensionless temperature number

Subscripts

M – mode
R – real
t – thermal
e – electric
1 – related to primary air-flow
2 – related to secondary air-flow.

1 Introduction

This paper presents the results of the first part of a complex research program [1] based on holistic approach of management and engineering psychology applied to a coal-fired energy system to reduce pollution and increase quality of life as having a total novelty and originality on national level.

All the scientific and technical activities that will be conducted during the research will contribute to the development of a new clean-burning coal technology applicable to about 20 units of steam generation with capacities of 525 and 420 t/h operating on solid fuel, requiring urgent upgrades according to current environmental regulations.

Romania's integration in the European Union structures requires today the strict application of international environmental standards. In this regard, EU directives were transposed into national legislation by laws and regulations, requiring that the NO_x emission limit values expressed in mg/Nm^3 (at 6% O_2 content in flue gas) applicable to large solid fuel combustion plants are the following:

a) 600 mg/Nm^3 for combustion units of 50–500 MW_t

b) 500 mg/Nm^3 for combustion units larger than 500 MW_t, value that will decrease to 200 mg/Nm^3 from January 1st 2016.

The idea of reducing NO_x emission through staggered combustion is not innovative, our research being focused on the old burner retrofitting into a less pollutant one with lowest cost.

2 Technologies for NO_x reduction

2.1 NO_x generation

During the combustion of fuels, nitrogen oxides occur as a side effect of the high temperature combustion, due to the reactions of oxygen in excess with nitrogen from the air and fuel. The main parameters influencing the NO_x formation are: flame temperature, residence time in the reaction, concentration of oxygen, nitrogen content of the fuel. Other parameters that influence the formation of NO_x, such as gas-dynamic flame, its turbulence, design of the furnace are considered as secondary ones [5].

2.2 NO_x reduction methods

They can be divided into three generations, as follows:

- first generation includes the following methods:
  – lower air excess,
  – reducing air preheating temperature,
  – burners with preferred fuel and air distribution,
  – flue gas recirculation in the furnace;
- second generation is based on:
  – 1st level of low NO_x burners (burner air injections),
  – flue gas recirculation at burner level,
  – instilled air above the combustion (tertiary air);
- third generation includes:
  – 2nd level of low NO_x burners (controlled injection of air and fuel to the burner),
  – reduction of NO_x in the entire furnace (re-combustion in furnace).

The proposed solution will choose the optimal combination of primary measures to achieve the lowest level of NO_x (preferable under 300–350 mg/Nm^3), meaning a decrease of NO_2 concentration of about 20–30%, by introducing the staggered combustion. This action will decrease the temperature in the flame main nucleus and complete the combustion using the over-fire air system (air situated above the combustion zone). Figure 1 shows the future division of the furnace in three combustion zones: MCZ (main combustion zone), RZ (reduction zone) and BDZ (burning delimitation zone).

The researches to achieve a new industrial burner will include:

- Design of a functional burner model that will be tested on an aerodynamic tunnel and by numerical modeling.
- Design of a pilot burner that will be tested on 2 MW_t pilot boiler.
- Technical design and adaptation of the existing industrial burner to the new technology.

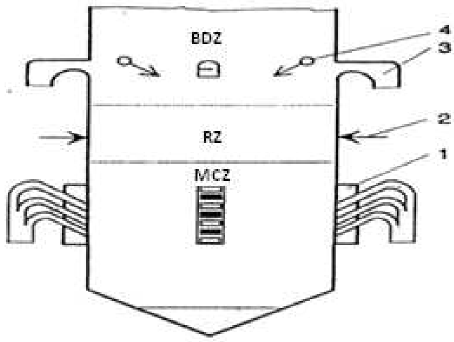

Figure 1. Scheme of the staggered combustion (1 – coal-dust burner slots, 2 – natural gas startup/backup burner, 3 – aperture for flue-gasses extraction, 4 – tertiary air nozzles).

2.3 New burner model for low NO_x emissions

According to the technical issues emphasized in the Section 2.2, we designed and built-up a burner model. In Fig. 2 is shown a longitudinal section of this burner. The pulverized coal is blown in the furnace together with the primary air through two rectangular slots, while preheated secondary air is provided by the third slot. Figure 3 shows two sides of the model: the slots in the left side and the supply channels in the right side.

2.4 Theory/calculation of the processes in the burner module installed in the aerodynamic tunnel

The purpose of the test is to achieve a dynamic similitude between the model burner and the real burner, respecting the turbulence criteria of the jets at the burner exhaust, including the drag and transportation of coal particles. Due to the fact that the geometrical scale of the model tested on the aerodynamic tunnel and the real burner that will be tested in the pilot furnace is 1:1, the observance of the geometrical criteria $G_a = \frac{a}{L}$, $G_b = \frac{b}{l}$, $G_l = \frac{l}{h}$ imposes the analysis of the development structure of the jets interaction on the dimensions l and h of the furnace.

