NO_x-Reduction in a Pressurized Pulverized Coal Flame by Flue Gas Recirculation

C. Fielenbach, Th. Holfeld, C. von Petery, U. Renz

WÜK, Aachen University, Germany

J.G. Wünning

WS Wärmeprozesstechnik GmbH, Renningen, Germany

1 Introduction

In recent years oil and gas burners with high flue gas recirculation rates have been successfully developed to reduce NO_x-emissions. The hot recirculating flue gas dampens the temperature fluctuation and reduces the maximum temperatures within the reaction zone. In literature this type of combustion is often called “flameless oxidation” (FLOX®[i]) or “high temperature air combustion” (Wünning, J.A., 2001, Weber, 2001).

An experimental investigation was carried out at Aachen University (RWTH Aachen) in cooperation with WS Wärmeprozesstechnik GmbH to find out if the flameless oxidation with low NO_x can be realized for a pressurized pulverized coal combustor, too. Based on the positive results with an oil burning device a modified swirl burner has been designed with a high primary air momentum entraining recirculating hot flue gas. Furthermore, a staggered air concept proved to reduce the NO_x-emission due to fuel nitrogen.

The tests were carried out in a Pressurized Pulverized Coal Combustor (PPCC) at Aachen University, which is a part of a research program to further develop combined steam and gas turbine power cycles using coal as a fuel. This pilot PPCC facility with a maximum thermal power of 400 kW has been built up in order to investigate the basic physical process of coal combustion under atmospheric and pressurized conditions. The combustor is designed with emphasis on optimum accessibility for optical and probe measuring techniques to determine e.g. emissions, gas and particle temperature, velocities and particle sizes.

This paper provides experimental and numerical investigations on FLOX combustion. The first part describes the experimental setup including the design of the FLOX burner. In the second part experimental and numerical results are presented with emphasis on the characteristic structure of the FLOX combustion. Finally, the potential of NO_x-reduction with this burner is shown.

2 Experimental Setup

2.1 PPCC Facility Aachen

The measurements were performed at the PPCC facility Aachen shown in Fig. 1. This facility can be operated at a maximum pressure of 10 bars and a thermal power of 400 kW. The diameter of the vertical furnace is 400 mm and the burner is placed centrally at the top of the combustion chamber. For heating up the combustion chamber and to ignite the coal, electrical heaters and oil firing is used. The furnace can be operated in dry ash and slag tap firing.

A special feature of the combustion chamber is the axially movable burner. The burner can be moved by a hydraulic system so that it is possible to map the entire flow field from one measuring plane. A detailed description of the PPCC facility can be found in Lockemann et al., 1999.

Main focus of the investigations at this facility is the combined steam and gas turbine process with Pressurized Pulverized Coal Combustion (PPCC). This concept promises a significant increase of the overall efficiency to 50 % and more (Renz 2000, Weber et al., 1993). Considering the economical and ecological benefits this technology shows a high potential in improving the generation of electrical power. However, problems such as the separation of the particles from the flue gas, the reduction of alkalis and the high NO_x-emissions have to be solved before a demonstration plant can be realized. Solutions concerning primary measures within the flame have been provided as results of the investigations at this facility.

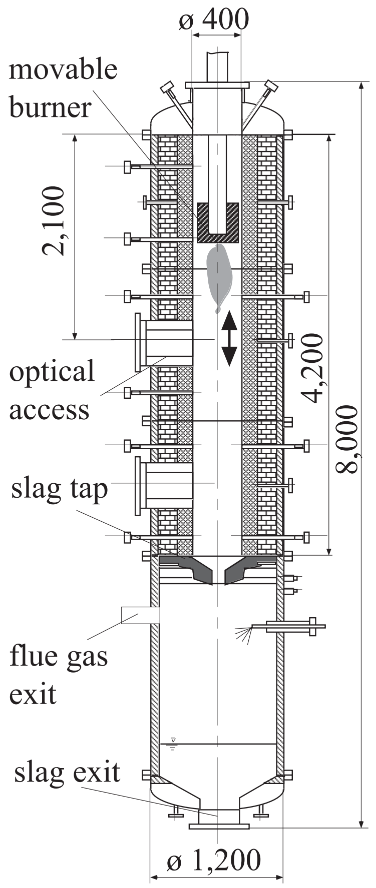

Fig. 1: Furnace of the PPCC facility Aachen

2.2 Burner Concept

Two different burners are shown in Fig. 2, the standard (reference) swirl burner and the FLOX burner. As a standard technique for a swirl burner three inlets exist to stage the combustion causing low NO_x-emissions (Weber et al., 1990, Bertolo et al., 1994). Due to the increased pressure level the proportions of the burner have been scaled down in comparison to an industrial burner. The primary air transports the coal into the furnace. The secondary stream induces a swirl and supplies further oxygen to the coal particles within the quarl causing a flow with internal recirculation zone. The tertiary air is used to stage combustion (Goerner, 1991, Smoot, 1993).

