HEFAT2012
9th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
16 – 18 July 2012
Malta

CFD AND INFRARED COMBINED ANALYSIS OF A FURNACE BELONGING TO A 420 T/H BITUMINOUS COAL STEAM GENERATOR

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ABSTRACT

Some years ago an old lignite fired power plant provided with two steam generators of 420 t/h, has been revamped in the northern part of Romania. This operation was focused mainly upon the changing of the initial type of fuel – Romanian lignite – into bituminous coal, including new type of burners also. At the same time, some geometrical modifications have been added to the furnace due to the new burners' particularities.

After two years of operation, a lot of functional problems have been recorded especially regarding the high flue gas temperature at the end of the furnace (sometimes greater that the melting point of the ash) due to a lower intensity of the heat transfer process; at the same time a great difference between the flue gas temperature occurs on the left part of the furnace in comparison with the right part.

This paper presents a PhD task focused upon the heat transfer phenomena analysis inside the above mentioned furnace.

INTRODUCTION

It starts with the principal procedures regarding the new coal type elemental analysis, coal and ash particles distribution diameters, in order to evaluate the basic radiative properties of the new flame (flame absorption coefficients). Then an experimental combustion test have been performed upon the 1 MW pulverized coal pilot furnace of the Politehnica University of Bucharest laboratory; this test used the same type of bituminous coal and the same type of burner that was used in the revamped power plant and was designated to calibrate the CFD combustion model. The validation of this model has been performed by comparison of the flue gas temperature distribution and components inside the furnace volume with the values derived from the CFD numerical model, taking into consideration the same boundary conditions. This validation procedure was based upon a CEDIP Silver 420 infrared camera, some thermocouples and two HORIBA PG250 flue gas continuous analyzers. The paper describes all the CFD model settings and also the experimental data in the background used to create them.

NOMENCLATURE

a_{an}	[-]	Ash fraction transported by the flue gas
A^i	[%]	Ash content with reference to the initial state
C^i	[%]	Carbon content with reference to the initial state
d	[μm]	Diameter
H_f	[m]	Furnace height
ΔH	[m]	Height difference between the upper and lower burner levels
k	[1/(mMPa)]	Furnace radiation attenuation coefficient
L	[m]	Equivalent thickness of radiative layer
p	[MPa]	Pressure
q_m	[%]	Heat loss due to mechanical incomplete combustion
r	[-]	Gas volumetric participation
T_g	[K]	Flue gas temperature at the end of the furnace
V^{mc}	[%]	Volatiles content with reference to fuel mass
V_g	[m_N^3/kg]	Real volume of flue gas
Special characters		
ε	[-]	Emissivity factor
λ	[-]	Air excess
μ	[g/m_N^3]	Mass concentration
Subscripts		
a		Ash particles in flue gas
c		Coke particles
fl		Flame
g		Tri-atomic gas

BASIC REAL SITUATION. MODELING AND VALIDATION

Basic situation consisted in analysing the present situation of the furnace operation, considering the completely replacement of the burners. The main technical specifications of this furnace are the following: coal low heat value – 6.5 MJ/kg; fuel flow rate – 70.83 kg/s; excess of air at the burner's level – 1.25; preheated air temperature – 300°C; furnace dimensions – 11.88 x 11.88 x 30 m.

The furnace enclosure has been modelled as it is shown in the Figure 1, taking into consideration all the burners details (8), such as primary air cross section inlet, core secondary air cross section inlet, central secondary air cross section inlet, inferior secondary air cross section inlet and superior secondary air cross section inlet. In the same model, support burners (7) have also been considered, because they are cooled by secondary air also during a normal operation. For the basic situation flue gas re-circulating outlets have been also considered (3) as a 24.5 % flue gas is normally re-circulated to dry the coal. The end of the furnace has been considered the face no. 1.

To reduce the whole presentation, all the preparations for the future steps have been also presented on the same figure (it is about the indexes 2, 4, 5 and 6 which are described later).