The considered criteria of dynamic similitude are:

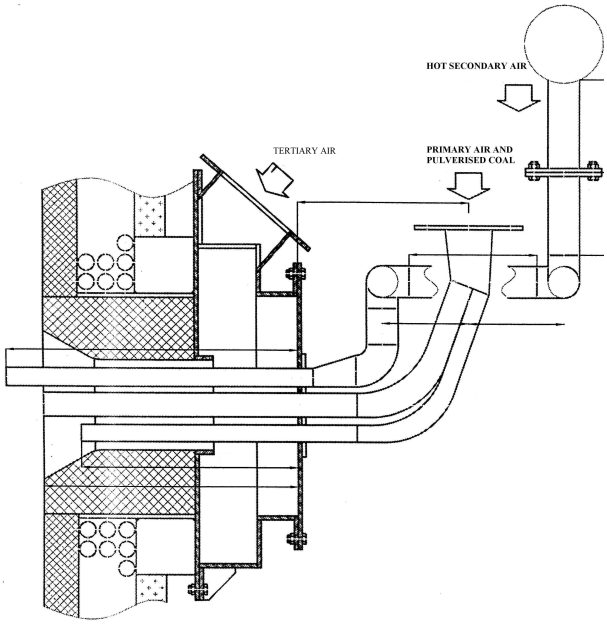

Figure 2. Cross-section of the model burner.

Figure 3. The model burner.

- Reynolds numbers $\mathrm{Re}_M = \mathrm{Re}_R = const$, where $\mathrm{Re} = \frac{w \cdot d}{v}$.
- Velocity numbers $V_{1M} = V_{1R}$, where $V_1 = \frac{w}{u}$, w is the air velocity and u is the coal particle velocity.
- Temperature numbers $\vartheta_M = \vartheta_R$, where $\vartheta = \sqrt{\frac{T_2}{T_1}}$, T_1 and T_2 are the temperatures of the primary air flow, respectively the secondary air flow.

Reynolds number should be maintained in the self modeling domain ($\mathrm{Re} > 10^5$), while the dimensionless velocity criterion $V_1 = 1$, in order to obtain the equality between the air velocity and the coal particle velocity, in the burner exhaust [3]

According to the geometry and usual operating conditions of this type of burner, the following numerical values have been imposed or calculated:

primary air velocity	w_1=15 m/s
secondary air velocity	w_2=40 m/s
tertiary air velocity	w_3=10 m/s
primary air temperature (model)	T_{1M}=295 K
secondary air temperature (model)	T_{1M}=358 K
primary air temperature (real)	T_{1R}=373 K
secondary air temperature (real)	T_{1R}=523 K
temperature (model) number	ϑ_M=1.10
temperature (real) number	$\vartheta_R = 1.18$
Reynolds (model) number for the primary air	$\mathrm{Re}_{1M} = 1.49\times10^5$
Reynolds (model) number for the secondary ant tertiary air	$\mathrm{Re}_{1M} = 1.26\times10^6$
mass-flow of the primary air	$\dot{m}_1 = 0.093$ m^3/s
mass-flow of the secondary air	$\dot{m}_1$= 0.94 m^3/s
furnace length	$l = 2.4$ m
furnace height	$h = 7.5$ m

Due to the fact that the primary and secondary air velocities are imposed by the coal quality, the variable parameter of staggered combustion is the staggered intake in space of these jets, as shown in Fig. 3.

3 Testing the new model burner

3.1 The wind channel

The wind tunnel was designed to emphasize the functional features of the installations, where gas-dynamics has a leading role, such as burners. It enhances the influence of gas-dynamics on the general operating characteristics, such as jet interaction, the general contour of the flame, flame penetration in furnace.

The tunnel consists of two air fans of 22 kW (Fig. 4), which can be connected in serial or in parallel mode, according to the experiment requirements. Central air channel is provided with a Venturi tube accurately calibrated to measure the air flow and with a butterfly valve that ensures the overall air-flow control [6,7].

3.2 Experimental stand

The experimental stand is presented in Figs. 5 and 6. The burner model is placed on the metallic stems and is connected to the aerodynamic tunnel by means of flexible pipes. A pitot tube is firmly mounted on a fixed pipe, with possibility of vertical and horizontal sliding. In this manner, the axe of pitot tube can be easily lined up with the center of the air slot or with the space between slots. The distance between the tube and the burner exhaust can also be accurately chosen.

