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Experimental Study on NO_x Formation in Gas-staged Burner

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The paper deals with the experimental investigation of combustion operating parameters and burner's constructional parameters on the formation of nitrogen oxides. The tests were performed using the burner prototype with the maximal capacity of 1.5 MW. The burner is both fuel-staged and air-staged. During the testing campaign, various geometries of secondary nozzles and their position towards the burner quarl, and various geometries of the so-called swirl generator were investigated. The observed parameters included NO_x and CO emissions, turndown ratio, flame stability, flame length and flame shape, heat transfer from hot flue gas to the combustion chamber's shell and the distribution of in-flame temperatures measured in the horizontal symmetry plane of the chamber.

The results showed that in cases when the minimum of NO_x emissions was reached, the flame instability was observed. When the length of flame was about 4 m, the NO_x emissions were low too, however, the heat transfer in the radiation section significantly decreased. Better results were obtained when the flame length was up to 2 m at the maximal burner capacity and the primary stage was highly fuel-lean while the balance of fuel was combusted in the secondary stage. The minimum NO_x was about 30 ppm.

1. Introduction

Due to rapidly growing energy consumption and increasing volume of pollutant emissions, the main objective in the field of industrial combustion for upcoming years is to improve the efficiency of combustion process and to reduce the emissions, especially the emissions of nitrogen oxides (NO_x). The main factors, which contribute to the NO_x formation, are the temperature of combustion air, combustion air excess, temperature peaks in the flame zone and long residence time of reactants in high temperature zones. Many review works on NO_x abatement have been performed recently, e.g., Normann et al. (2009), Hill and Smoot (2000). The common targets of all primary NO_x-control techniques are the reduction of high temperature peaks, creation of oxygen deficient stoichiometric conditions and short residence time of reactants in high temperatures zones (Baukal, 2004). The primary techniques have been investigated by many research groups and include (a) fuel-staging (Bělohradský and Kermes, 2012), air-staging (Ballester et al., 2008), flue gas recirculation (Liuzzo et al., 2007), and fuel-reburning (Smoot et al., 1998).

Swirl motion of combustion air is one of key burner design parameters that significantly influence the mixing intensity of fuel with combustion air and subsequently the flow pattern in the combustion chamber, in-flame temperatures distribution and NO_x formation. The swirling flow is particularly important for the flame stabilization. For example, Vondál and Hájek (2014) have been investigated the influence of swirl generator's geometry on the flow pattern downstream the swirl generator.

The aim of the present work was to optimize the current geometry of the mono-block automatic burner equipped with the standard burner head in terms of NO_x reduction, thermal efficiency increase and stable flame. Newly designed burner head utilizes both fuel-staging and air-staging, and the swirl generator for the flame stabilization. In the present work, the effects of fuel distribution between primary and secondary stage, position of secondary nozzle heads, combustion air distribution between primary and secondary stage and geometry of swirl generator on NO_x and CO emissions, flue gas temperature, heat flux distribution from hot flue gas to the wall of combustion chamber, in-flame temperatures distribution in the horizontal symmetry plane of the combustion chamber, and flame stability were investigated in detail.

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2. Experimental setup

2.1 Testing facility

The combustion tests were carried out at the burners testing facility located at Brno University of Technology. The key apparatus of the facility, shown in Figure 1, 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 thus enables to partially simulate conditions similar to the ones in fired process heaters and to assess the heat extracted from the hot flue gas to the combustion chamber wall lengthwise the flame. The chamber is equipped with eight inspection windows along the cylindrical part and two inspection windows on the rear side of the chamber opposite the burner. The windows can be used for the installation of additional measurement instrumentation (e.g., thermocouples) and also allow to observe the flame on the burner. Flue gas is exhausted from the combustion chamber through the flue gas stack where the measurements of pressure in the combustion chamber, flue gas temperature and flue gas composition (O_2, CO, NO, NO_2) are located. The detailed description of the testing facility can be found in the work of Bělohradský et al. (2014).