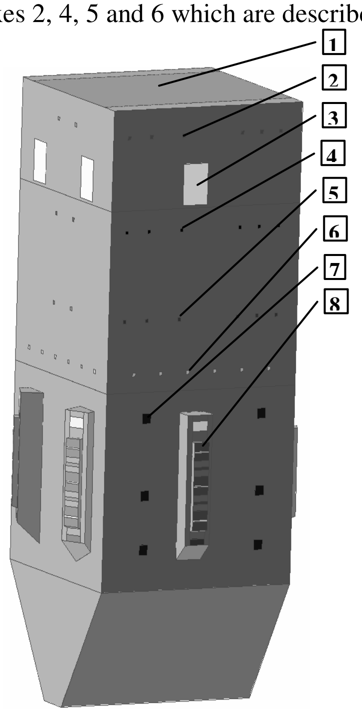

Figure 1 Furnace geometrical model

Mesh has been generated by zones, using hexahedrons and tetrahedrons, depending upon the burner details. A number of 761000 cells have been used.

Fuel (brown coal) has been milled up to 10 % refuse upon the 1mm sieve separator and 55% refuse upon the 90 μm sieve separator.

For burning process simulation a *pdf* partially premixed combustion process has been prepared using Fluent 6.3 [1] facilities. Three streams have been initialized coming from the burners or from the others inlet cross sections: the first stream has been considered as the fuel one, followed by the secondary stream composed by air (primary and false) and flue-gas and the third stream has been the oxidant as preheated air [2].

After the boundary conditions have been initialised, the numerical model has been calibrated and the validated by in situ determinations. Average end furnace flue gas temperature together with SOx, NOx and carbon monoxide concentrations have been considered as validation criteria for this numerical model. All the flue gas components concentrations have been continuously determined by a HORIBA PG 250A analyser using chemiluminescence's effect to determine NO and nondispersive infrared methods to determine carbon and sulphur oxides during six hours and a half operation time. Oxygen participation has been determined by paramagnetic method. Validation of the simulation has been accepted under a range of error of 5% for every critical value due to the flue gas mass balance comparison between the plant recordings and the model results. All the input/validation data are presented inside the Table 1.

Table 1 Input/validation data

Burner	Primary air+ recirc. flue gas+ false air, [kg/s]	Primary air, [kg/s]	Core air, [kg/s]	Central air, [kg/s]	Superior air, [kg/s]	Inferior air, [kg/s]
1	1.7*	1.7*	1.7	2.6	4.1	1.8
2	24.6	4.75	2.25	6.7	10.9	4.2
3	24.6	4.75	2.25	6.7	10.9	4.2
4	24.6	4.75	2.25	6.7	10.9	4.2
5	24.6	4.75	2.25	6.7	10.9	4.2
6	24.6	4.75	2.25	6.7	10.9	4.2
Total		25.45	12.95	36.1	58.6	22.8

By post-firing grate 19.8 kg/s of primary air is injected as well as by starting burners.

Due to the fact that one burner is stopped during a full load operation, primary air, false air and dry recirculated flue gas repartition is presented in the Table 2.

Table 2 False air and dry recirculated flue gas repartition

Burner nozzle	Primary air, [kg/s]	Central air, [kg/s]	Core air, [kg/s]	False air, [kg/s]	Dry recirculated flue gas, [kg/s]
1	0.25	0.8	0.25	0	0
	0.3			0	0
	0.26		0.25	0	0
	0.3	0.8		0	0
	0.26		0.25	0	0
	0.25			0	0
2-6	0.8	3.3	0.8	1.6	2.3
	0.95			1.6	2.8
	0.7		0.8	1.4	2.1
	0.95	3.3		1.7	2.8
	0.7		0.8	1.6	2.1
	0.8			1.7	2.3

Validation data – computed values and measured ones - are presented in the Table 3, for 92% of the full load boiler operation regime.