Figure 4. The wind tunnel.

Figure 5. View of the experimental stand (1).

Figure 6. View of the experimental stand (2).

3.3 Tests (results and discussions)

The purpose of the tests was to find the air-flow velocities in several sections of the burners, in order to verify the jet interactions according to the theory from Section 2.4. The measurement points are presented in Fig. 7.

The measurements have been made both in vertical and horizontal planes. In vertical plane there are 7 measurement points, presented in Fig. 7. The air velocity is measured in middle of the slot and in the space between slots. In horizontal axis there are 5 planes of measurement: at 0, 200, 400, 600 and 800 mm from the burner embrasure. The test results are graphically presented in Figs. 8 and 9.

The measurement system consists of a pitot tube connected to a U tube (Fig. 6), attached to flexible spatial platform.

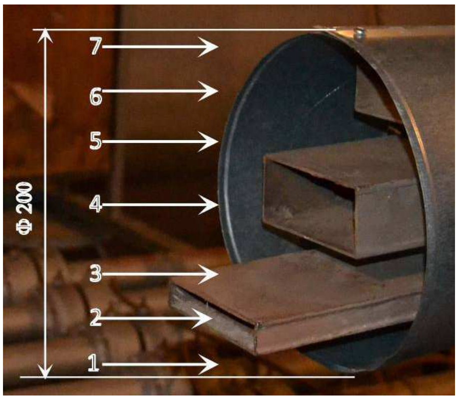

Figure 7. Measurement points in vertical plane.

It is possible to observe that the secondary air velocity (measurement point 2) decreases in the axial dimension from 40 to 10 m/s, maintaining the values higher than all the other mass-flows. This fact allows to the secondary air to accompany the primary air and fuel particle jets with high oxygen contents and to penetrate them continuously during common evolution. In this manner the primary combustion can be under-stoichiometric ratio, resulting lower NO_x concentrations. The primary air velocity (measurement point 4) decrease to, but more gentle than the secondary air one, from 14 to 6.6 m/s. Regarding the tertiary air flow (measurement points 1, 3, 5, 7), its velocity decreases to, but very slow, from 10 to 4.7 m/s, wrapping the primary and secondary jets and offering oxygen as needed at distances larger than 1 m to ensure the complete combustion.

The results of the aerodynamic jets interaction will allow the calculation of a transfer function F of the secondary air jet to the primary air/lignite particles jet, corresponding to a gradual combustion.

3.4 Numerical modeling

The jet flow has a symmetry plane (x=0), so that only half of it is used in the computation. Thus, the external boundary of the computing domain is half of a cylinder enclosing the injection jet devices, having a radius of 1 m and a length of 5 m. Figure 10 show the computing domain and the boundary conditions used in the numerical simulation. Note that the velocity inlet boundaries consist of the jets inflow areas as well as the area between the wall embrasure and all jet ports.

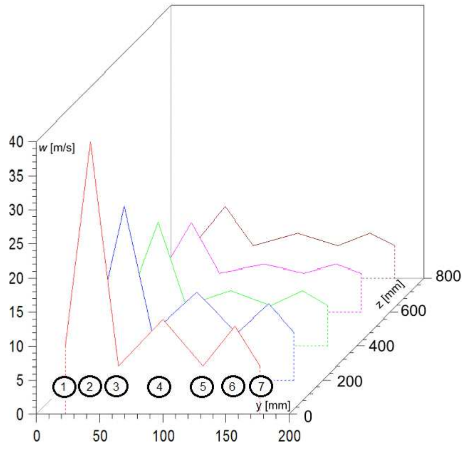

Figure 8. Spatial plots of the velocities.

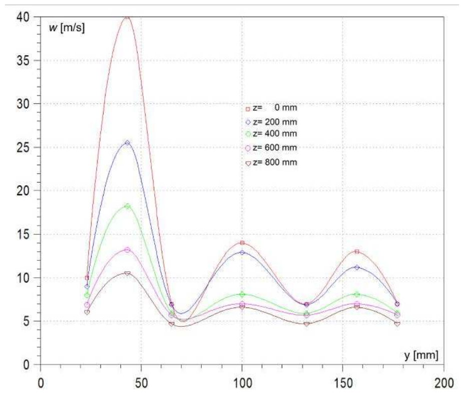

Figure 9. Velocities versus vertical Pitot tube position.

