OPTIMISATION OF CONVENTIONAL BIOMASS COMBUSTION SYSTEM BY APPLYING FLAMELESS OXIDATION

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ABSTRACT

The utilisation of low-grade biomass requires an appropriate technology that meets the increased demands regarding emission reduction (e.g. NOx). Within this work a new burner for low calorific value (LCV) gas applying flameless oxidation (FLOX®) will be presented that replaces the conventional flame burner of a dual-chamber furnace. The integration of an adapted FLOX®-burner has shown several benefits. Different bio-residues were tested and a more stable combustion with enhanced burnout was achieved for all tested fuels. Furthermore, the burner can be operated in broader range of operation and closer to stoichiometric conditions. Due to the high power density of a FLOX®-burner the complete facility could be downsized in the future. Still, the tests have shown that the NOx reduction potential of a FLOX®-burner is limited for LCV gas combustion since the most NO emissions are related to fuel-bond nitrogen.

In the LCV gases generated from wheat pellets and rape cake pellets high concentrations of NO-precursors (NH_3 and HCN) are measured that are subsequently be oxidized to NO in the FLOX®-burner. Therefore, an air-staged burner for N-rich LCV gases based on flameless combustion is proposed where NO-precursors can be reduced to N_2 in a first substoichiometric region. CFD simulations were applied to investigate an appropriate design of an air-staged FLOX®-burner. Special emphasis is placed on the creation of a sufficient internal recirculation of flue gases required for flameless combustion. First results of CFD simulations are presented.

1 INTRODUCTION

The utilisation of biomass to produce bio-fuels and other bio-based materials in biorefineries is considered to grow steadily within the next years. These processes suffer oftentimes from the fact that the generated bio-residues can not furthermore be used internally due to their poor quality. The European project BIO-PRO [1] is aiming on overcoming this drawback by developing easy and robust technologies to convert the residues of the biorefinery processes to energy, thus allowing them to self-supply the required energy. The core activity of the project is to transfer new burner technologies, originally developed for natural gas, to burn LCV gas generated from biomass. One of these innovative burner technologies is the flameless oxidation.

At the Institute of Process Engineering and Power Plant technology a new combustion system for solid residues is under development. In a first step solid bio-residues are gasified in a commercial fixed-bed gasifier and subsequent the hot LCV gases are directly burned in an adopted FLOX®-burner developed within the project.

The presentation will give an overview of the test results with the new combustion system using four different bio-residues. The emission behaviour depending on different fuel qualities will be shown with special emphasis on the NOx formation process. In order to get a better understanding of the NOx conversion within the combined gasifier-FLOX®-burner-system a detailed analysis of the produced LCV gas was carried out and will show the potential for NOx reduction. The applicability of an air-staged FLOX®-burner for nitrogen rich fuels was investigated by applying numerical simulations using a three-dimensional Computational Fluid Dynamics (CFD) program "AIOLOS". First simulation results of the air-staged burner will be presented.

2 EXPERIMENTAL

In the following section the test facility that was built-up for the experimental investigations is described. Different bio-residues are tested for the utilisation in the new combustion system.

2.1 Test facility

For the experimental investigations a 116 kW commercial dual-chamber furnace for wood chips was applied. For the utilisation of low-grade bio-residues the first chamber will be operated as a fixed-bed pre-gasifier and the subsequent combustion of the LCV gases shall be improved by the integration of a FLOX®-burner adapted to LCV gases. A detailed description of the originally test facility can be found in a previous publication [2]. According to the boundary conditions determined in preliminary tests a FLOX®-burner suitable for integration to the fixed-bed pre-gasifier was designed and the original burner was replaced (Figure 1). The FLOX®-burner was integrated in the flame pipe - the connection of pre-gasifier and boiler.

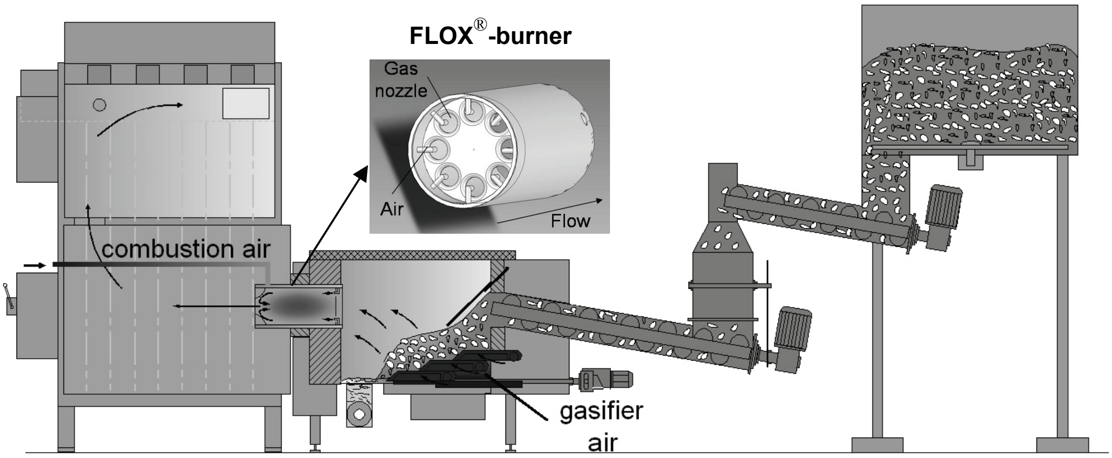


Figure 1. Fixed-bed pre-gasifier with subsequent FLOX®-burner

The developed FLOX®-burner is a multi-nozzle burner that consists of eight gas nozzles each with its own air supply. Due to limited accessibility the combustion air is supplied from the backside of the boiler. The air passes the double jacket of the burner and is thus pre-heated. The complete burn out of the LCV gas takes place in the cylindrical combustion chamber of the burner. The exhaust gases pass then both of the original combustion chambers before entering the water boiler system.

