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Experimental Study on NO_x Formation in Gas-staged Burner Based on the Design of Experiments

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The presented paper is focused on the experimental study of the influence of combustion operating conditions and burner constructional parts on the formation of nitrogen oxides. The combustion tests were carried out at the large-scale burners testing facility that enables to test the burners up to the heat output of 1,800 kW. The tested burner was the low-NO_x type burner, namely the two-staged gas burner.

The paper describes in detail the tested burner and the parameters which were changed during the combustion tests. Since the number of parameters was high and if the tests were carried out for all mutual combinations of parameters, the scope of experiment would be disproportionately large, expensive and time consuming. For that reason the combustion tests were carried out according to the sophisticated statistical approach called the design of experiment. Based on the acquired experimental data the mathematical model predicting NO_x concentration in flue gas depending on the investigated parameters was developed.

1. Introduction

The combustion of fossil fuels is a primary source of air pollution. One of the key pollutants nitrogen oxides (NO_x) are considered. In terms of rising regulatory emission limits, improvement of currently used combustion methods and development of new and alternative technologies are necessary. Nowadays, numerous technologies are available to control NO_x formation. A wide array of reviews is available on the subject of NO_x abatement, e.g. (Normann et al., 2009) or (Hill and Smoot, 2000). The primary NO_x-control techniques are based on combustion process modifications. The main targets of these techniques are the reduction of high temperature peaks and of the residence time, and the creation of oxygen deficient stoichiometric conditions (Baukal, 2004). The techniques include fuel-staging (Bebar et al., 2002), air-staging (Ballester et al., 2008), fuel-reburning (Smoot et al., 1998) and flue-gas recirculation (Liuzzo et al., 2007). On the other hand the secondary NO_x-control technologies are applied downstream of the combustion process. The disadvantage of these techniques is the requirement of additional equipment and additives. Two most common secondary techniques are selective catalytic reduction and selective non-catalytic reduction (Radojevic, 1998).

The present work was undertaken to investigate more thoroughly the effects of fuel-staging. The fuel staging is one of the most effective methods for reducing NO_x. Generally, the reduction ranges from 50 % to 60 %. As the key parameter influencing the behaviour of burner is the distribution of fuel between the primary and secondary (in some cases even tertiary) nozzles. It holds that the higher fraction of secondary fuel is, the lower NO_x is formed. However, below a certain value of primary fuel fraction the combustion becomes unstable, since the primary flame acts as a pilot flame for the secondary stage.

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The further research of the workgroup is going to be focused on another combustion technology, namely on oxygen-enhanced combustion - OEC (Baukal, 1998). Partial substitution of combustion air with high purity oxygen is beneficial for many reasons like increase of adiabatic temperature of flame, fuel savings; decrease of volume of produced emissions, higher product quality and better flame properties. Disadvantages of OEC are mostly attributed to more intensive combustion. The most significant disadvantage is increase of NO_x emission in slight increase of concentration of oxygen on air due to rising flame temperature consequently speeding up NO_x formation. However, subsequent increase of oxygen concentration decreases concentration of nitrogen in air and therefore NO_x formation.

2. Experimental setup

2.1 Burners testing facility

The combustion tests were carried out at the burners testing facility (Figure 1). The key apparatus of the facility is the two-shell horizontal water-cooled combustion chamber with the inner diameter of 1 m and the length of 4 m. The cooling shell of chamber is divided into seven individual sections with independent supply of cooling water. Each section is equipped with sensors for measurement of cooling water flow rate, inlet and outlet temperature. This unique construction enables to partially simulate conditions similar to the ones in fired process heaters and to assess the heat transfer to combustion chamber wall lengthwise the flame.

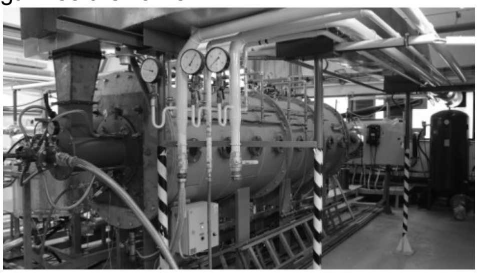

Figure 1: Water-cooled combustion chamber in burners testing facility

Flue gas is exhausted from the combustion chamber through the flue gas stack where three measurement and sampling spots are located for measuring of pressure in the combustion chamber, flue gas temperature and pollutant concentration. Flue gas is sampled from the flue gas stack using a probe connected via pipe to flue gas analyzer TESTO 350-XL. Analysis box is equipped with electrochemical sensors for determination of concentrations of O_2, CO, CO_2, NO, NO_2, SO_2 a C_XH_Y.