Contrary to this concept of a stabilized flame with a hot recirculation zone induced by swirl, the combustion zone of the FLOX burner is not stabilized in this way. One aim of the design is to suppress a stable flame front, thus avoiding zones of high temperatures. In the case of gas and oil burners a visible flame front can completely be prevented. Another aim is to dilute the reactants with inert gases before combustion takes place. This can be achieved by a high flue gas recirulation rate leading to reduced local temperatures. The FLOX burner shown in Fig. 2 is designed in order to increase the velocity of the central stream, including the primary air with coal and the secondary air, and of the outer six nozzles with tertiary air. These high inlet momentums lead to a delay of the mixing of fuel and oxidizer and to a high entrainment rate of flue gases. Thus, a delay of pyrolysis and char burn-out can be achieved.

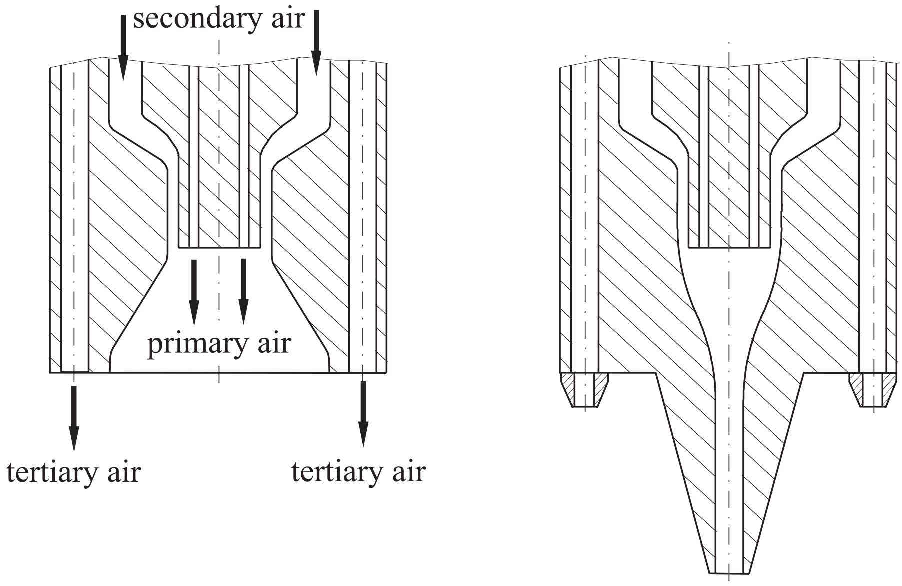

Fig. 2: Swirl (left) and FLOX burner (right) of the PPCC facility Aachen

2.3 Measurement Techniques

Several ports for measuring access exist at the combustion chamber. At the combustion zone there are four ports for optical and probe measurements (Fig. 3) and at the end of the combustion chamber there is another port to extract flue gas samples. The ports are equipped with a gate valve system. Thus, the windows can be cleaned and probes can be changed without interrupting the pressurized operation.

In order to measure emissions, there are two suction pipe probes. One of them is mounted on the same level as the optical ports (Fig. 3) and has access to the reaction zone. It can be traversed in order to measure radial profiles. Owing to the axially traversable burner it is possible to measure profiles on different axial positions of the flame. The second probe is mounted in the lower section of the combustion chamber. Samples can be taken from the axis of the furnace, enabling measurements at the end of the reaction zone. Both of the probes are connected to the same flue gas analysis system determining concentrations of CO_2, CO, O_2 and NO.

Velocity measurements were carried out using Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV). The Laser Doppler Anemometry permits non-intrusive measurements of axial and tangential velocities with high spatial and temporal resolution. It can be assumed that the slip between particle and gas is negligible as most of the particles are rather small. Because of the large working distance between the optics and the measuring position within the flow a single beam optics with single beam adjustment is used as a transmitting optics. Hence a reasonable small measuring volume of 0.15 mm diameter and 2.5 mm length can be obtained by increasing the beam distance (s = 210 mm). In order to reduce the effort of alignment a back scattering setup is chosen where transmitting and receiving optics are mounted on a single frame.