2.2 Fuels

Tests with the new developed FLOX®-burner were carried out with wood chips, rape cake pellets, wheat husks and wheat pellets (with 2 % limestone added). The characteristics of all tested fuels are given in Table 1. The four fuels differ mostly by their moisture, ash and nitrogen content. Rape cake pellets have the highest ash and nitrogen content, but also the highest heating value. Wheat husks and pellets have also a considerable amount of fuel-bond nitrogen, but only half of the amount that rape cake pellets have. The addition of limestone to wheat pellets is increasing the ash content, but prevents the ash slagging problems observed in the tests with wheat husks.

Fuel		**Wood chips**	**Rape cake pellets**	**Wheat husks**	**Wheat pellets (+2 % limestone)**
Moisture	wt-% (ar)	21.1	8.7	12.4	14.4
Ash	wt-% (ar)	0.2	5.4	2.6	3.7
C	wt-% (ar)	38.3	45.8	38.1	38.0
H	wt-% (ar)	5.1	7.5	8.6	6.2
N	wt-% (ar)	< 0.3	4.7	2.0	2.1
S	wt-% (ar)	< 0.3	0.5	< 0.3	< 0.3
H_U (LCV)	MJ/kg (ar)	13.6	18.8	15.6	16.2

Table 1. Composition of tested bio-residues

2.3 Analyses

During the tests exhaust gas was continuously sampled and analysed at the exit of the boiler with respect to O_2, CO_2, CO, NO, NO_2 and NOx.

For determination of LCV gas quality the produced gas from the pre-gasifier was sampled at the end of the pre-gasifier; directly in front of the FLOX®-burner by a gas probe. The gas was then cooled and the condensed water and tars removed. The LCV gas was analysed with respect to CO, CO_2, CH_4, H_2 and O_2.

Furthermore the content of NH_3, HCN and NO in the produced gas was determined to evaluate the conversion of fuel-nitrogen to NO-precursors (mainly NH_3 and HCN) and to NO that is formed already in the pre-gasifier. For NO determination the gas was sampled via gas probe at the end of the pre-gasifier. The gas was then cooled and the condensed water and tars removed before entering the NO analyser. For NH_3 and HCN determination the gas was again sampled via gas probe at the end of the pre-gasifier. The gas sampling pipe was as short as possible and insulated to prevent condensing of ammonia already in the sampling pipe. The gas was then lead to an ice bath with impinger bottles, where NH_3 and HCN are solved in the corresponding solvent. A 0.01 M H_2SO_4 solution was used for NH_3 determination and a 2.0 M NaOH solution for HCN determination. The gas flow was measured and controlled by a gas pump. The content of NH_3 and HCN in the solutions was afterwards analysed in laboratory according to VDI 2461/2 and DIN 38406 E5. For each setting two (wheat pellets) or three (rape cake pellets) gas samples were collected. The content of NH_3 and HCN is given as average value of the analysed samples.

3 OPERATION EXPERIENCE WITH DIFFERENT BIO-RESIDUES

3.1 State-of-art furnace

Preliminary tests with the conventional dual-chamber furnace were carried out to assess the fuel flexibility of the state-of-art technology. The tested fuels are wood chips (reference fuel), residues of flour mills (wheat husks) and residues of oil mills (rape cake). For the combustion of wood chips under conventional operation conditions CO emission between 100 and 150 mg/m^3 (@ 13 % O_2) and NOx emissions between 150 and 200 mg/m^3 were observed (Figure 2). As soon as lambda in the pre-gasifier was reduced below 0.4 high CO emissions were observed. Changes of the primary air in the pre-gasifier were counterbalanced with adjustments of the secondary air to keep a constant overall lambda. With increase of secondary air the flame is extended and then quenched at the backside of the combustion chamber that results in high CO emissions.

The tests with wheat husks have shown similar trends regarding CO emissions as in the previous tests with wood chips. At low lambda in the pre-gasifier the secondary air flow is increased and thus the flame is stretched and finally quenched. In Figure 2 CO and NOx emissions are shown for a lambda in the pre-gasifier of 0.7. Very low CO emissions (below 30 mg/m^3) can only be obtained at lambda higher than 1.0 in the pre-gasifier. Then the fuel is mostly oxidised in the pre-gasifier and the benefit of air-staging, NOx reduction, is lost. At all, the NOx emissions are higher due to higher N-content in the fuel than for the tested woody fuel. The NOx emissions varied between 320 and 510 mg/m^3 depending on the CO level.

The rape cake was used as received from the oil mills. However due to the small particle size the fuel bed on the grate of the pre-gasifier was very dense and the air did not homogeneously pass the fuel bed. Thus, the emissions of CO and hydrocarbons were very high and even soot were observed. A complete burnout was not established. It can be concluded that the rape cake in this shape can not be used in a fixed-bed gasifier. Further tests will be implemented with rape cake pressed as pellets.

3.2 Combined system of pre-gasifier and FLOX®-burner

A FLOX®-burner suitable for integration to the fixed-bed pre-gasifier was designed based on gas quality measurements that will be presented in the next section. The integrated multi-nozzle is shown in Figure 1.

