

FUEL- OXYDANT FLEXIBLE COMBUSTION WITH FLAMELESS OXIDATION

A. Milani, J.G. Wüning - WS GmbH

Recent and expected measures for reducing CO_2 released from combustion equipment affect the composition of both fuel and oxidant with respect to established fossil fuel combustion practice. Natural gas has allowed a great step forward in optimizing process and plant performance: it is the best clean and stable fuel with favorable hydrogen to carbon ratio. However, cheap natural gas will not be available for ever and will be partly substituted by gasification products containing hydrogen and CO. Furthermore, GHG constraints tend to mitigate CO_2 release with capturing techniques applied to coal combustion.

Representing the fuel with the crude formula CH_x and the inert component IG , the present tendency is to increase the hydrogen content X while also increasing IG (typical with lean gasification processes, biogas and the like) or inversely to decrease the N_2 ballast in order to concentrate CO_2 for subsequent capturing (oxy-coal combustion):



where IG = inert gas component including:

- inert gases in the oxidant and $N_2 + CO_2$ in the fuel
- excess oxidant
- RFG (Recirculated Flue Gases).

This balance is referred to a *local* gaseous mixture *before* combustion: assuming that an adiabatic complete oxidation reaction occurs, the theoretical temperature *after* reaction depends very much on the *ballast* term IG .

Both increased hydrogen concentration and oxygen enrichment favor the establishment of a stable flame front. However, the higher flame speed can provoke too early ignition and flashback and unwanted hot spots may occur with increased oxygen concentration in the oxidant. Inversely, an increased proportion of IG produces a very lean fuel impossible to fire without the support of a rich fuel. Therefore burners and combustors designed for natural gas require modifications or new designs to fire the new expected gaseous fuels and also liquid or solid ones.

This design inflexibility derives from the basic requirement of setting up and keeping stable a steady flame front. This implies that the composition of the gaseous

reacting mixture is within flammability limits (Figure 1); in the magnified diagram close to the IG apex, lines of constant air ratio λ and of constant recirculation factor K_V are reported. This parameter is defined as the ratio of recycled flue gases (RFG) referred to the input flow of air and fuel.

A turbulent flame front has to be *locally* supported by recycling hot reactive species into a low velocity region (Figure 2): local mixture must be flammable and adiabatic temperature must be high in order to ensure *high gradients* for flame front propagation. These conditions are fuel and oxidant dependent, so that a burner designed for one particular fuel does not accommodate easily different fuels.

If conditions allow flameless oxidation, shortly *FLOX®* [1], there is no more a flame front and the combustion reaction is supported by recycling hot RFG that are above ignition temperature (order of 500-650 °C for most fuels), as shown in Figure 3. With large enough entrainment of RFG, which can be carried out inside the combustion chamber by means of high momentum imparted to the injected reactants, high K_V ratios (~ 3) can be easily achieved and even irregular local flame fronts lifted from the burner can be avoided. If air and fuel are injected at high velocity in a large chamber, they will entrain RFG linearly with the distance from the origin (circa doubling the mass flow every three burner diameters according to the free jet theory).

Figure 4 has been calculated for a combustion chamber supposed at 1200 °C and air preheated at 400 °C: assuming to mix the quantity K_V from RFG with the pure reactants, the temperature of the mixture *before reaction* increases gradually towards 1200 °C. If an adiabatic reaction occurred according to the balance above (1), the product temperature would decrease from the adiabatic value of about 2000°C towards 1200°C. The ΔT "after - before" reaction will decrease with K_V and the range of gaseous temperature within the chamber will be *clamped* from ~ 550 -650°C (threshold of self-ignition) and ~ 1400 °C in the example.

In flameless conditions, the current assumption *mixed=burnt* is no longer true and the reaction rate is instead temperature and mixing controlled. Combustion is gradual and distributed in a relatively large volume. This is the secret to avoid temperature peaks conducive to high NO_x emissions.