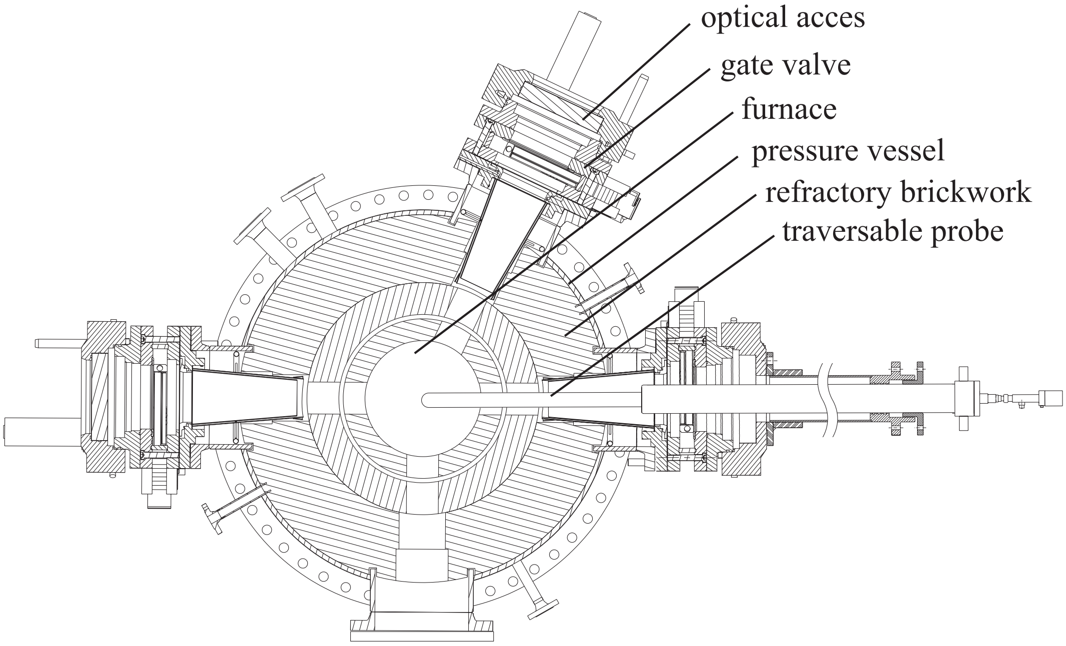

Fig. 3: Measurement ports of the PPCC facility Aachen

The Particle Image Velocimetry is a measurement technique that determines particle velocities as well. In order to examine the flow field a light sheet is formed by a laser beam passing through a lens system. During two short laser pulses particles in the plane of the light sheet are illuminated and images of the scattered light during each pulse are recorded with a camera. A mean displacement of the particles in the two images is determined for subareas by a statistical correlation examination. By dividing the displacement by the elapsed time between the two laser pulses the local velocity can be calculated thus giving the complete velocity field in the area of interest.

PIV and LDA measurements complement each other as radial and axial velocities are determined with the PIV system while the LDA system is used to gain tangential and axial velocities. While the short time needed by PIV to measure a whole velocity field is an advantage over the LDA measurement principle there is the disadvantage that the results obtained by the PIV system are neither temporal nor spatial as highly resolved as the ones obtained by LDA measurements.

Gas temperatures were measured with a traversable thermocouple in order to obtain radial profiles of the gas temperature. Due to temperatures of more than 1300 °C a PtRh/Pt thermocouple has to be used. As direct contact between thermocouple and flue gases or slag would damage the thermocouple it has to be protected. For this reason it is integrated in a two layer ceramic jacket. Under atmospheric conditions the traverse system can be demounted and thus the thermocouple can be replaced.

3 Mathematical Models

For gas phase and coal combustion calculations the standard FLUENT 6.0 solving procedures are used. The gas phase is calculated by the common conservation equations for mass, momentum and energy considering the turbulence by the k,ε-model. For simulating the chemical reactions within the gas phase an equilibrium model with probability density function (PDF) is employed.

According to the various physical processes during coal transformation such as devolatilization or char burnout the combustion process is separated into different stages which are calculated successively. The rate of devolatilization is being calculated with a single kinetic rate model which assumes that the mass flow released is first order dependent on the amount of volatiles remaining in the particle (Fluent, 2001). After complete devolatilization the char burns out in an heterogeneous surface reaction which is either controlled kinetically or by diffusive transport mechanisms (Smoot, 1993). During char burnout the carbon released is treated as a mass source term and the reactions to carbon dioxide are calculated within the gas phase. The parameters needed for characterizing and modeling the different processes of coal combustion are based on an analysis done from the coal used in the experiments.