At the same time an oxygen concentration (determined by paramagnetic methods) has also been recorded together with a flue gas average mass flow rate of 235 kg/s.

Table 3 Computed and measured values

Name	Computed value	Measured value	UM	Method
Flue gas flow rate	285.07	272.56	kg/s	Plant registration
Average flue gas temperature at the furnace exit	1176.3	1138.5	^{o}C	Aspiration izo-kinetic thermocouples
O_2 volumetric concentration *	3.01	3.11	%	Paramagnetic
CO volumetric concentration*	82.43**	77.27**	mg/Nm^3	NDIR
CO_2 volumetric concentration*	14.24	14.33	%	NDIR
SO_2 volumetric concentration*	4325.5**	4376.2**	mg/Nm^3	NDIR
NO volumetric concentration*	556.52**	548.31**	mg/Nm^3	Chemo luminescence

* after the first heat exchanger; ** values corrected to 6% O_2.

THE FIRST STEP TOWARDS NOX REDUCTION

Due to the fact that NOx level is expected to be increased (low heating value of the brown coal is greater than the correspondent value of the lignite) some supplementary measures to reduce NOx emissions should be considered.

The first step has been focused to practice a superior level of sixteen nozzles (index 2 in Figure 1) in order to reduce the excess of air at the burner's level and to complete combustion by injecting over fire tertiary air. Considering all the other input conditions as constant values like the basic model, the temperature variation along the central axis of the furnace has been converted as in Figure 2.

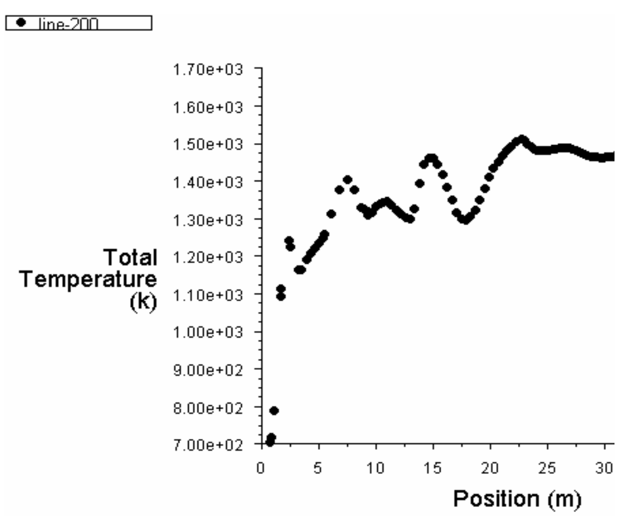

Figure 2 Temperature distribution along the central axis of the furnace

In the spite of the fact that the flue gas temperature has been uniformized along this axis some peaks can be observed and these can generate some thermal regions for NOx generation.

This technical solution has the advantages to be the cheapest, due to the particular fact that some of these nozzles are already practiced by the boiler manufacturer due to different purposes. So that new development costs are very low (only for six nozzles) and the owners have to consider practically the furniture cost for the necessary pipes and also the labour costs. All these values have been considered at the amount of 250 000 USD, per installation (design included).

THE SECOND STEP TOWARDS NOX REDUCTION

For the second step more others nozzles at different levels have been considered. All these levels can be examined on the Figure 1: a low level tertiary air injection has been considered at the index 5; a medium level tertiary air injection has been considered at the index 4; an over fire tertiary air level has been considered at the index 6. In this condition the air excess at the burner's level has been decreased at the value of 0.94, considering a severe reduction of the secondary air cross sections in order to conserve the same inlet velocities. A supplementary observation has to be mentioned here about the inferior secondary air and the superior secondary air injections; all these flow rates have been reduced also in order to have enough penetration on the over fire nozzles. After finishing the numerical simulation of the process the flue gas temperature distribution along the central axis of the furnace is like in the Figure 3.