The advantage of the flameless oxidation is that combustion is temperature controlled (must be above ~ 800 °C for safety), which depends on process and on plant design, but is quite tolerant about fuel and oxidant *composition*. *FLOX®* can work in a wider range of the triangle in Figure 1.

Flameless oxidation is suitable in the following conditions [1,2]:

- for gaseous, liquid and solid fuels
- with and without air preheat
- with and without fuel preheat
- for lean, near stoichiometric and rich combustion (e.g. λ 0.3 - 3 and more)
- for diffusion, partially premixed and premixed combustion
- for oxygen depleted and oxygen enriched oxidant
- for low volumetric reaction intensity (furnaces) up to gas turbine combustors
- no catalyst is involved

which can be certainly defined as flexibility. Originally the technique was developed and investigated for high temperature furnaces with high air preheat, that requires suitable countermeasures to control thermal NO_x emissions.

A hot furnace above $\sim 850^{\circ}\text{C}$ is possibly the easiest and certainly most common application to embody flameless combustion, featuring

- high velocity free jets of combustion air, often hot or very hot,
- or even sonic jets of pure oxygen
- high velocity jets of pressurized fuel (often natural gas)
- both jets issuing into an almost *infinitely large* and *hot* environment

for this reason *FLOX*[®] has been largely applied and NO_x emissions have been effectively abated (Figure 5) in many furnaces in the steel industry.

In power generation, the flue gases leave the equipment at low temperature and can not be used directly to keep flameless oxidation going (*external FGR*). Then the process must be carried out within a confined combustion chamber, that may be almost adiabatic. This is the case of the *FLOX*[®] combustor sketched in Figure 6: a central torroidal vortex is set up by several high momentum nozzles distributed all around. The system requires a start up burner, but is then capable of self-sustaining, provided of course that the *after-reaction* temperature is safely above $\sim 850^{\circ}\text{C}$.

The principle has been applied to the design and development of a combustor for gas turbines (Figure 7) that has been extensively investigated [3,4] and is still being studied experimentally and with numerical modeling, in particular at the DLR laboratories [3]. Figure 8 provides a pictorial example of the flow pattern; air and gas are premixed at the nozzles and the NO_x emissions are satisfactory. A great advantage with respect to the present *dry premixed* GT design is that no vibration or *humming* whatsoever has been observed (because in fact these depend on the flame front instability).

Another example of the combustor concept (Figure 9) is provided by the family of burners and equipment designed and manufactured for lean gases by the company *E-flox* [5,6]. Performance tests carried out at the Oekozentrum laboratories [7] in Switzerland prove that the system is capable of firing landfill mixtures down to LHV about 2-2,5 MJ/m³ which is a record: this means some 20 times less than natural gas and implies a stoichiometric air requirement of about 0.5 instead of 10 m³/m³ of gas. The system requires preheating and a way to start up to *FLOX*® threshold; however, a flame front would never hold. Many applications have been built and are in satisfactory operation [6]. Way of reducing fuel NO_x (from impurities in the fuel gas) by means of air staging are also being investigated (Figure 11). Applications range from *thermal oxidation* of exhaust streams to firing of slip streams from CH₄ upgrading plants (membranes) from biogas (in flares or furnaces with heat recovery).

Flameless oxidation of pulverized coal at atmospheric and under pressure has been tested with encouraging results concerning not only the expected abatement of thermal NO_x, but also the possibility of reducing fuel NO_x as well [8]. Furthermore, the cooperative R&TD project OXYCOAL-AC is being carried out at the facilities of the WSA (Institute of Heat and Mass Transfer) of the RWTH Aachen with funding of major power generating companies in Germany and involving several academic partners [9]. The project is based on the hot membrane to separate O₂ without resorting to the traditional energy consuming ASU (air separating unit), as it may be seen in Figure 12. The hot RFG should in this way be composed of O₂ and CO₂ + H₂O, so that CO₂ can be captured after water condensation. *FLOX*® test burners have been investigated successfully at Aachen and developments are going on to reduce fuel NO_x to minimum levels, while burn-out of coal is satisfactory.