2.2 Burner

The burner used in the experimental study was two-staged burner fired by natural gas. The 3D model of burner is shown in Figure 2. The gas inlet consists of twelve primary nozzles and eight secondary nozzles. The primary nozzles are drilled in the primary nozzle head and are aligned in two circular sets. There are four nozzles with the diameter of 3.0 mm in the first set and eight nozzles with the diameter of 2.6 mm in the second set. The maximum heat output of the primary stage is regulated by the exchangeable primary gas throttle of different diameters. The throttle is placed before the inlet to the burner as it is marked in Figure 2.

The secondary gas inlet is provided by four nozzle heads that may have different pitch angles of head. Each head has two nozzles with the diameter of 3.3 mm. The burner is constructed so that it is possible to change the position of nozzle heads towards the burner tile, namely in axial, tangential and radial direction. In the reference tangential position the nozzle heads are oriented directly towards the burner axis. It is possible to change the orientation both clockwise (in the direction of flame's swirl motion – positive angle) and counter clockwise (negative angle).The burner is equipped with the so-called swirl generator that ensures the turbulent flow of incoming combustion air. The geometry of swirl generator is described by two parameters – its diameter and pitch angle of blades.

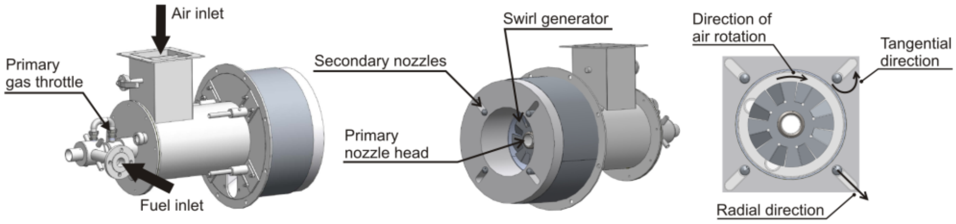

Figure 2: Model of two-staged gas burner

3. Experimental plan for burner testing

This study applies the statistical methodology called Design of Experiments (Montgomery, 2009) to evaluate the influence and the significance of various parameters on NO_x formation. The methodology distinguishes so called design variables (factors) which are varied throughout individual combustion tests and response variables which are measured and are supposed to be influenced by different factors.

Table 1 gives nine factors (two combustion operating conditions and seven burner constructional parameters) that were chosen and systematically varied during the combustion tests. As the response variable was measured the concentration of NO [ppm] in dry flue gas.

Table 1: Investigated factors

Factors		Factor's unit	Factor's level		
			Lower	Middle	Upper
X_1	Burner heat output	[kW]	740	930	1120
X_2	Air surplus	[-]	1.1	1.15	1.20
X_3	Diameter of swirl generator	[mm]	240	260	280
X_4	Pitch angle of swirl generator blades	[°]	35	45	55
X_5	Diameter of primary gas throttle	[mm]	5.5	6.0	6.5
X_6	Pitch angle of sec. nozzles	[°]	20	30	40
X_7	Tangential orientation of sec. nozzles	[°]	0	+22.5	+45
X_8	Radial position of sec. nozzles	[mm]	0	25	50
X_9	Axial position of sec. nozzles	[mm]	0	40	80

The objective of the experiment was to find the relationship (model) between the response and the factors, and then to optimize the response by locating the optimal operating conditions and burner setup. In order to find the relationship the Response surface methodology, which is very effective for most engineering applications, was implemented.

Since the curvature effects were supposed in the system, e.g. the dependence of NO_x formation on air surplus, the experimental data had to be fitted to the polynomial of higher degree, namely of the second degree. In order to detect the curvature the experimental design requires at least three levels for each factor. The so called face-centred central composite design was selected for the experiment. The main advantage of this design is that it enables to construct the second-order model without a need to carry out the full three-level factorial experiment and therefore less runs have to be carried out. The proposed design consisted of three parts that are following:

1. **Cube points:** forms the core of design. Here the core corresponds to the fractional factorial layout 2^{k-2}. Thus for k = 9 of input factors the number of cube points (corresponding to the number of test runs) is 128.
2. **Axial points:** are the points along the coordinate axis. The number of axial points is $2k$ = 18.