Tests with the integrated FLOX®-burner were carried out with woods chips, wheat husks, wheat pellets and rape cake pellets. In Figure 2 the relation between CO and NOx emissions and excess oxygen content in the flue gas for wood chips is presented at a lambda in the pre-gasifier of 0.4. The FLOX®-burner can be operated over a broad range of excess oxygen and down to 3 % excess oxygen ($\lambda = 1.16$) with very low CO emission before CO emissions increase significantly. This is a considerable improvement compared to the test results with the conventional dual-chamber furnace that is normally operated between 7 to 9 % excess oxygen and CO emissions in the range of 100 to 400 mg/m^3 (Figure 2).

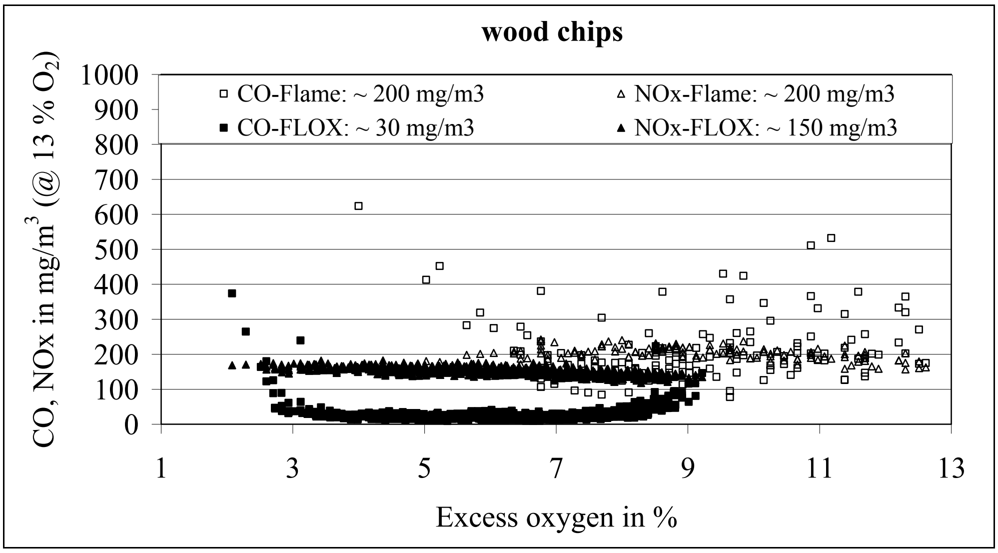


Figure 2. Comparison of CO and NOx emissions for conventional dual-chamber furnace and new system with integrated FLOX®-burner using wood chips

The influence of excess oxygen on NOx emissions is marginal. NOx emissions for the tests with the new system are slightly lower than the ones observed during the tests with the conventional dual-chamber furnace.

During the tests with wheat husks also a very good burnout was achieved and CO emissions were again at a low level (below 20 mg/m^3). NOx emissions depend on the lambda in the pre-gasifier. At lambda higher than 0.5 NOx emissions were at a low level, between 480 and 550 mg/m^3 (at 13 % O_2), considering the N-content of 2.0 % in the fuel. Higher NOx emissions (between 880 and 1000 mg/m^3) were measured when the pre-gasifier is operated at lower lambda. In Figure 3 CO and NOx emissions for wheat husks combustion applying the conventional dual-chamber furnace and the new system with integrated FLOX®-burner are compared. Similar to the results with wood chips the new system can be operated over a broad range of excess oxygen and down to 4 vol.-% excess oxygen without a significant increase of CO emissions. CO emissions using the state-of-art technology are at a higher level over the entire operation range and increase at excess oxygen contents lower than 7 vol-%. Furthermore, it has to be mentioned that even at constant operation conditions the excess oxygen varied in a broad range (2.5 to 12 vol.-%). Still, the burner can handle the changing gas composition and the burn-out of the LCV gas can still be complete. The changing LCV gas composition is probably caused by fluctuations in the pre-gasification step. Reasons for that are both the small fuel particle sizes and generated ash slagging on the grate that creates a very dense fuel bed influencing the air penetration through the fuel. Further tests were conducted with wheat pellets that contain 2 wt.-% limestone to prevent ash slagging on the grate. While on one hand a broad operation range, a better burnout of the gases and thus lower CO emissions are achieved applying the new system the NOx emissions are on the other hand raised by about 50 %.

