ANALYSIS OF THE FLAME FRONT GEOMETRY RESPECT TO THE NOX FORMATION

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Natural gas is one of the cleanest organic fuels, nevertheless it produces pollutants in combustion process. The major pollutants of the combustion in the atmosphere are carbon monoxide CO, nitrogen oxides NO, NO2, sulphur dioxide SO2 and hydrocarbons. Current article deals with the problematic of the high NOx formation rates under the high power operation. The object under research was middle pressure natural gas boiler with the power of 35 MW. The reason of high NOx formation rate was eliminated due to primary deNOx methods.

KEYWORDS

Boiler, burner, heating, natural gas, ANSYS

1. INTRODUCTION

Natural gas is the most common fuel nowadays [Rimar 2014]. The process of burning gas is a chemical reaction in which natural gas interacts with oxygen, which is contained in the air [Smeringai 2015]. In the gaseous fuel there is a combustible and non-combustible parts [Smeringai 2014].

To ensure high-quality gas combustion, it is necessary to supply sufficient air to the combustion zone and achieve good gas mixing with air [Varga 2015]. The optimum ratio is approximately 1:10 [Rimar 2013]. Such significant ration is a results high N2 concentration in the air [Tolias 2018].

The major pollutants of the combustion in the atmosphere are carbon monoxide CO, nitrogen oxides NO, NO2, sulphur dioxide SO2 and hydrocarbons [Panda 2014]. The most toxic emissions are nitrogen oxides [Dzurnak 2015]. The largest component of natural gas is methane, a compound with one carbon atom and four hydrogen atoms (CH4). Natural gas also contains smaller amounts of natural gas liquids (NGL; which are also hydrocarbon gas liquids), and nonhydrocarbon gases, such as carbon dioxide and water vapor.

The research subject of the current work is overlay of the flame fronts in the combustion chamber in the two burners system.

2. MATERIALS AND METHODS

2.1 Equipment description

The subject under research is the 35 MW boiler with two equal 17.6 MW burner installed in the horizontal axis of the combustion chamber.

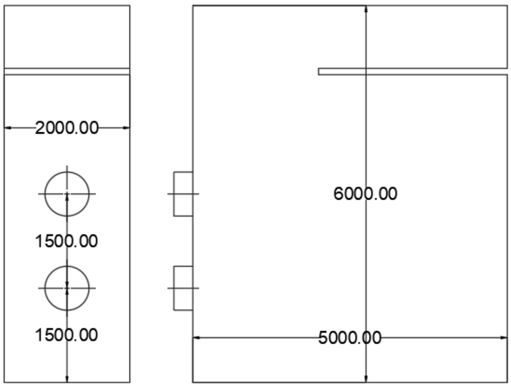

Figure 1. Model of boiler

The technical parameters of the boiler and burners are at the table 1.

Table 1. Technical parameters of the boiler

Boiler type	Middle pressured
Manufacturer	ČKD Tatra Kolín
Highest overpressure	4.5 MPa
Nominal overpressure	3.8 MPa
Designed overpressure	4.0 MPa
Hearth type	over pressure
Nominal steam output	40 t.h-1
Efficiency at nominal parameters	90%
Fuel	NG/HFO
Minimum output	10 t.h-1
Nominal steam temperature	720 K
Nominal feed water temperature	420 K
Burner type	VKH-17.8-1P
Manufacturer	HT a.s.
Nominal thermal output	17.6 MW
Gaseous fuel NG consumption	1 750 m3.h-1
Nominal pressure of gaseous fuel – NG	50 kPa
Liquid fuel HHO consumption	1.6 t.h-1
Nominal pressure of liquid HHO fuel	3.2 MPa
Number of air fans	1
Output of air fans	2 x 12 m3.s-1
Output of smoke fan	37.6 m3.s-1
Designed under pressure in the hearth	20 Pa
Combustion air temperature	475 K
Number of burners	2

Burner type	VKH 17.6 1P
Gaseous fuel consumption	1 820 Nm3.h-1
Burner regulating range at gaseous fuel	1:5
Gas overpressure before the burner	100 kPa
Combustion air pressure	1 600 Pa

2.2 Model creation

The simulations of the two burners combustion chamber were made in ANSYS Fluent 19.0. The geometry of the model was made in ANSYS DesignModeller according to the technical and geometry parameters of the burners and boiler. The redrawn geometry was simplified to decrease the numbers of the nodes and elements in the mesh to reduce calculation time of the simulation [Krenicky 2010]. Nevertheless, any changes in the geometry does not influence thermodynamics or chemistry processes in the boiler [Jandacka 2015].