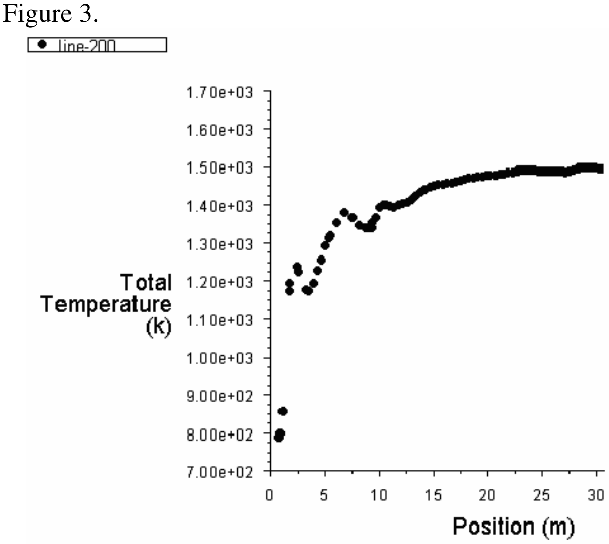

Figure 3 Temperature variations along the central axis of the furnace

As it can be observed from the Figure 3 the flue gas temperature variation is smoother than in the first case and the average value is lower. That means that we can expect a lower NOx thermal concentration at the end of the furnace. The NOx formation model has been considered to be influenced also by the fuel nitrogen concentration and the Fenimore [3] mechanism. Nitrogen mass fraction of the fuel (1.01%) has been totally bounded by the fixed carbon and the specific BET of the milled coal has been considered with a value of 95 m2/kg. All these supplementary constructive measures have been evaluated at a total cost of 1500000 USD, including the labour costs also.

NOx predicted concentrations have situated arround the value of 400 mg/ (corrected value) as been presented in the Figure 4.

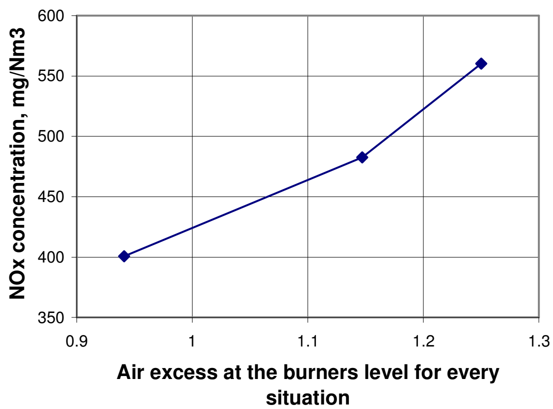

Figure 4 NOx concentration for every analyzed constructive solution

ASPECTS REGARDING NUMERICAL SIMULATIONS AND VALIDATION TECHNIQUES

The first point in this strategy was to use the pdf models of combustion, assuming higher obtained values of flue gas temperature from the beginning. This idea has been based upon the general observation that important gradients of temperature can be seen around the particles' clouds within the coal flames [4]; they are formed especially within the low vorticity oxygenated zones (in the neighbourhood of the secondary air injection) .

The second important aspect of the numerical simulation technique was to evaluate the emissivity factor of the flame volume cells. Mitor empirical relations have been used [5] as an user defined function (*udf*) procedure in order to take into consideration both cell's temperature, its water vapour and carbon dioxide concentration and the soot concentration [6]. A special technique to validate this *udf* procedure has been developed upon a 1MW pilot pulverized coal furnace of the Politehnica University of Bucharest laboratory. There, a CEDIP 420 Silver infrared camera has been used to determine the temperature inside the volume cells; first time the camera has been set to four ranges of wavelengths corresponding to the water vapour and carbon dioxide emission bands as it follows: 2.5-2.99 µm, 4.1-4.4 µm, 5.36-8.33 µm and 13.4-18.3 µm [7]. Than the emissivity has been adjusted until the indicated flue gas temperature value turned very closed to those obtained by the aspiration izo-kinetic thermocouples. Getting many values of the emissivity, some small adjustments of the Mitor relations have been performed.