3. **Centre points:** are the points in the centre of design. Only one centre point was chosen in the design.

The structure of design gives 147 test runs without their replication. However, in order to estimate the experimental error, to increase the reliability of conclusion and to check the model adequacy, the basic experiment was replicated three times. The total number of test runs was then 441.

4. Results and discussion

The experimental data was fitted to the second-order model providing good approximation of the investigated region. After excluding of statistically non-significant terms based on the calculation of P-values for each of the terms, checking model adequacy and making analysis of residues, the model was developed. The coefficient of determination of model was R^2 = 85.6 %. The mean relative deviation between measured NO values and those predicted by model was approximately 6.5 %, at the maximum 27 %.

The results are interpreted graphically as the function of one of the factors. It is important to emphasize that the given amount of NO [ppm] is good when only one factor is in interest, while the rest of factors is kept at the fixed value, namely at the middle level. For this reason the given NO values have mainly informative character.

4.1 Burner heat duty and air surplus

Generally known influence of burner heat duty and air surplus on NO formation was proved by the experiment. It holds that with increasing burner heat duty the flame temperature peaks as well as the volumes of regions with high temperature increase. Both facts significantly support NO formation. As for the air surplus the maximum of NO formation was reached for α = 1.15. Next increase of the amount of combustion air resulted in significant decrease of flame temperature peaks due to flame cooling by ballast air and consequently in NO reduction.

4.2 Geometry of swirl generator

The geometry of swirl generator (Figure 3) influences the amount of air passing between the edge of swirl generator and the burner quarl (the diameter of burner quarl is 300 mm) in axial direction and the amount of air passing through the blades in tangential direction. It holds that the bigger the diameter of generator is, the larger amount of air enters the combustion space in rotation, which speeds up mixing of fuel with air. The combustion is then faster and more intensive, which results in higher temperature peaks and NO formation.

On the other hand simultaneously the more the blades are opened, the weaker swirl motion of air is generated and the less intensive the mixing of fuel with air is. Consequently NO is reduced. However, the experiment revealed that for pitch angle larger than 45° NO starts to increase again. It can be supposed that the increase signalizes the formation of prompt NO.

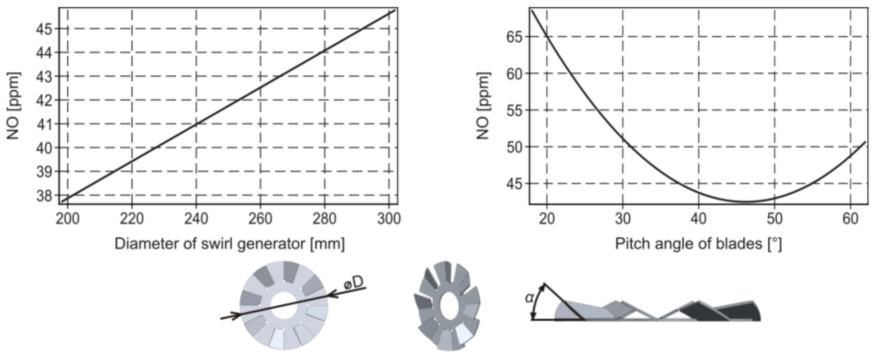

Figure 3: Influence of geometry of swirl generator on NO formation

4.3 Diameter of primary gas throttle

The experiment validated the positive effect of staged combustion on NO reduction. NO is decreasing if the ratio of secondary fuel is increasing (i.e. the diameter of primary gas throttle is decreasing). However, it is not possible to decrease the diameter of throttle to zero because very low flow rates of primary fuel can cause the flame instability. The problem with flame instability at low flow rates of primary fuel can be partially solved by the improvement of distribution of primary fuel into the combustion space, e.g. by high number of primary nozzles in burner head.

4.4 Geometry of secondary nozzles

If the nozzles with small pitch angle are used, the fuel is distributed for longer distance along the flame and the combustion runs slowly. However, if the fuel is injected directly into the flame core (i.e. large pitch angle), the fuel-air mixing and the combustion are more intensive and fast, and therefore NO formation is supported (Figure 4).