2.3 The mesh

The mesh was developed in ANSYS for the CFD Fluent solver with proximity and curvature advanced size function [Deshpande 2017]. Owing to the differences of the input and output dimension proximity minimum size was selected as 1.6 mm while the maximum was 500 mm [Song 2018]. The growth rate parameter was applied at 1.30 [Saini 2018]. The quality of mesh was next: 75% of all elements had orthogonal quality more than 0.78 while the lowest rate was 0.41 at less than 1% of the elements, the worst skewness of the grid was 0.65 at less than 8% of the elements [Garre 2018]. According to that parameters the quality of mesh was appropriate for the simulation without dependences on the calculation results [ANSYS 2019]. Total number of the elements in the model mesh is 10 118 163. Example of the generated mesh is in the figure 2.

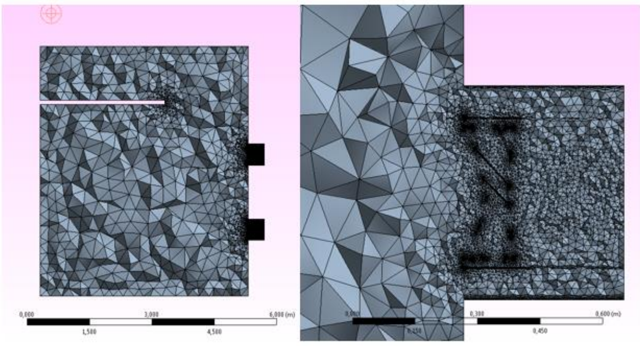

Figure 2. Generated mesh

When defining the turbulence model, verification simulations were implemented using integrated modules RANS and then LES. The results of the boiler simulations showed that from the point of view of the calculation stability, the realizable k-epsilon model, which was also applied for the simulations, was the best.

The solved transport equation for the realizable k-epsilon model has the following form:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}(\rho k u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \tag{1}$$

and

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_j}(\rho\varepsilon u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+\rho C_1 S_\varepsilon-\rho C_2\frac{\varepsilon^2}{k+\sqrt{\varepsilon v}}+C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b+S_\varepsilon \tag{2}$$

Where

$$C_1=max\left[0.43,\frac{\eta}{\eta+5}\right],\eta=S\frac{k}{\varepsilon},S=\sqrt{2S_{ij}S_{ij}} \tag{3}$$

- In these equations, G_k represents the generation of kinetic energy of turbulence due to mean velocity gradients.
- G_b is the generation of kinetic energy by turbulence considering buoyancy.
- Y_M represents a manifestation of fluctuating dilation in compressible turbulence to the overall scattering rate.
- $C_{1\varepsilon}$, $C_{3\varepsilon}$, and C_2 are constants.
- σk and σε are turbulent Prandtl numbers for k and e.
- S_k and S_ε are user-defined source formulas.

The transport equation PDF is derived from the Navier-Stokes equation as (Smeringai 2014):

$$\frac{\partial}{\partial t}(\rho P)+\frac{\partial}{\partial x_i}(\rho u_i P)+\frac{\partial}{\partial \psi_i}(\rho S_k P)=-\frac{\partial}{\partial x_i}\left[\rho\langle u_i^{''}|\psi\rangle P\right]+\frac{\partial}{\partial \psi_i}\left[\rho\left\langle\frac{1}{\rho}\frac{\partial J_{i,k}}{\partial x_i}\middle|\psi\right\rangle P\right] \tag{4}$$

Where

P – common composition of PDF and Favre,

ρ – average liquid density,

u_i – Favre velocity vector,

S_k – rate of reaction of k elements,

ψ – space composition vector,

$u_{i''}$ – vector of fluid velocity fluctuation,

J_{ik} – molecular diffusion flow vector.