Combustion tests have been realized on the 1 MW (thermal) pilot furnaces belonging to the Politehnica University of Bucharest, Thermal Research Centre (CCT), Figure 5, using pulverized Romanian hard coal. This installation is a very complex one allowing studying a lot of aspects concerning the combustion process of the pulverized coal in a very high degree of similitude with the industrial furnaces due to its initial conception. In this case, flame emissivity depending upon the soot concentration has been analyzed with a high accuracy.

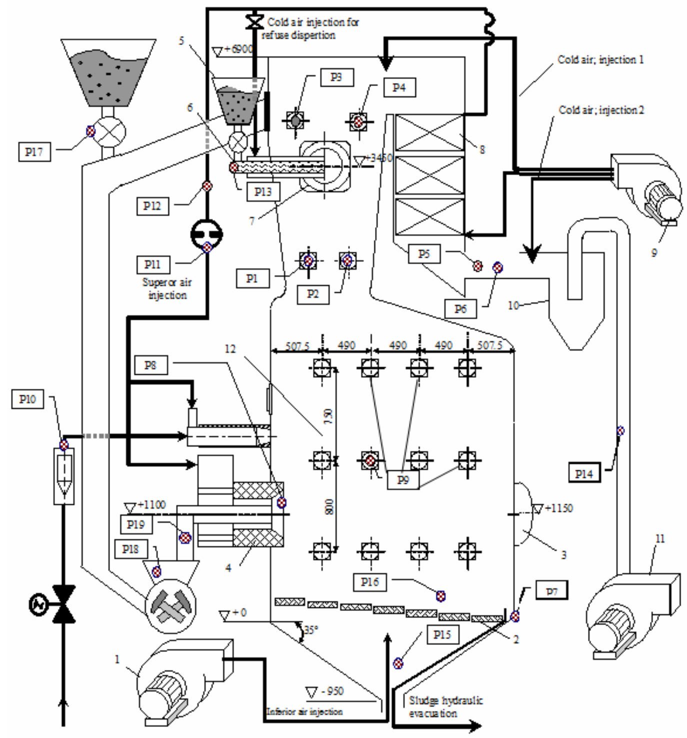

Figure 5 The 1 MW pilot furnace (all dimensions are in millimetres)

1) Cold air ventilator supplying the grate ; 2) Post combustion grate ; 3) Visit hole; 4) Main burner; 5) Secondary biomass bunker; 6) Secondary feeding installation; 7) Secondary feeding orifice; 8) Tubular air pre-heater; 9) Main air ventilator; 10) Flying ash separator; 11) Flue gas ventilator; 12) Combustion chamber; P9) – First HORIBA PG 250 sample; P2) – Second HORIBA PG 250 sample, flue gas temperature measurement; P1) – HORIBA MEXA 7000 gas analyzer to validate CO2, CO and O2 measurements; P8) JEROME J605 gas analyzer to measure H2S ; P17) – Crushed coal bunker; P18) – Ventilator mill.

The crushed coal is injected into the dryer tower (supplied with the hot flue gas from the end point of the furnace) towards the ventilator mill (P18). Pulverized coal is then led to the burner (4). The flame is developed inside the combustion chamber (12) till the up-end of the furnace. An air pre-heater (8) is positioned after the furnace. The flying ash is captured by the cyclone (10) installation and the cleaned flue gas is exhausted by the ventilator (11) to the stack. Two continuous HORIBA PG 250 flue gas analyzers have been installed to take the flue gas samples both from the combustion chamber (P9) and from the end of the furnace (P2), in order to measure the CO2, CO, O2, SO2 and NO within the combustion chamber. This type of gas analyzer is characterized by ±1% precision (from the full scale) for all the measured species, exception is SO2 where this value is ±2%. A HORIBA MEXA 7000 gas analyzer has been used to validate the CO2, CO and O2 species determination and also a JEROME J605 gas analyzer to determine the H2S content within the flue gas. This type of analyzer has a precision of ±0.3 ppm at every 5 ppm on the range of 1-10 ppm. The team has not measured the H2 content in the flue gas. Also a data acquisition system NI PXI-1000B 8-slot 3U PXI Chassis with 10-32 VDC, using an acquisition program developed on LabView platform has been used.