For the calculations of the coal combustion process numerical grids with 90,000 to 430,000 cells were used. Because of the axial symmetry of the combustion chamber only a 60° sector with cyclic boundary conditions had to be considered.

4 Results and Discussion

For the measurements presented a bituminous coal from Poland and a Rhenish lignite, both ground to a particle size smaller than 50 µm were used. The particle size distribution was chosen because of the scaled down burner and combustion chamber geometry. The measurements were performed at a pressure of 3 bars and a thermal load of 100 kW in dry ash firing.

4.1 Modeling

During the preparation of the experiments a set of numerical calculations was performed to compare different geometries. As a reference case the burner depicted in Fig. 2 (left) was calculated for two different operation modes. Both modes, the swirl and the jet flame, can be achieved by increasing the amount of staged air while the other settings were kept constant.

They have proven to ensure a stable flame. Concerning NO_x-emissions, the jet flame has shown much lower values. The calculated temperature fields of these flames are presented in Fig. 4 together with those of two FLOX-burner geometries. The FLOX-3-burner corresponds to the burner shown in Fig. 2 (right). It becomes apparent that the ignition behavior of these flames is totally different. The swirl flame is stabilized by an inner recirculation zone, which leads to quite high temperatures on the furnace axis. The jet flame ignites much further downstream quite similar to the reaction of the FLOX-4-burner. These three cases can be characterized by at least one hot zone in the furnace, causing high thermal NO_x-emissions. Contrary to these cases, the reaction of the FLOX-3-burner does not show such hot zones. From an axial distance to the burner of approximately 500 mm onwards (even in greater distances, which are not plotted in Fig. 4) a uniform temperature distribution can be seen. Thus, a decrease of NO_x-emissions could be expected.

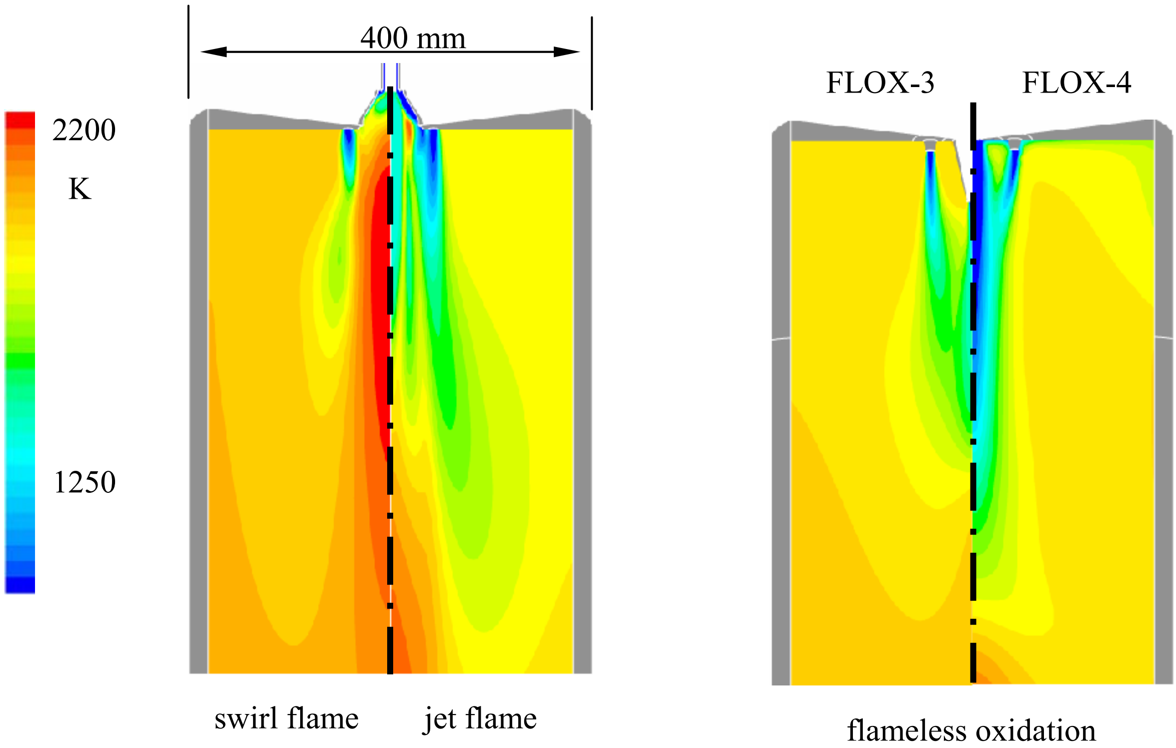

Fig. 4: Calculated temperature distribution of swirl and jet flame (left) and of FLOX combustion (right) (Hecken, 2003)