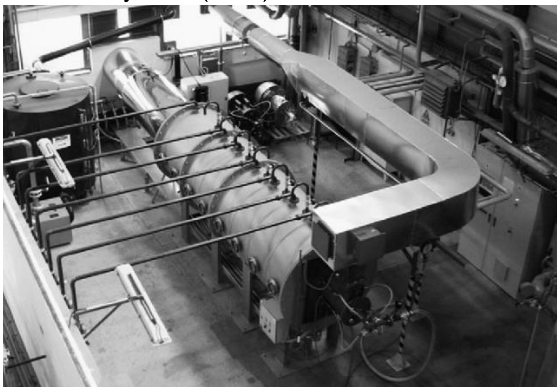


Figure 1: Water-cooled combustion chamber in burners testing facility.

2.2 Tested burner

The tested gas burner is shown in Figure 2. The burner is of a diffusion-mixed type fired with natural gas and its maximal capacity is 1.5 MW. Non-preheated atmospheric air is used as the oxidizer. The burner is designed as a mono-block and thus the air fan is a part of the burner's main body. This type of burners is a suitable source of heat for overpressure and under pressure applications, especially for steam and hot water boilers. Originally, the burner was designed with one-staged fuel supply and one-staged air supply. The standard achieved values of NO_x emissions were 50 - 70 ppm.

Within the scope of the research work a new burner head was designed to suppress NO_x formation. This new burner design enables two-staged supply of both fuel and combustion air (Figure 3). 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 six 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 thermal input of the primary stage can be regulated by the exchangeable primary gas throttle of different diameters placed before the inlet to the primary stage of the burner.

The secondary gas inlet is provided by four secondary nozzle heads with the varying pitch angle of head's tip from 0° to 30°. Each head has two nozzles. The first nozzle with the diameter of 6 mm is located on the pitched tip of the head. The second nozzle with the diameter of 2.3 mm is located on the cylindrical part of the head. It is possible to change the position of secondary nozzle heads towards the burner tile in tangential direction. In the reference tangential position the secondary heads are oriented directly towards the burner axis, i.e. angle 0°. The head's orientation can be changed both clockwise (i.e. in the direction of flame's swirl motion – positive angle) and counter clockwise (i.e. negative angle).

The burner is equipped with the flame holder that has the form of swirl generator. The swirl generator consists of six pitched blades and is mounted on the burner head.

The burner channel is split into two channels with the cylinder that is inserted between the pipes for secondary fuel and the swirl generator. The primary combustion air flows through the inner channel where the combustion of primary fuel also takes place. The combustion of primary and secondary fuel is then completed by the secondary combustion air that flows through the outer channel.

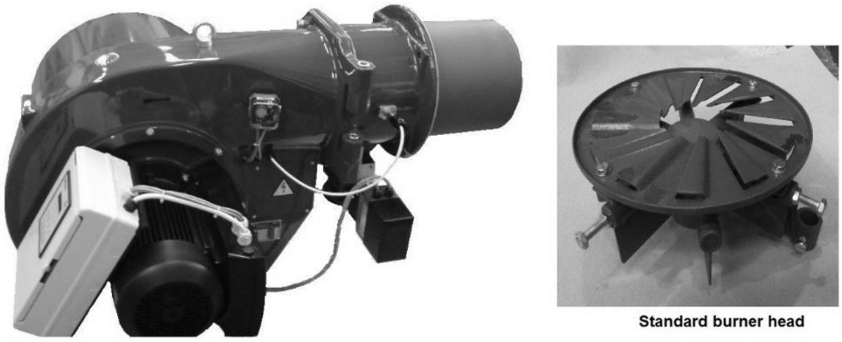


Figure 2: Tested mono-block burner.

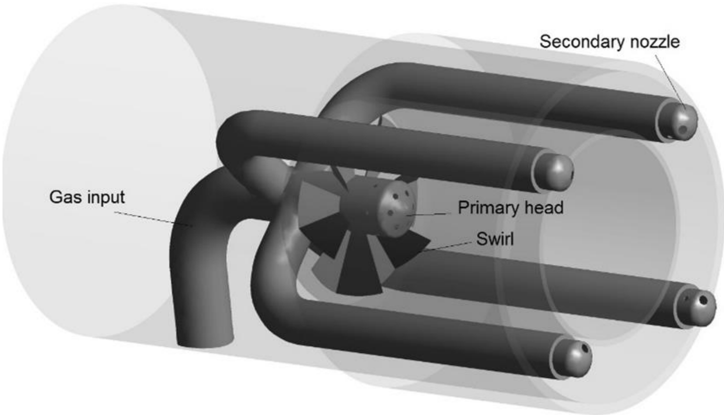


Figure 3: Detail of new burner head design.