The infrared camera Cedip SILVER 420 has been installed to visualize the P9 and P4 observation windows. On the other side of the furnace (furnace deepness is about 1230 mm) an aspiration izo-kinetic thermocouple has also measured the flame temperature to achieve the reference value.

To build a user defined function to evaluate the emissivity factor of the flame in different cell-volumes of the furnace means to use some classic relations [5]:

$$\varepsilon_{fl} = 1 - e^{-kpL} \tag{1}$$

and k can be calculated using

$$k = k_g r_g + k_a \mu_a + k_c \tag{2}$$

For k_g, r_g and k_a there are clear relations to calculate as it follows:

$$k_g = \frac{7.8 + 16 r_{H_2O}}{\left(3.16\sqrt{p\left(r_{H_2O} + r_{CO_2} + r_{SO_2}\right)L} - 1\right)}\left(1 - 0.00037\, T_g\right) \tag{3}$$

$$r_g = r_{H_2O} + r_{CO_2} + r_{SO_2} \tag{4}$$

$$k_a = \frac{4.1}{p\sqrt[3]{T_g^2 d_a^2}}\left[1 - \frac{0.6}{1 + 0.0134 T_g^2 \left(\mu_a L\right)^{-2}}\right] \tag{5}$$

Regarding the μ_a, k_c and μ_c relations are not so simple to be used at the microscale of the mesh volume elements due to the fact that they are using elements depending upon the solid particles concentration:

$$k_c = \frac{10}{p\sqrt[3]{T_g^2 d_c^2}}\mu_c \tag{6}$$

$$\mu_c = \frac{5.5 C^i \left(10 + q_m\right)}{\left(100 + V^{mc}\right) V_g(\lambda)}\left(1 + \frac{\Delta H}{H_f}\right) \tag{7}$$

$$\mu_a = 10 \frac{a_{an} A^i}{V_g(\lambda)} \tag{8}$$

It is to be observed that the char particles concentration (μ_c) is a function of the excess of air (λ) in the flue gas. This parameter is varying along the height of the furnace, so is difficult to use it as a single value. By the flue gas measurements inside the flame space a certain function for the λ could be approached. Another difficult problem was to evaluate the mechanical heat loss q_m in the particular case of a certain type of burner. Using the pilot furnace with a similar swirling burner the value of mechanical heat loss could be determined, by measuring the total quantity of the sludge and flying ash, together with laboratory analysis of the unburned carbon inside. At the same time the transported ash fraction (a_{an}) has been also determined in the same manner. All those values that have been determined on the pilot installation have been validated using the infrared camera to verify that the emissivity factor calculated by the general relation (1) is quite the same with that one set on the camera.

CONCLUSION

After all these minor modifications of the furnace, the flame has fulfilled quite the whole volume of the furnace and the volumetric thermal load has been decreased. The flame temperature along the vertical path of the flue gas has been smoothed at a lower average value (Figure 3).

Nitrogen predicted concentrations for every analysed case are presented in Figure 4. The main conclusion can be considered to be that NOx corrected concentration around the value of 400 mg/ m_N^3 of flue gas can be obtained by a specific price of no more of 10 USD/kWe installed, without heavy modifications towards the existent burners and the pressure parts.

ACKNOWLEDGEMENTS

The work has been funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Romanian Ministry of Labour, Family and Social Protection through the Financial Agreement *POSDRU/107/1.5/S/76909.*

Authors want to express their gratitude to the whole technicians' team of Classical and Nuclear Thermal Equipment Laboratory from the Politehnica University of Bucharest for their help during the long sessions of experiments.

At the same time many thanks must to be addressed to the engineers from the Turceni Energy Group (Power Plant), Romania for their help during the validation stage of the work.

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