4.2 Structure of FLOX combustion

Although not compulsory FLOX combustion can often be characterized by its visible impression. Fig. 5 shows photographs of standard swirl and jet flames. In both pictures the reaction zone can be deduced from the bright areas in the photographs. The swirl flame is very bright in the prolongation of the burner nozzle. The jet flame has a dark zone in the middle of the flame, where the coal is injected. Around this zone reactions take place.

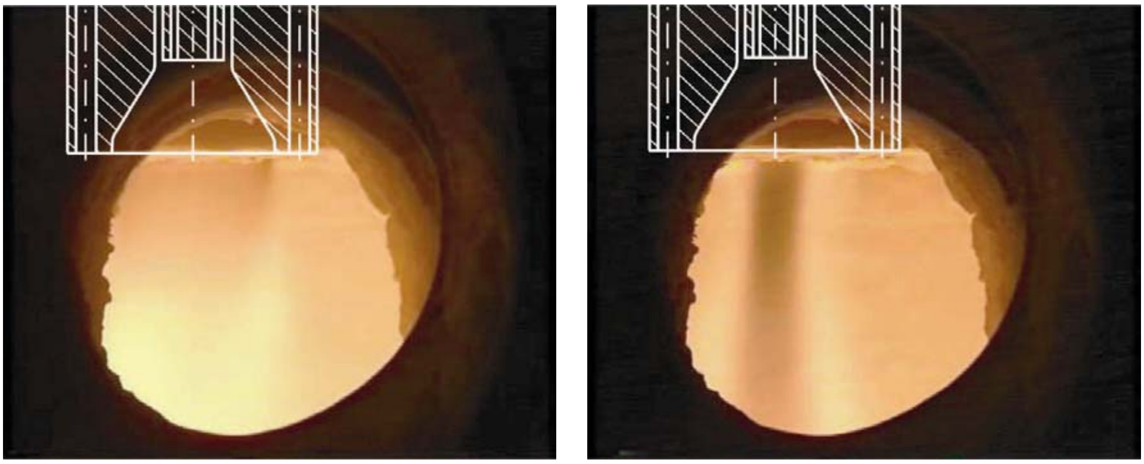

Fig. 5: Photo of a swirl (left) and a jet flame (right) in the burner vicinity

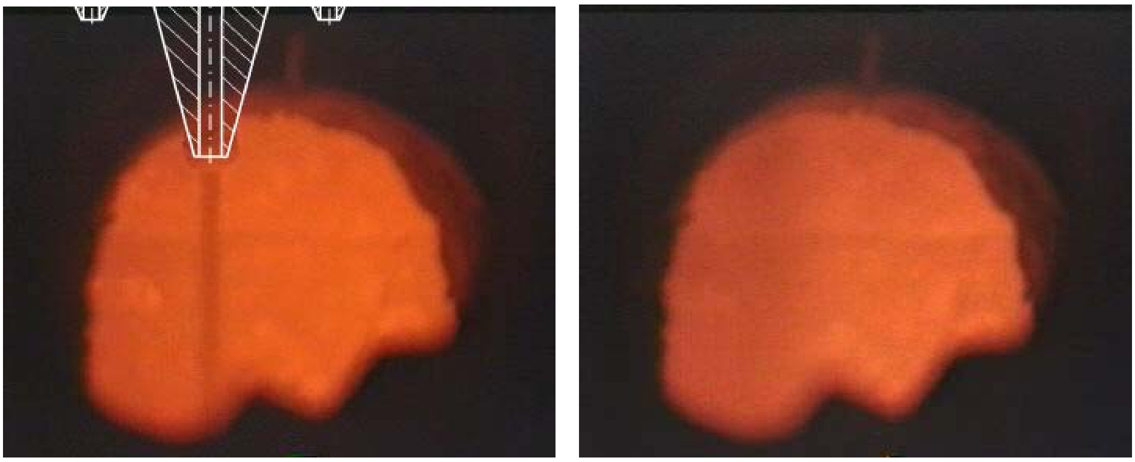

Fig. 6: Photo of FLOX combustion in the burner vicinity (left) and at an axial distance to the burner of z = 200 mm