3. Plan of combustion tests

The aim of combustion tests was to investigate the combustion quality and flame properties while changing various constructional burner's parameters and operating parameters. Measured and observed parameters included concentrations of NO_x and CO in dry flue gas, flue gas temperature, heat transfer from hot flue gas to the combustion chamber's shell, the distribution of in-flame temperatures measured in the horizontal symmetry plane of the combustion chamber, and the observation of flame stability, flame shape and its colour. During all tests, the target oxygen concentration in dry flue gas was kept at 3 % by volume (corresponding to air excess of 1.15) and the pressure in the combustion chamber was kept around -100 Pa.

The combustion tests were carried out both with the standard burner head and with the new burner head design. During the tests with the new burner head design, following parameters were varied:

- Pitch angle of swirl generator's blades: 30° and 45°.
- Pitch angle of secondary nozzle head's tip: 0° and 30°.
- Tangential orientation of secondary nozzle heads: 0° and 30°.
- Ratio of primary/total fuel: 0.17 and 0.2 (the ratio changed by the diameter of primary gas throttle).
- Ratio of primary/total combustion air: 0.5, 0.7, 0.75, 0.8 and 0.9 (the ratio changed by decreasing/increasing flow area of the secondary air channel).

4. Results and discussion

In Table 1 the results obtained during the burner testing with the standard burner head are summarized. The results show that NO_x emissions are within the range between 59 and 70 ppm. The efficiency of heat transfer in the radiation part of the chamber ranges from 48 % to 54 % and decreases with increasing burner capacity.

Table 1: Results from testing with the standard burner head.

Burner head	Burner capacity [kW]	NO_x [ppm]	Flame length [m]	Flame diameter [m]	Flue gas temperature [°C]	Heat transfer efficiency [%]
Standard	500	70	1.8	0.3	748	54.2
Standard	750	68	2.3	0.3	800	54.1
Standard	1,000	61	2.8	0.4	880	53.1
Standard	1,200	60	3.0	0.5	931	50.2
Standard	1,400	59	3.5	0.6	970	47.8

Table 2 summarises the results of tests with the new burner head design. First, the tests were performed using the secondary nozzle heads with the pitch angle of the tip equal to 30°. When the secondary heads were directed at the burner axis (i.e. the angle of rotation is 0°) and the secondary air channel was fully opened, NO_x emissions were ranging from 50 to 55 ppm (at 3 % O_2 in dry flue gas). When the tangential orientation of the secondary heads was set up to 30° and the secondary air channel was gradually closed, NO_x decreased to 44 ppm. During all tests, CO emissions did not exceed the value of 5 ppm, the flame was observed stable and was characterized with distinctly separated primary and secondary flames.

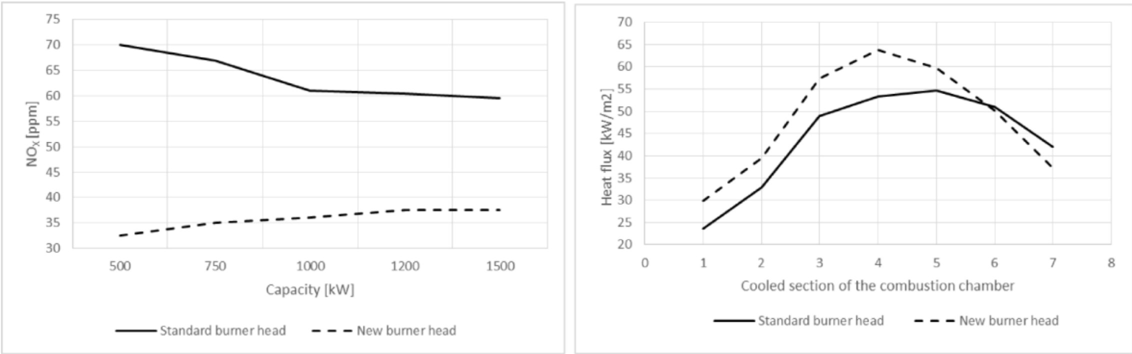
Moderate improvement was achieved when the angle of the tip of secondary heads was 0°. Then NO_x emissions decreased to 40 - 42 ppm. However, when the ratio of primary fuel was less than 0.2 or the ratio of primary air was higher than 0.8, the burning began to be unstable.