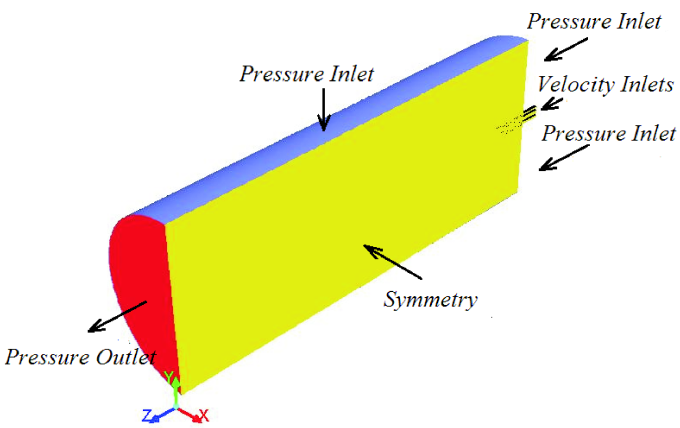

Figure 10. Computational domain and boundary conditions.

A thickness of 2 mm was considered for all channel jet walls, while the embrasure wall thickness was set to zero. The density node on the symmetry plane was set after performing a grid sensitivity analysis for a 2D planar flow case. By using this value, a 3D grid with about 2.5 billion of nodes was constructed as a multi-block structured hexahedral mesh. Figure 11 shows a detail of the computational meshed domain consisting of all channel and embrasure jets and also the attracted inflow external jet surrounding the embrasure.

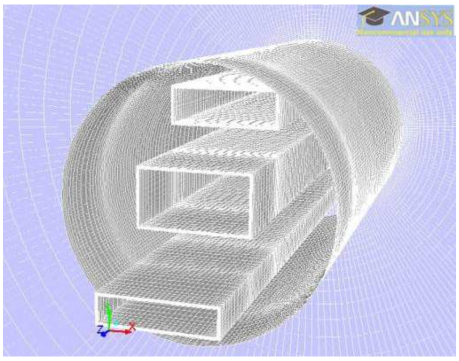

Figure 11. Details of computational domain encompassing the channel and embrasure jet zones and the surrounded attracted inflow jet zone.

The mathematical model consists of full Reynolds averaged Navier-Stokes equations (RANS). The k–ε RNG turbulence model with scalable wall function was used for closing the RANS equation system [4].

The computation was performed by means of the commercial software on a Supermicro platform having 48 GB of main memory and two Intel six core 2.4 GHz CPU. The pressure based solver in addition to the least squares cell based gradient algorithm was used in the numerical simulation. The mean momentum and the turbulence equations were solved by employing the second order upwind and the QUICK discretization schemes, respectively. The pressure (Poisson) equation was solved by the aid of standard procedure, while the pressure-velocity coupling was assured by using the SIMPLE algorithm.

The velocity profiles delivered trough numerical modeling looks similar to those obtained by measurements. There are however slight differences, especially at the distances from burner embrasure larger than 600 mm, when the jets seem to mix faster than in experiment, creating a single jet.

The primary jet velocity is constant, while the tertiary air is drawn in interaction with the primary and the secondary air-flow jets, demonstrating the interaction and penetration between them.

4 Conclusions

The experimental and numerical tests have proven the possibility to obtain the staggered combustion for pulverized coal slot burners. This fact was possible due to the combination between de velocity differences and the different lengths of the burner channels. While the secondary/primary air velocity ratio (40/15) is usual for lignite burners, the values of the length differences were a strict objective of our research, in order to obtain a staggered burning. It was revealed a significant

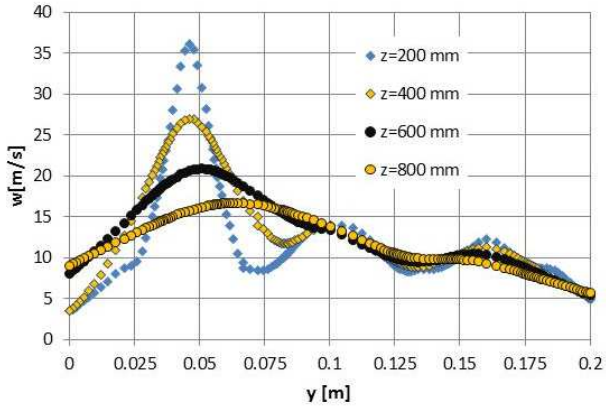

Figure 12. Predicted velocity profiles at a given z-locations measured from the embrasure exit section on the symmetry plane ($x = 0$).

penetration of the secondary air-flow for a distance at least equal to four times the equivalent diameter of the embrasure. This distance represents the domain where the coal particle will be in contact with the secondary air in order to create the second zone of combustion.

Experimental results have been confirmed by numerical modeling, setting-up the base for further developments. The emission of NO_x reduction will be dependent of the transfer function F.

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