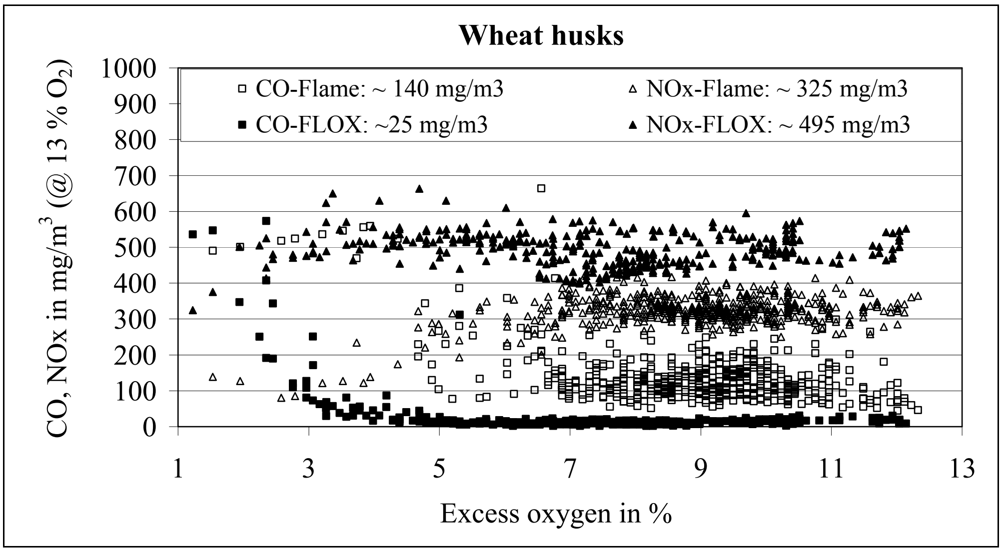


Figure 3. Comparison of CO and NOx emissions for conventional dual-chamber furnace and new system with integrated FLOX®-burner using wheat husks

Similar results are obtained for the tests with wheat pellets, but the ash slagging on the grate was prevented and thus a more stable operation was achieved. NOx emissions were at a slightly higher level (600 to 800 mg/m^3) obviously due to the higher nitrogen content in fuel.

The fourth tested fuel is rape cake, but now pressed to pellets. Remarkable again is the broad range of operation of the new system from 1.17 to 1.7 (3 to 9 % O_2) at very low CO emissions down to less than 10 mg/m^3 (at 13 % O_2). Higher NOx emissions were measured once more when the pre-gasifier is operated at lower lamda. Obviously, the lower the lambda in the pre-gasifier is the higher the NOx emission. Or in other words, the more the oxidation reactions are shifted to the FLOX®-burner the better the N-conversion to NOx due to the good mixing and oxidation conditions in the burner.

Table 2 summarises the emission levels and operation limits that can be achieved with the state-of-art technology and the new system with integrated FLOX®-burner for the tested bio-residues.

Fuel	**CO in mg/m^3**		**NOx in mg/m^3**		**Excess oxygen (lower limit) in vol-%**	
	Flame	**FLOX**	**Flame**	**FLOX**	**Flame**	**FLOX**
wood chips	~ 200	< 30	~ 200	100 - 150	7	3
rape cake pellets	n.o.	< 30	n.o.	800 - 950	n.o.	3 - 4
wheat husks *	100 - 200	< 30	350	500 - 600	7	3 - 4
wheat pellets (2 % limestone)	n.t.	< 30	n.t.	600 - 800	n.t.	4

* – slagging problems
n.o. – operation not possible
n.t. – not tested

Table 2. Overview of CO and NOx emissions for conventional dual-chamber furnace and new system with integrated FLOX®-burner

4 CHARACTERISATION OF LCV GAS

The experimental investigations with the new combustion system for low grade bio-residues have shown that due to the perfect mixing in the FLOX®-burner, CO emissions can be decreased significantly. Moreover, this can be achieved with very low oxygen concentrations in the flue gas. Still, higher emissions of NO_x were measured while burning nitrogen rich fuels in FLOX®-burners when compared to classical flame burners.

A detailed characterisation of the LCV gas was carried out to determine the quality of the generated gas and to evaluate the influence of the FLOX®-burner on the emission results. In a first step the LCV gases generated from wood chips, rape cake pellets and wheat pellets were analysed regarding to H_2, CH_4, O_2, CO_2 and CO at different lambda in the pre-gasifier. Table 3 gives an overview of the measured gas composition and the thus calculated heating values of the LCV gases.

Fuel		**wood chips**			**rape cake pellets**			**wheat pellets**		
$\lambda_{pre\text{-}gasifier}$		**0.5**	**0.7**	**0.9**	**0.7**	**0.9**	**1.2**	**0.8**	**0.9**	**1.1**
H_2	vol-%	2.4	2.3	1.4	3.4	1.2	2.8	3.2	2.1	1.7
CH_4	vol-%	0.5	0.6	0.4	1.5	0.6	1.5	1.2	0.9	0.5
O_2	vol-%	3.1	3.2	2.0	1.9	1.1	0.9	2.1	0.5	2.5
CO_2	vol-%	14.8	15.1	17.0	13.3	15.6	14.5	15.4	17.2	15.5
CO	vol-%	5.2	5.0	3.3	6.7	3.3	6.2	5.5	4.5	4.0
H_U (LCV)	MJ/m^3	1.2	1.1	0.8	1.9	0.8	1.7	1.6	1.2	0.9

Table 3. Gas concentrations and heating values of LCV gases generated from the test fuels

For all tested fuels the generated LCV gas is of poor quality and the heating value is below 2 MJ/m^3. With decreasing lambda in the pre-gasifier the gas quality is slightly improved except for the tests with rape cake pellets. Lowest heating values are measured for wood chips (0.8-1.2 MJ/m^3) and the highest ones for rape cake pellets (0.8-1.9 MJ/m^3). Oxygen concentrations are always on a high level even at substoichiometric conditions. On the other hand incomplete combustion was observed even in excess of stoichiometry and unburned compounds were measured even under superstoichiometric conditions ($\lambda>1$). This indicates that the local conditions differ a lot from the global lambda due to insufficient mixing of air and fuel in the pre-gasifier. A better mixing of air and fuel will enhance the gas quality enormously.

Furthermore, it has to be mentioned that the gas composition is measured only at a single point in the pre-gasifier and it can be assumed that the gas composition also vary both in vertical as in horizontal profile. Still, the FLOX®-burner was able to burn the LCV gases despite its changing composition and low heating value during all tests.