Notation ⟨…⟩ indicates expectations, and ⟨A|B⟩ is the conditional probability of event A when event B occurs.

The turbulent scalar flow is not closed and is modelled by the assumption of diffusion gradient transition (Song 2012):

$$-\frac{\partial}{\partial x_i}\left[\rho\langle u_i^{''}|\psi\rangle P\right]=\frac{\partial}{\partial x_i}\left(\frac{\rho\mu_t}{Sc_t}\frac{\partial P}{\partial x_i}\right) \tag{5}$$

Where

µt is turbulent viscosity,

S_{ct} is Schmidt number.

The Turbulence model specifies µt for the composition of PDF simulation.

The inlet boundary conditions for turbulence parameters were chosen through determination of turbulent intensity what depend on the Reynolds numbers.

Better analysis of chosen model was made in earlier studies [Rimar 2016]. The convergence of calculation was archived approximately after 9500 iterations, when the parameters of continuity, velocity, energy, temperature, radiation, NOx and other reduced min. under 10^{-5} [ANSYS 2019].

3. SIMULATION

To understand the thermos mechanical processes inside the boiler simulation of the non-premixed combustion was made. All input physical parameters were chosen according to the normal operation conditions of the boiler and the burners.

The PDF (Probability density function) settings were made according to the air fan normal operation conditions and natural gas composition according to the SPP (Slovak gas industry) report [Dobakova 2018]. The natural gas composition is at the table 2.

Table 2. Natural gas composition, (%)

Methane	Ethan	Propane	Bethan	Nitrogen	Other
95.3658	2.4716	0.6724	0.1007	0.8131	0.5764

Results of the reference simulation are at the figure 3 (temperature contours), figure 4 (NO mass fraction).

At the upper part of the figure 3 are shown temperature contours in XY axis, at the lower part of the figure 3 are shown temperature contours in ZX axis. The maximum flame temperature in the combustion chamber is 2229 K, while the volume average temperature is 1900K.

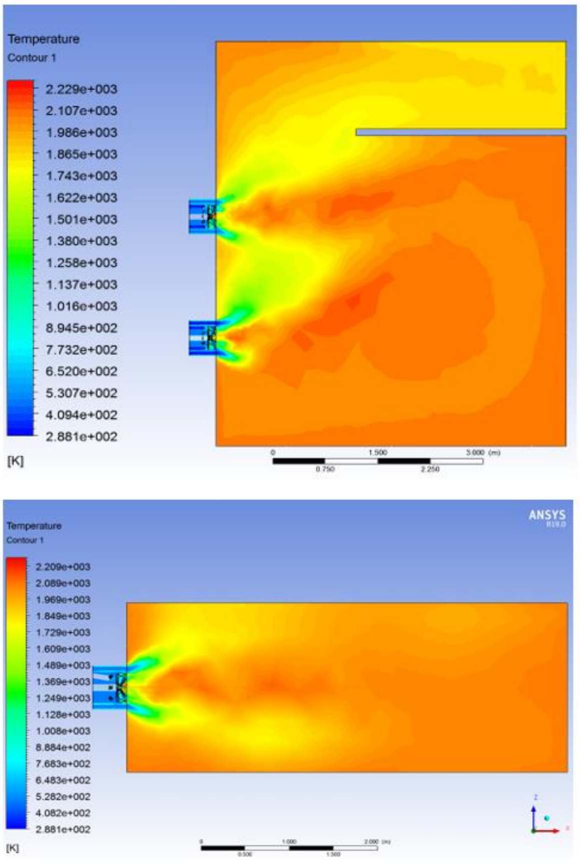

Figure 3. Simulation results. Temperature contours

According to the Arhenius formulation of the thermal nitrogen oxides formation the critical internal temperature is 1500K. Above this temperature NOx production raise exponentially.

Nevertheless, the reduction of the internal temperature under critical will lead to the reduction of the power and then production efficiency of the boiler.