Fig. 6 presents photographs of FLOX combustion in the burner vicinity and at a larger distance to the burner. The visual impression is quite similar to the FLOX combustion with gaseous and liquid fuels. On the combustion chamber axis the injected coal can be seen in the burner vicinity (Fig. 6 left). This jet expands slowly with increasing burner distance, without an ignition at the jet boundary. At a burner distance of z = 200 mm a bright furnace can be seen without visible flame front. Thus, no concentrated reaction zone is formed. Instead the reaction occurs within a large volume consisting of a mixture of coal, the products of pyrolysis and recirculating flue gases.

This visual impression is backed up by a set of measurements of the gas velocity, gas temperature and gas species at a burner distance of z = 200 mm (Fig. 7 and 8).

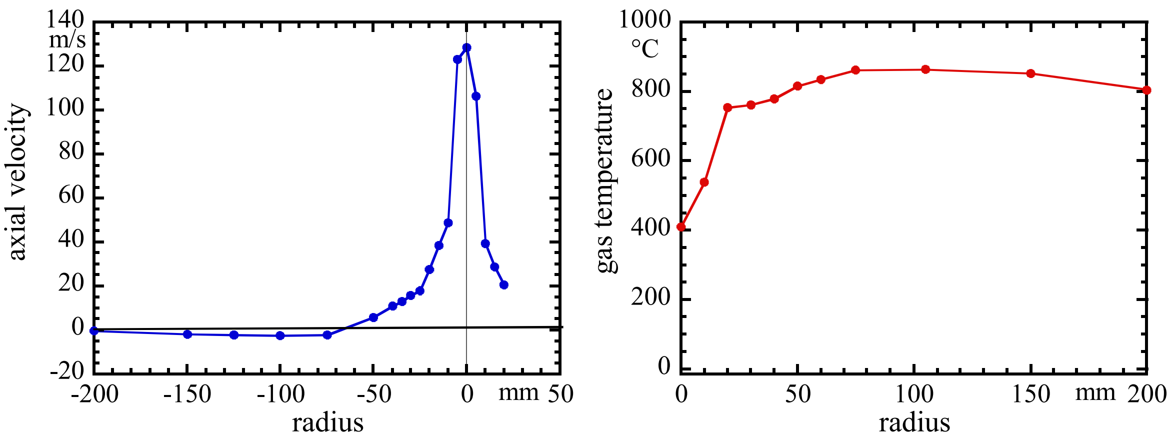

Fig. 7: Axial velocity (left) and gas temperature profiles (right) during FLOX combustion (axial distance to the burner z = 200 mm)

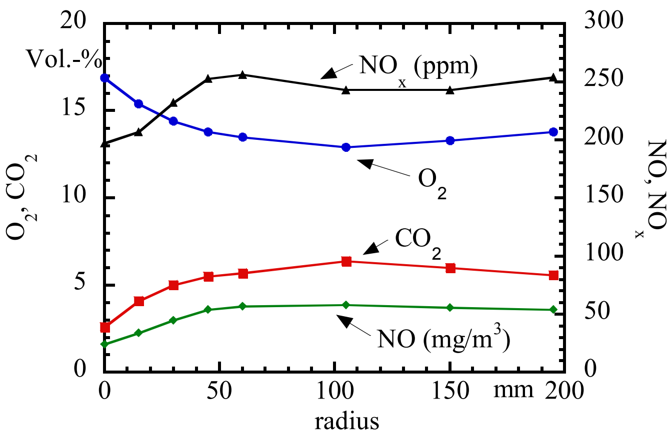

Fig. 8: Radial profiles of gas concentration during FLOX combustion (axial distance to the burner z = 200 mm)

At this burner distance the axial velocity shows a strong forward directed flow on the furnace axis with a maximum velocity of approximately 130 m/s and steep radial gradients. Outside a radial position of 50 mm an outer recirculation zone can be seen. Correspondingly, the gas temperature around the axis is quite cold due to the cold coal/primary air jet and the radial gradients are steep as well. From the radial position of approximately 20 mm outward the temperature is almost constant. The measured gas concentrations (Fig. 7) show quite constant profiles in the radial range 40 to 200 mm. In the vicinity of the furnace axis an increase of the O_2-concentration and a decrease of CO_2- and NO-concentrations is detected. Since at this burner distance high O_2-concentrations can still be found a low reaction rate on the burner axis is probable.