Due to the high oxygen concentrations in the generated LCV gas it is likely that NO-precursors (mainly NH_3, HCN) formed during the gasification are already converted to NO in the pre-gasifier before entering the FLOX®-burner. Therefore, further analyses were carried out to assess the influence of the FLOX®-burner on the NO formation process for nitrogen rich bio-residues. Additional tests with wheat pellets and rape cake pellets were conducted in order to evaluate the degree of NO formation in the pre-gasifier. In Figure 4 the concentrations of NH_3, HCN and NO measured in the LCV gases generated in the pre-gasifier at different equivalence ratios are presented.

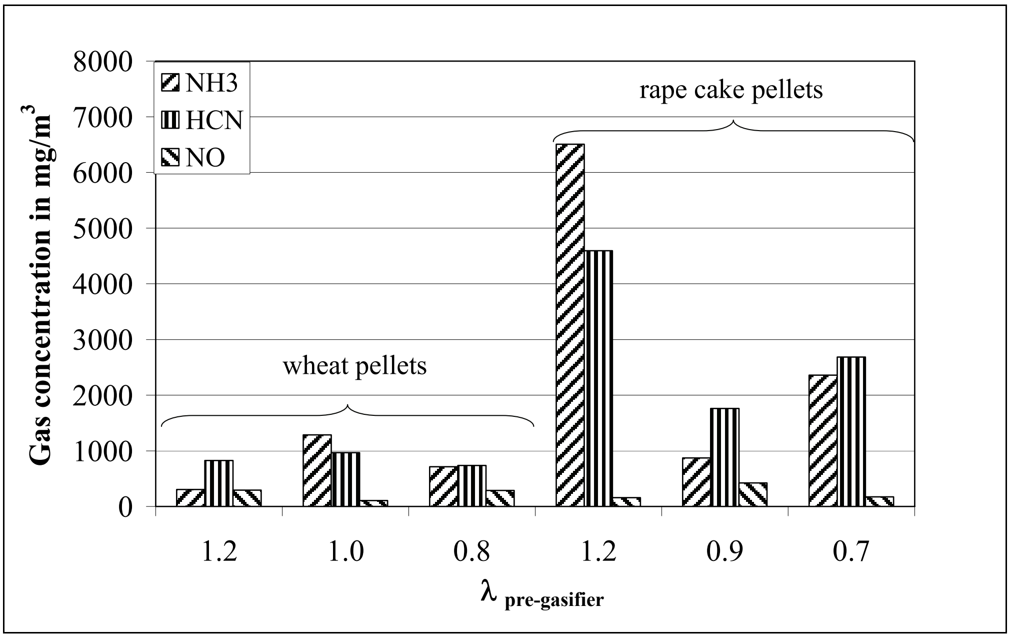


Figure 4. N-compounds in LCV gas generated in pre-gasifier using wheat husks and rape cake pellets

In the tests with wheat pellets concentrations of NH_3 and HCN up to 1280 and 970 mg/m^3 were measured, respectively. Due to the higher nitrogen content in rape cake pellets the concentrations of NO-precursors were higher and up to 6500 mg/m^3 (NH_3) and 4590 mg/m^3 (HCN). NO is already formed to some extend in the pre-gasifier and concentrations between 110 and 420 mg/m^3 were measured. It is obviously that the amount of NO-precursors is correlated to the amount of NO present in the gas. In gases with a high content of NO the concentration of NH_3 and HCN is low. Here, a higher rate of NO-precursors is already converted to NO. Normally higher NH_3 and HCN concentrations shall be found in gases generated in the pre-gasifier at low lambda. Even though the highest NO-precursor concentrations were detected in the LCV gas generated at $\lambda = 1.0$ (wheat pellets) and $\lambda = 1.2$ (rape cake pellets). Here, it is proven again, that lambda represents only the global conditions in the pre-gasifier, but local conditions in the pre-gasifier are of particular importance for the quality of the gas including the nitrogen conversion.

5 CFD-MODELING OF THE AIR - STAGED FLOX-FLOX BURNER

Detailed investigation of the product gas from the gasifier showed very high concentrations of NO_x precursors such as NH_3 and HCN as well as high concentrations of NO_x already created in the gasifier. These compounds can be reduced to N_2 in substoichiometric regions created in the burner. Such regions can be generated through air staging. Therefore, the further development of FLOX®-burners for LCV gases is focused on staged burners. There are three types of staged burners which are feasible [3]. In the case of Flame-FLOX-type burners, a mixing chamber is installed before the FLOX-combustion chamber which shall ensure more defined reducing conditions. The second feasible type is FLOX-Flame burner. The FLOX part of the burner will be operated substechiometric, thus providing perfect mixing and good reduction conditions. In the downstream part of the burner additional secondary air will be added to ensure a complete burnout. However, the FLOX-FLOX burner should result in the best operating conditions. This combination should not only ensure the best reducing conditions in the first substoichiometric zone but also excellent mixing and complete combustion in the second oxidation zone of the burner [3]. Therefore only the FLOX-FLOX combination has been investigated and will be presented in the following. To support the development process of such two-stage burners, CFD modelling was carried out. All presented numerical simulations were performed using the program ‘AIOLOS’ [4].

5.1 Code description

The code is based on a conservative finite-volume formulation, using a standard k-ε model for turbulence. The interaction of turbulence and chemistry is modelled using Eddy Dissipation Concept (EDC). The chemistry used in AIOLOS is based on a set of global reaction mechanisms. The radiative heat transfer is calculated by the discrete-ordinates method. More detailed information about the program code is available in [4, 5].