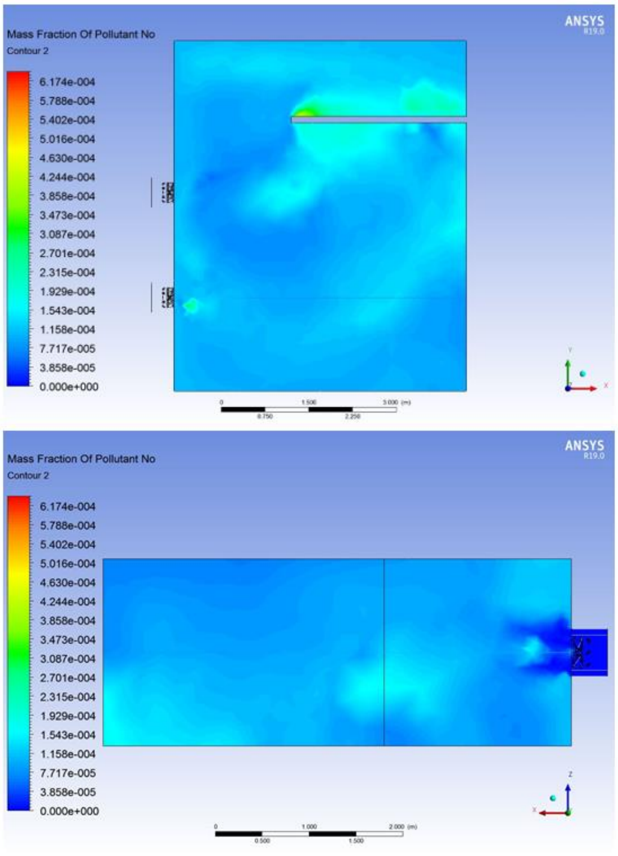

Figure 4. Simulation results. NOx Mass Fraction

Figure 4 represents mass fraction of the NO. Maximum concentration of the NOx in the boiler is 193 mg/m^3. The average concentration inside the combustion chamber is 124 mg/m^3, concentration at the exhauster is 138 mg/m^3. From the EU legislative the maximum possible NOx exhausting for such thermal equipment is 250 mg/m^3 (taking to account year of reconstruction and burners type).

According to the results the most of the NO is produced at the end of the flame, close to the wall and at the area at the end of flame fronts. As it is represented in the figure 4 the thermal NOx are the main source of the pollutants. According to the simulation results approximately 70% of NOx inside the combustion chamber were produced via thermal NOx production scheme, while via the rapid and fuel were produced 25% and 5% accordantly.

The main problem of the high NOx production is the flames conjunction in vertical axis. Such conjunction lead to the increasing of the temperature at the end of the flame fronts. To disconnect the flames was proposed to use primary deNOx methods. As an advantages of the primary methods are minimum impact to the power of the boiler and relatively small investments. As the most appropriate were chosen next steps:

- Change the natural gas distribution between the burners – increase the power of the upper burner by 3% and decrease the power of the lower burner by 3%
- Change the combustion air ratio at the lower burner – the basic ratio was 70% of primary to 30% of secondary air, the new ration 65% of primary air to 35% of secondary air.

The results of the simulation with the new combustion parameters are at the figure 5 (temperature contours), figure 6 (NO mass fraction).