The flow field measured by PIV is mapped in Fig. 9. The settings are different as these measurements were performed during another test series, so that the velocities measured by

LDA and PIV can not be compared directly. Nevertheless, this two-dimensional flow field summarizes the structure of FLOX combustion quite well. The flow enters the furnace with a very high momentum. In the vicinity of the axis a jet with maximum velocities of 150 m/s delivers the coal to the combustion chamber. Around this jet the flue gas recirculates.

4.3 Comparison of the NO_x-emissions

According to the measured structure and to the numerical calculations a decrease of the NO_x-emissions would be expected. To quantify the potential of NO_x-reduction, measurements of the overall NO_x-emissions were carried out for two different coals at a combustion pressure of 3 bars in dry ash firing. Fig. 10 presents the results of the FLOX combustion in comparison to reference flames. These reference flames are jet flames which had previously shown the lowest NO_x-emissions in this furnace.

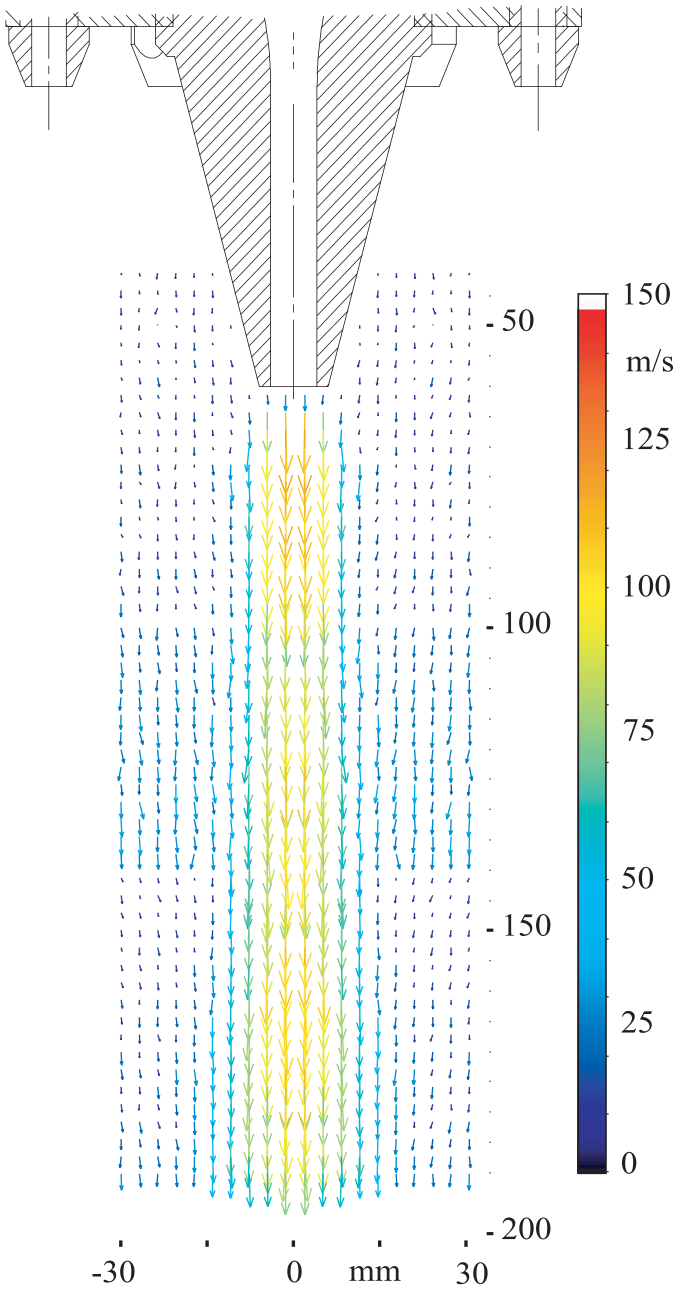

Fig. 9: Flow field of the radial and axial velocity of a flox flame

The comparison of the results makes obvious, that a significant decrease of the NO_x-emission can be achieved with the FLOX-technology. The potential of reduction seems to be dependent on the fuel. Whereas the NO_x-reduction while combusting Rhenish lignite is approximately 25 %, the NO_x-emissions firing Polish coal could be reduced by 65 %. This high decrease is even more suprising as the combustion temperature was below 1000 °C. At this temperature level the thermal NO_x-production is negligible compared to the fuel NO_x-production. Thus, it seems to be possible to reduce the fuel NO_x-emission by using the FLOX-technology.