It has to be noted that in the case of flameless combustion, usage of such simplified chemistry models lead to the local overestimation of temperature. The prediction of CO concentration is also not sufficient [6]. However, such numerical modelling can be use as a tool to solve the main technical problems concerning the flow and combustion-related stability problems.

5.2 Burner design and boundary conditions

As mentioned above, in the case of FLOX-FLOX air-staged burner, there are two zones working with internal flue gas recirculation. Nevertheless, such construction requires that enough air can be injected to generate sufficient mixing and flue gas recirculation in both zones. It has to be taken into account that this burner is designed for LCV gases combustion. It means that the required amount of air might exceed the amount needed to complete combustion. The better the quality of gas, the more air can be use to force the recirculation, and the better reduction and oxidation in the burner. Therefore, geometry of such burner has to be optimized to ensure good conditions in both mixing zones with a limited amount of air. Moreover, these zones have to be separated from each other in order to avoid sucking of the oxygen rich gaseous mixture from the oxidation zone to the reduction zone.

In the first modelling step, a simple air-staged burner design was modelled. The 3-D cross section of this burner in presented in Figure 5. This design is based on the original, multi-nozzle single staged construction.

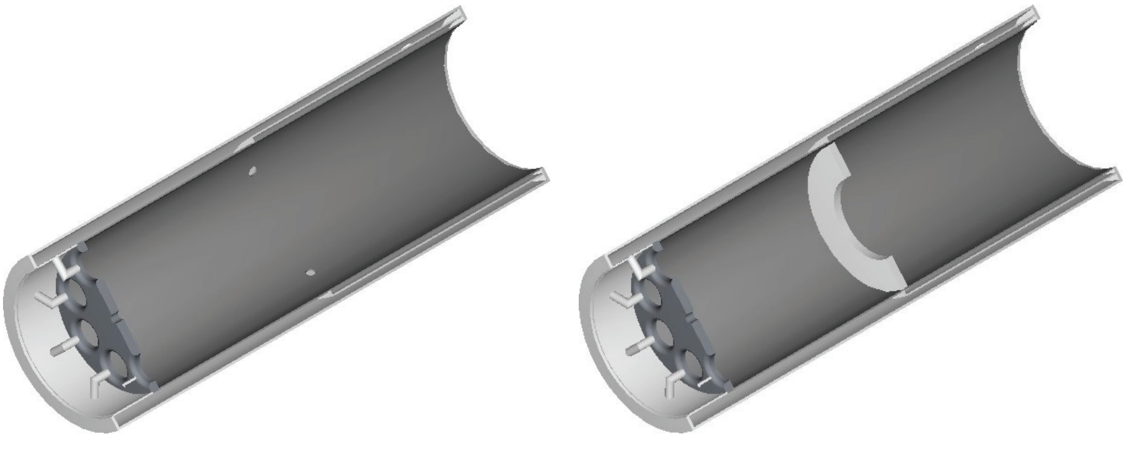


Figure 5. Air-staged FLOX-FLOX burner **Figure 6. Air-staged FLOX-FLOX burner with orifice**

The hot product gas generated in the gasifier is fed through the large circular nozzles. Air is injected in two stages: via eight nozzles in the front and via four in the middle of the burner. The secondary air nozzles are placed 30 cm downstream from the gas nozzle plate. The boundary conditions are presented in the Table 4.

	Flow rate (kg/h)	Temperature (°C)	Composition (wt. %)
Product gas	86.3	900	CH_4 – 3.7 H_2 – 0.2 CO – 5.2 CO_2 – 24 H_2O – 9.2 O_2 – 1.5 N_2 – 56.2
Total air	106.5	Primary Air – 600 Secondary Air – 300	Dry Air

Table 4. Boundary conditions

The total flows of air and product gas as well as temperatures were assumed to be constant. The influence of lambda in the reduction zone on internal recirculation was investigated (λ_{red}=0.6, λ_{red}=0.8, λ_{red}=1).It has to be noted, that lambda in the burner is related to the product gas coming from the gasifier.

In the second step of modelling, different geometry variations were modelled. All cases were calculated assuming λ_{red}=0.8 in the reduction zone. At first, the angle of secondary air injection was changed. After that, the design with the orifice between the first and second zone was modelled. The orifice is placed directly before the secondary air nozzles (Figure 6).

Finally, modelling of the burner without secondary air was carried out with thus the total lambda is equal to the lambda in the first stage of the burner (λ_{red}= λ_{tot}=0.8). The last modelling result provides information about flue gas recirculation in the first zone without disturbance caused through the secondary air injection.

5.3 Modelling results and discussion

Influence of equivalence ratio on recirculation. Three different cases with λ = 0.6, 0.8 and 1 in the reduction zone were modelled. The total amount of air has been assumed to be constant. This results in an oxygen level of about 5 vol-% in dry flue gas.