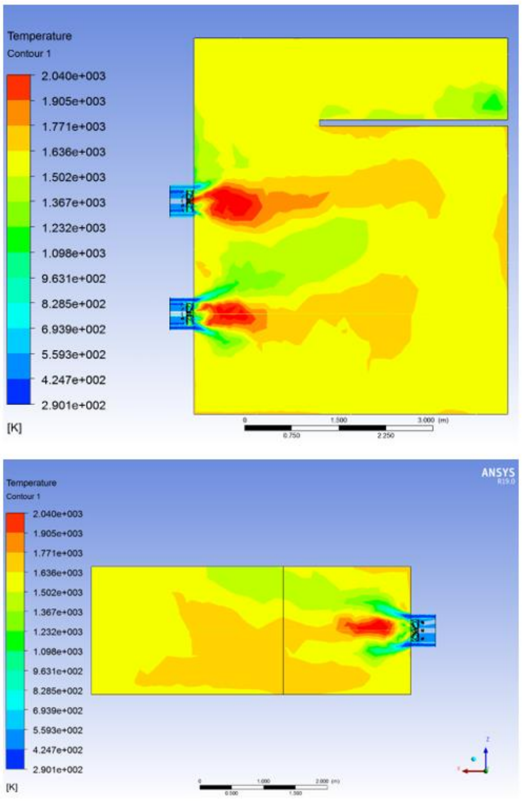

Figure 5. Simulation results. Temperature contours

At the upper part of the figure 5 are shown temperature contours in XY axis, at the lower part of the figure 3 are shown temperature contours in ZX axis. The maximum flame temperature in the combustion chamber is 2041 K, while the volume average temperature is approximately 1800K.

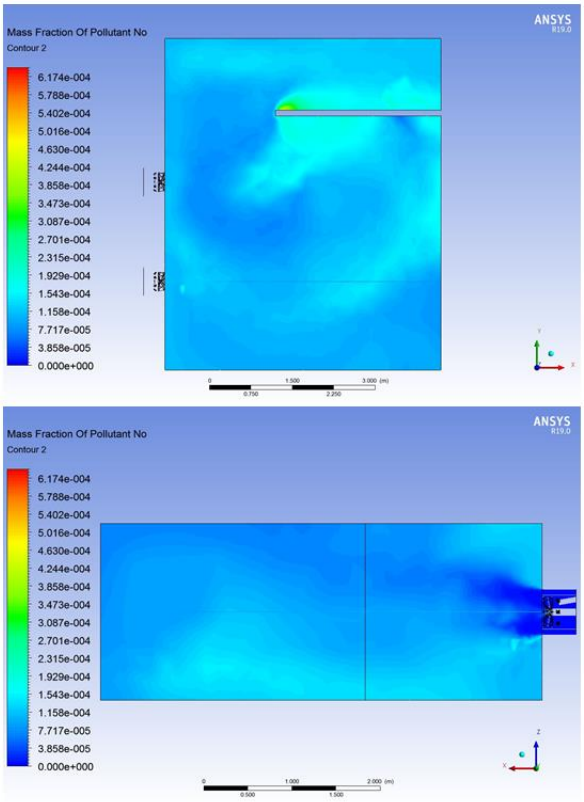

Figure 6. Simulation results. NOx Mass Fraction

Figure 6 represents mass fraction of the NO. Maximum concentration of the NOx in the boiler is 113 mg/m^3. The average concentration inside the combustion chamber is 84 mg/m^3, concentration at the exhauster is 82 mg/m^3.

According to the simulation results NOx concentration at the exhauster of the boiler reduced by almost 40% to 82 mg/m^3 while the power of the boiler decreased only by 5% to approximately 33.5 MW.

To validate the results of the simulation the real measurements were made according to the new combustion parameters. The results of the measurements are at the table 3.

Table 3. Measurement results

Time	Power, MW	NOx [mg./m^3]	CO [mg./m^3]	CO_2 [%]	O_2 [%]
9:45-10:15	33.5	80	1	3.45	3.34
15:00-15:30	33.4	79	1	3.32	3.29

According to the measurements results and difference between the simulation and confirmed assumptions and efficiency of the proposed methods. The different between the simulation and real measurement was approximately 1-2%.

4. CONCLUSIONS

The theoretical and experiential knowledge which you can read above allow understanding and predicting the thermal NOx formation as well as the methods of their reduction.

Simulations also confirm the mechanism of the NOx formation according to the Arrhenius formulation in the thermal equipment with high thermal load of the combustion chamber. To decrease the NOx concentration in exhausted gases was proposed:

- Change the natural gas distribution between the burners – increase the power of the upper burner by 3% and decrease the power of the lower burner by 3%
- Change the combustion air ratio at the lower burner – the basic ratio was 70% of primary to 30% of secondary air, the new ration 65% of primary air to 35% of secondary air.

Implementation of these steps allowed reduce NOx concentration by almost 40% to 82 mg/m^3 while the power of the boiler decreased only by 5% to approximately 33.5 MW.

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