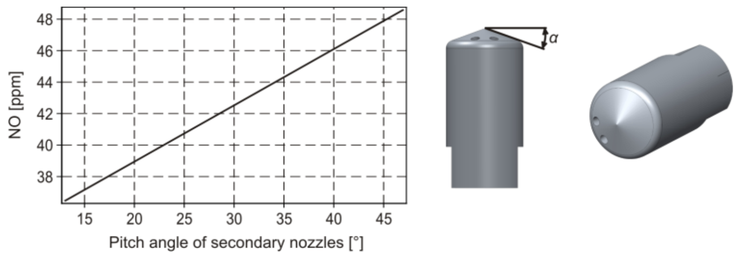

Figure 4: Influence of geometry of secondary nozzles on NO formation

4.5 Position of secondary nozzles

At the reference tangential orientation (0°) the NO formation reaches its maximum. Next increasing of position angle leads to NO reduction. This fact can be explained based on the secondary fuel distribution. At position angle 0° the fuel is injected directly into the flame core, the temperature peaks increases as well as NO. However, with increasing position angle the fuel is injected out of the main flame area, where the combustion is completed at decreased temperatures. At position angle 35° the NO formation starts to increase. The increase can be explained again based on the formation of prompt NO. The large orientation of secondary nozzles causes slow and/or imperfect mixing of secondary fuel with combustion air. As a result the regions rich for fuel are generated that are beneficial for prompt NO formation.

The increase in radial position of nozzles from the burner axis had the positive impact on NO reduction. It is caused by that the time of fuel burn-out was extended and simultaneously temperature peaks were decreased. If the nozzles were placed further from the burner axis (approximately 230 mm from burner axis), the volume of flame significantly expanded and the flame contacted the walls of combustion chamber. This fact is, however, inadmissible from the view of chamber construction.

The change of axial position had minimal impact on NO formation and for this reason the influence of this factor can be neglected. Moreover the insertion of nozzles far into the combustion space would shorten their lifetime period as a consequence of high temperatures.

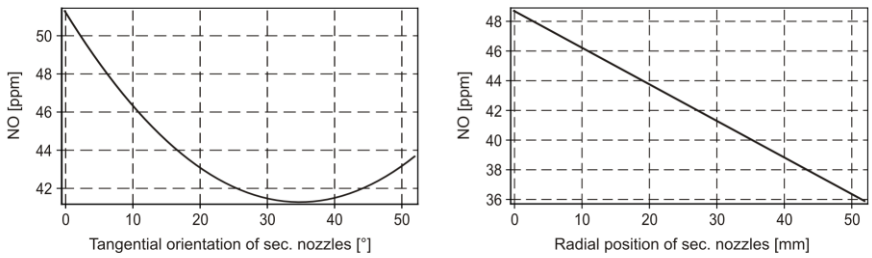

Figure 5: Influence of position of secondary nozzles on NO formation

5. Further research

Further work is going to be focused on the study of the influence of volume fraction of oxygen in combustion air on NO_x formation. First the oxygen content in the combustion air will be increased by the oxygen injection directly into the incoming air stream before entering the burner. Then the method of oxygen lancing into the combustion space will be applied. The combustion tests will focus on the assessment of the impact of oxygen content in the combustion air (> 21 %) on the heat transfer to the combustion chamber wall, the flue gas temperature, the geometry and the stability of the flame, the NO_x emission formation and last but not least on the amount of the consumed fuel per unit of released heat so that the financial assessment may be also performed.

6. Conclusion

In the present study, the NO emission characteristics were experimentally investigated in two-staged gas burner. The experimental plan included high number of burner setups and operational conditions. Based on the measured data the mathematical model was developed that enables to predict NO_x concentration in flue gas based on input parameters. The disadvantage of the model is that it can be applied only for this type of burner and does not give any information about shape and stability of flame. However, the acquired curves are generally true from the qualitative view. The model also enables to find the optimum setup of burner geometry and operational conditions.
In conclusion it can be claimed that the use of fuel-staging is well-founded and can be recommended as the technique for NO_x reduction. Moreover by the application of fuel-staging the shape and the dimensions of flame can be influenced according to the requirements of the particular facility, which the burner should be installed in.

Acknowledgements

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