It means, the more air injected in the first section of the burner, the less amount of air is injected in the second section. In order to better describe the recirculation the parameter Local Recirculation rate (LR) has been introduced. This rate is calculated as a ratio between the mass flowing through the specified cross-section in the opposite direction to the main stream ($\dot{m}_{rec}$) and the total mass flow of fuel ($\dot{m}_{fuel}$) and primary air ($\dot{m}_{PA}$) introduced into the burner.

$$LR = \frac{\dot{m}_{rec}}{\dot{m}_{fuel} + \dot{m}_{PA}} \qquad (1)$$

Figure 7 shows the local recirculation rate in the substoichiometric zone for the first four modelled cases. The results show that the recirculation strongly depends on air distribution between primary and secondary stage. Decreasing the lambda in the first part of the burner to ensure good reducing conditions forces the recirculation zone to move to the vicinity of the secondary air injection. This causes sucking of the secondary air into the region where substoichiometric conditions should be achieved. On the other hand, increasing lambda in the first zone forces the recirculation zone in the direction of the gas nozzles, decreasing the amount of the secondary air transferred to the reduction zone. However, the effect of reduction decreases also because of the larger amount of injected primary air. In the Figure 9 and Figure 11 the velocity field has been presented with the help of two perpendicular surfaces. To better show the recirculation isosurface with an isovalue of -8 m/s has been used.

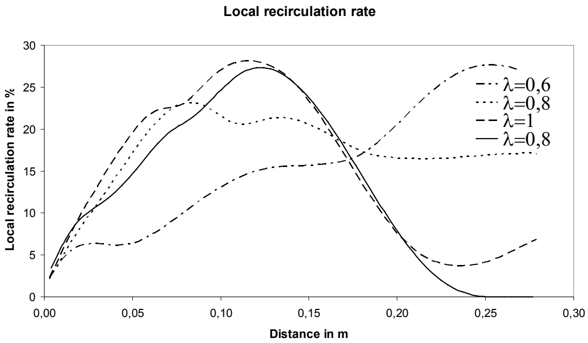


Figure 7. Local recirculation rate along the burner – lambda variation

It has to be noted, that using the proposed design, problems with mixing and cold areas (Figure 8 and Figure 10) in the secondary part of the burner can occur. With this geometry, sufficient recirculation in the second zone cannot be achieved.

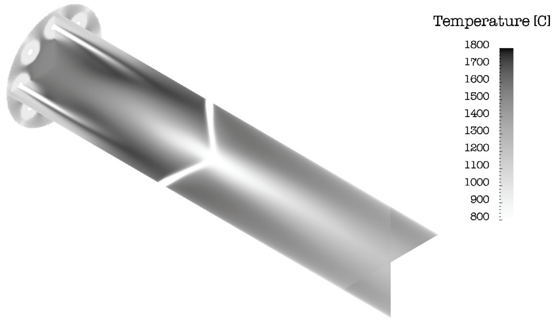


Figure 8. Temperature field; λ_{red}=0.8

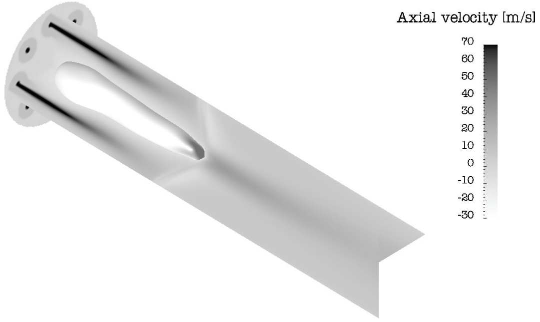


Figure 9. Velocity field; λ_{red}=0.8; Isosurface -8 m/s

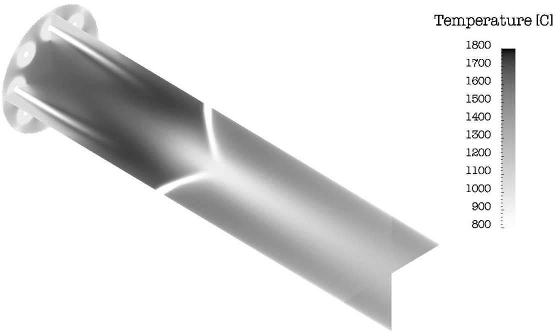


Figure 10. Temperature field; λ_{red}=1

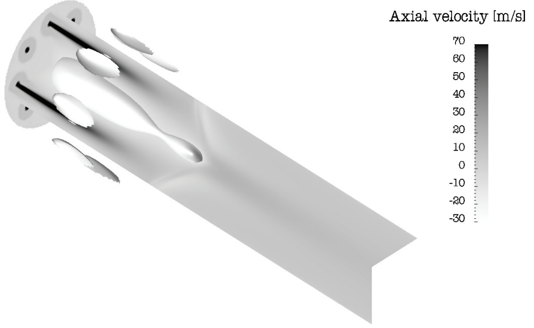


Figure 11. Velocity field; λ_{red}=1; Isosurface -8 m/s

Geometry variation. In order to obtain better separation of first and second zone as well as to minimize mixing problems, two other geometry settings have been modelled. Lambda in the first stage of the burner has been assumed to be 0.8. In the first case, the angle of secondary air injection has been changed from 90º to 45º. This results in good separation between the two stages. In Figure 12, local recirculation rate as a function of distance has been presented. It shows that for air injection with 45º, there is no recirculation in the vicinity of secondary air injection. Figure 9 shows that the recirculation zone has been moved in the direction of the gas nozzles. Unfortunately, the change of the angle has not minimized problems with the mixing in the second stage of the burner. To achieve stronger recirculation in the second stage, the geometry with an orifice has been designed (Figure 6). The results of numerical modelling show that in this case the recirculation generated in the first stage is a little bit weaker then in the other modelled cases. However, it is possible to achieve much better mixing conditions in the second stage. This geometry seems to be the best of those that have been tested.