As concluding remarks:

- ✓ *FLOX*® firing is flexible with respect to flame front combustion and can cope with all type of fuels in a wide range of oxygen concentration in the oxidant
- ✓ it is not limited to high temperature furnaces and preheated air, where flameless combustion has already found many common applications
- ✓ it is not confined to low volume combustion intensities either
- ✓ *FLOX*® is a very promising technique for several new processes and devices for *energy generation*, in small and large scale, aimed at reduced emissions and enhanced feasibility in particular for *difficult* fuels.

References:

- [1] Wüning J.G. , Milani A. "Handbuch der Brennertechnik für Industrieöfen" - *Vulkan Verlag, Essen* - ISBN 978-3-8027-2938-6
- [2] Wüning J.A., Wüning J.G. "Flameless oxidation to reduce thermal NO-formation" *Prog. Energy Combust. Sci., Vol 23, pp. 81-94, 1997 Elsevier Science- 0360-1285/97*
- [3] Lücknerath R., Meier W., Aigner M. - FLOX® combustion at high pressure with different fuel compositions - *Journal Eng. Gas Turbines and Power, Trans ASME, Jan 2008*
- [4] Flamme M., "New combustion systems for gas turbines (NGT)", *Applied Thermal Engineering, 24, 1551-1559, 2004.*
- [5] www.e-flox.de
- [6] Berger R., Wüning J.G. - Burners for the process integrated combustion and utilisation of biomass or waste derived low calorific value gases - *8th European Conference on Industrial Furnaces and Boilers, Vilamoura 2008*
- [7] Berger R., Schmid M., Wüning J.G. - Low-NO_x Schwachgasverbrennung mit Flammloser Oxidation - *GWI (54), 6/2005*
- [8] Ristic D., Schneider M., Schuster A., Scheffknecht G. , Wüning J.G. - Investigation of NO_x formation in flameless coal combustion - *7th HTACG 08, Phuket, 2008*
- [9] www.oxycoal.de