The burning stability was enhanced when the swirl generator with the pitch angle of blades of 45° was used. This enabled to operate the burner with the ratio of primary fuel less than 0.2 while keeping the burning stability. The redistribution of fuel between primary and secondary stage resulted in the reduction of NO_x to the level of 37 ppm. Further NO_x reduction (to 30 ppm) was achieved when the ratio of primary air was increased to 0.9, however, then the primary flame began to be unstable with the danger of blow-off.

The dependence of NO_x concentration on the burner capacity is displayed in Figure 4(a). When the burner capacity increases, NO_x has the descending behaviour for the standard burner head while NO_x slightly increases for the new burner head.

Table 2: Results from testing with the new burner head design.

Angle of swirl generator's blades	Ratio of primary fuel [-]	Pitch angle of secondary head's tip	Orientation of secondary heads	Ratio of primary air [-]	NO_x [ppm]	Flame length [m]	Flue gas temperature [°C]	Heat transfer efficiency [%]
30°	0.20	30°	0°	0.50	55	2.8	830	54.2
30°	0.20	30°	30°	0.50	55	2.5	820	55.0
30°	0.20	30°	30°	0.70	45	2.3	815	55.3
30°	0.20	30°	30°	0.80	44	2.3	817	55.9
30°	0.20	0°	0°	0.50	43	3.2	850	51.5
30°	0.20	0°	0°	0.75	40	3.0	830	54.1
45°	0.17	0°	0°	0.50	44	3.2	835	54.2
45°	0.17	0°	0°	0.75	36	3.2	835	54.1
45°	0.17	0°	0°	0.90	30	3.0	825	58.1
45°	0.20	0°	0°	0.50	48	3.2	833	56.2
45°	0.20	0°	0°	0.75	46	3.2	835	56.6
45°	0.20	0°	0°	0.90	44	3.0	830	56.6
45°	0.20	30°	0°	0.50	49	3.1	830	56.8
45°	0.20	30°	0°	0.75	45	2.9	828	57.2
45°	0.20	30°	0°	0.90	43	2.7	825	57.5



(a) (b)

Figure 4: (a) Comparison of NOx emissions for the standard and newly designed burner head, (b) distribution of heat fluxes for the standard and newly designed burner head.

Figure 4(b) shows the distribution of heat flux along the radiation part of the combustion chamber. The heat flux to the wall of each chamber's section was evaluated based on the measurement of cooling water flow rate, inlet and outlet temperature of cooling water. It is evident that the heat transfer rate was higher when the new burner head was used. This also corresponded to higher thermal efficiency.

Figure 5 shows the thermal field in the horizontal symmetry plane of the combustion chamber measured during the tests with the standard burner head. The-in-flame temperatures were measured using the water-cooled thermocouples of type R that were installed through the inspection windows. It is evident from the figure that the temperature peaks occur near the burner region in the core of the primary flame. It is generally known (Baukal, 2004) that the temperatures above 1,100 °C are favourable for the formation of thermal NO_x. For this burner configuration, the highest temperatures were about 1,350 °C and NO_x emissions were about 70 ppm.

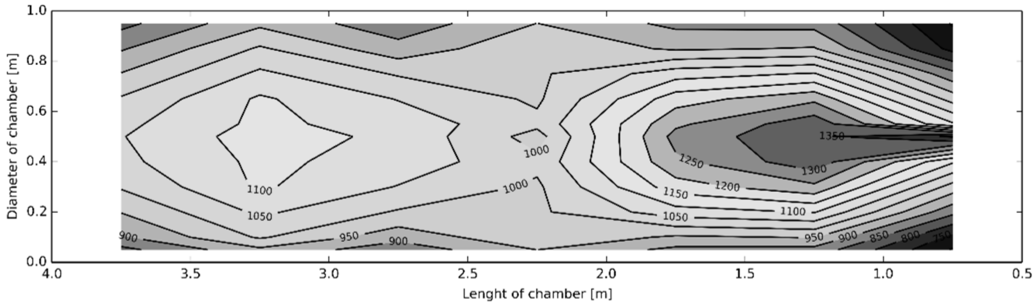


Figure 5: Temperature field for the standard burner head.