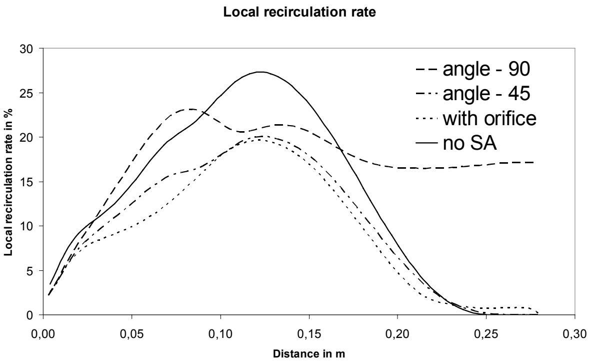
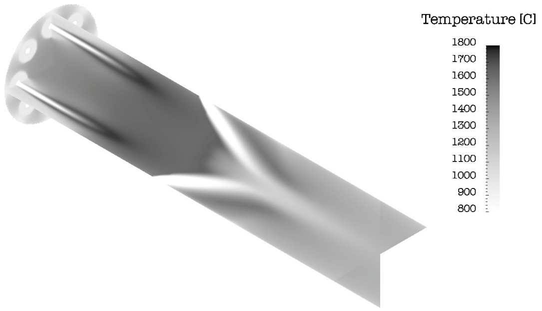


Figure 12. Local recirculation rate along the burner – geometry variation



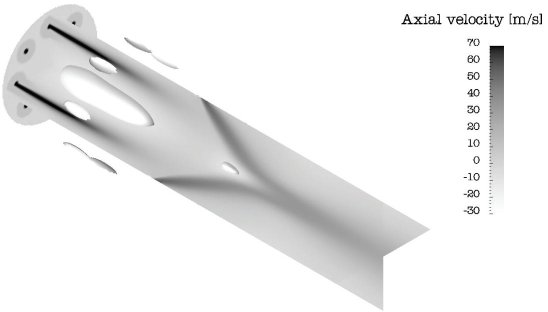
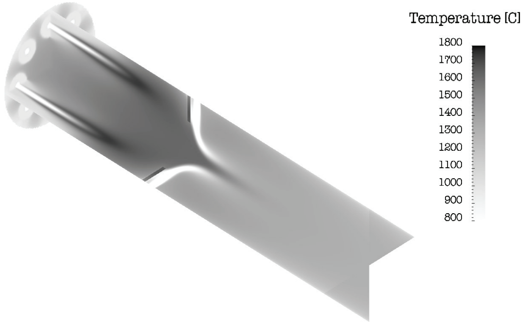


Figure 13. Temperature field; Geometry with the secondary air injection of 45°; λ_{red}=0.8

Figure 14. Velocity field; Geometry with the secondary air injection of 45°; λ_{red}=0.8; Isosurface -8 m/s



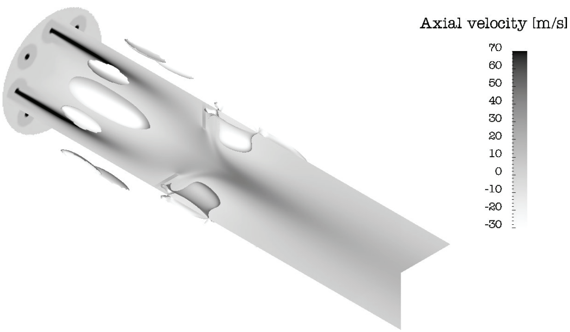


Figure 15. Temperature field; Geometry with orifice;λ_{red}=0.8

Figure 16. Velocity field; Geometry with orifice;λ_{red}=0.8; Isosurface -8 m/s

6 CONCLUSIONS

The integration of the FLOX®-burner brings several advantages compared to the configuration without the burner:

- A better burnout of the LCV gases is reached by a better mixing of the gases within the combustion zone.
- The burner can be operated at a low excess oxygen content that results in a higher efficiency compared to the original set-up.
- The combustion chamber of the FLOX®-burner is much smaller due to the better mixing and burn-out of the LCV gases that reduce investment costs.

Still one objective, the reduction of NOx emissions, is not achieved yet. Although there is less experience with the combustion of residues of flour and oil mills NOx emissions are still on an unacceptable high level. The tests have shown that an unstaged FLOX-burner indeed reduces thermal NOx emissions but the conversion of fuel nitrogen is even enhanced by the conditions within the FLOX-burner. For that a further NOx reduction technology has to be applied when fuel-N rich fuels are burned. The analysis of the LCV gas showed very high concentrations of NO-precursors such as NH_3 and HCN as well as high concentrations of NO already created in the gasifier. These compounds can be reduced to N_2 in substoichiometric regions created in the burner. Such regions can be generated by air staging. Therefore, the further development of FLOX®-burners for LCV gases is focused on staged burners. An air-staged FLOX-FLOX burner is proposed and numerical simulations using the code "AIOLOS" were carried out to investigate the design of such a staged burner. A staged FLOX®-burner should not only ensure the best reducing conditions in the first substoichiometric zone, but also excellent mixing and complete combustion in the second oxidation zone of the burner. The influence of equivalence ratio on recirculation within the burner was investigated. To optimize the recirculation, modelling of two other geometry variations was conducted. The results show that recirculation strongly depends on air distribution between the two stages in the burner. Sucking of secondary air into the primary zone can occur when decreasing lambda in the first stage of the burner, Moreover, using the design without an orifice between the stages, mixing in the second stage is not sufficient. To minimize these problems other geometry designs were proposed. The geometry with the orifice between the two stages provides the best stability, mixing conditions as well as good recirculation in both stages.

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