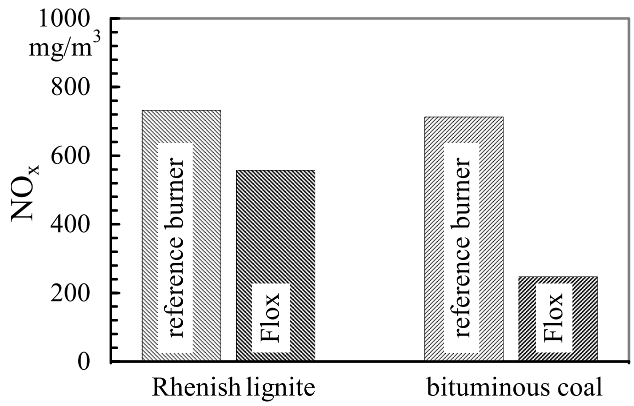

Fig. 10: NO_x-concentration at the end of furnace for the reference and the FLOX burner

5 Conclusion

Flameless combustion has shown a high potential to reduce NO_x-emissions for liquid and gaseous fuels. In this paper experimental investigations on flameless combustion of coal at the PPCC facility Aachen are presented. Additionally, results of numerical simulation of the coal combustion with different burner geometries are provided.

A FLOX burner has been developed in cooperation with WS Wäremprozesstechnik GmbH with a high primary air momentum based on an existing swirl burner. The structure of FLOX combustion could be characterized using different measurement techniques. Thus, gas velocity, gas temperature and species within the reaction zone were determined. Complementary, visual observations of the combustion using a video camera were performed. These measurements indicate a different reaction behavior in comparison to standard swirl and jet flames. As a result of the different flame structure the NO_x-emission could be reduced depending on the coal type by 25 to 65 %.

Further experiments have to be performed to analyze the influencing parameters. This study will include parameters such as further coal types with different grindings, different temperature and pressure levels and variations of the burner geometry.

6 Acknowledgements

The authors gratefully acknowledge the financial support of the Bundesministerium für Wirtschaft und Arbeit (BMWA), Berlin, the European Commission and the Aachen University. The authors also express their sincere thanks to the PPCC-team and the motivated student workers.

7 References

Breusin, F., Weber, R.:
Mathematical Modelling of a Highly Confined Isothermal Swirling Cold Flow, Assessment of the k,ε, RNG-k,ε, ASM and RSM Turbulence Models, IFRF, IJmuiden, 1989.

Fluent Inc.:
Fluent User’s Manual, Lebanon, USA, 2001.

Görner, K.:
Technische Verbrennungssysteme, Grundlagen, Modellbildung, Simulation, Springer Verlag, Berlin, 1991.

Hecken, M.:
Presentation at Aachen University, April 2003.

Lockemann, St, Alfermann, B., Ayar, A., Fielenbach, Ch., Hecken, M., Nobis, V., Schäfer, J., Hillemacher, B., Renz, U.:
Stickoxidmessungen bei der Druckverbrennung von Kohlenstaub mit einem Drallbrenner an der DKSF-Anlage Aachen, VDI Bericht Nr. 1492, 1999.

Renz, U.:
Research on Pressurized Coal Combustion for Power Application, 5th European Conference on Industrial Furnaces and Boilers, Lisbon, 2000.

Smoot, L. D.:
Fundamentals of Coal Combustion for Clean and Efficient Use, Elsevier Science Publisher, Amsterdam, 1993.

Weber, R.:
Combustion of Natural Gas, Oil and Coal with Air Preheated to Temperatures in Excess of 1000 °C, IFRF Research Station B.V., IJmuiden, The Netherlands, 2001.

Weber, E., Hübner, K., Pavone, D., Schulz, R., Wiggers, H.:
Entwicklungsergebnisse bei der Druckkohlenstaubfeuerung, VGB Kraftwerkstechnik 73, pp. 602-607, 1993.

Weber, R., Visser, B. M., Boysan, F.:
Assessment of Turbulence Modeling for Engineering Prediction of Swirling Vortices in the Near Burner Zone, Int. J. Heat and Fluid Flow, Vol. 11, No. 3, Sept. 1990.

Wünning, J. A.:
Ten Years of Flameless Oxidation - Technical Applications and Potentials, Proceedings of the 4th International Symposium on High Temperature Air Combustion and Gasification (HTACG), 2001.

---

[i] FLOX® is a registered trademark belonging to the company WS Wärmeprozesstechnik GmbH, Renningen