Figure 6 shows the thermal field measured during the tests with the new burner head design. The configuration of the burner was following: pitch angle of swirl generator's blades 45°, ratio of primary fuel 0.17, and pitch angle of secondary nozzle head's tip 0°. It can be seen that temperatures in the zone of primary flame are lower and distributed more widely compared with the temperature field of the standard burner head. Lower temperatures then contributed to lower NO_x formation.

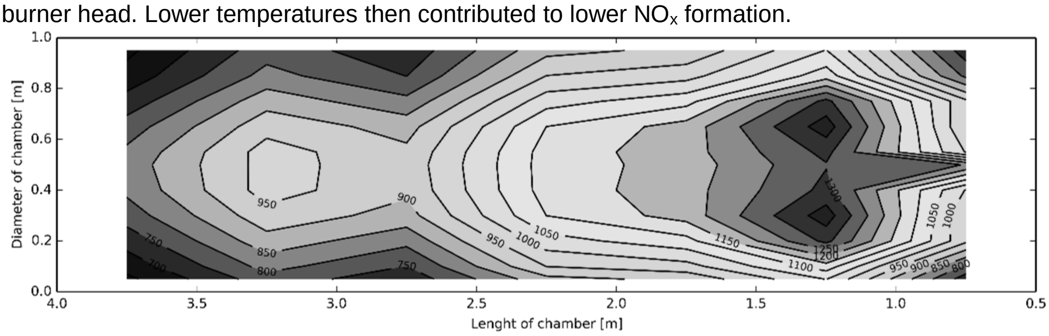


Figure 6: Temperature field for the new burner head.

5. Future work

The future work will be focused on the optimisation of burner geometry to achieve higher flame stability when the burner is operated with small ratio of primary fuel or high ratio of primary combustion air. The aim will also be to investigate the dependence of heat flux along the chamber's shell on the flame length and on the type of fuel.

6. Conclusions

The results showed that the fuel-staging and air-staging are efficient methods to suppress the NO_x formation. The NO_x reduction is achieved by decreasing of temperature peaks in the flame core and more uniform temperature distribution in the combustion chamber. This then resulted in higher heat transfer rate in the radiation part of the combustion chamber compared to the burner design without both low-NO_x methods. The lowest NO_x concentration was measured when the ratio of primary fuel was about 0.17 and the ratio of primary air was about 0.9. For this burner configuration NO_x was about 30 ppm. However, the flame was observed to be slightly unstable.

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References

Normann F., Anderson K, Leckner B., Johnsson F., 2009, Emission control of nitrogen oxides in the oxy-fuel process, Prog. Energy Combust Sci. 35, 385-397.

Hill S.C., Smoot L.D., 2000, Modelling of nitrogen oxides formation and destruction in combustion systems, Prog. Energy Combust Sci. 26, 417-458.

Baukal C.E., 2004, Industrial combustion pollution and control, Marcel Dekker, Inc., New York, USA.

Bělohradský P., Kermes V., 2012, Experimental study on NO_x formation in gas-staged burner based on the design of experiments, Chemical Engineering Transactions, 29, 79-84.

Ballester J., Sanz A., Gonzalez M.A., 2008, Investigation of the characteristics and stability of air-staged flames, Exp. Therm Fluid Sci. 32, 776-790.

Liuzzo G., Verdone N., Bravi M., 2007, The benefits of flue gas recirculation in waste incineration, Waste Manage. 27, 106-116.

Smoot L.D., Hill S.C., Xu H., 1998, NO_x control through reburning, Prog. Energy Combust. Sci. 24, 385-408.

Vondál J, Hájek J., 2014, Numerical Flow Field Prediction Downstream of Axial Guide, Vane Swirl Generator, Chemical Engineering Transactions, 39, 907-912.

Bělohradský P., Skryja P., Hudák I., 2014, Experimental study on the influence of oxygen content in the combustion air on the combustion characteristics, Energy 75, 116-126.