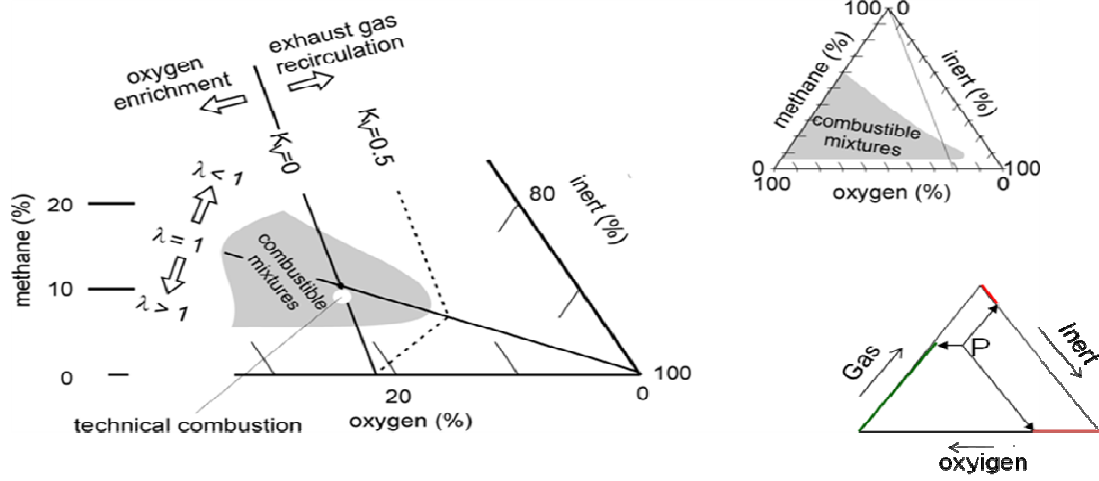


Figure 1 - Flammability limits

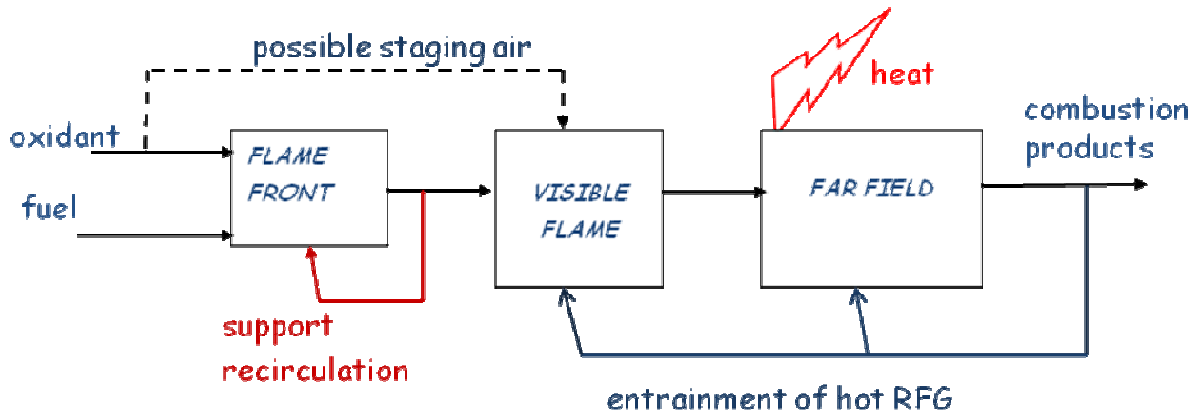


Figure 2 - Flame front firing

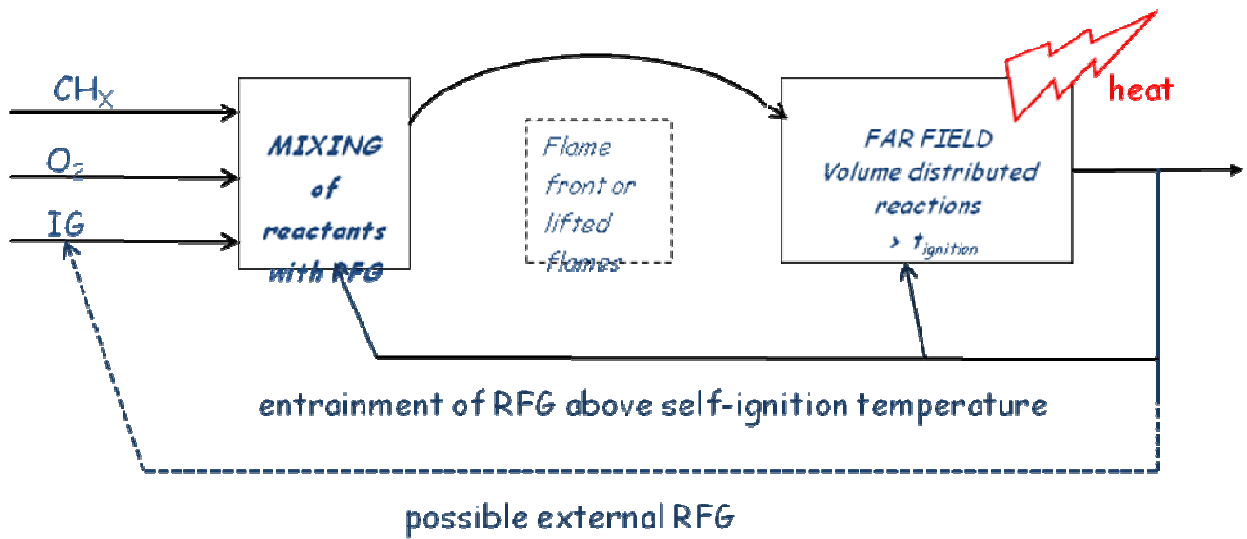


Figure 3 - Flameless oxidation firing

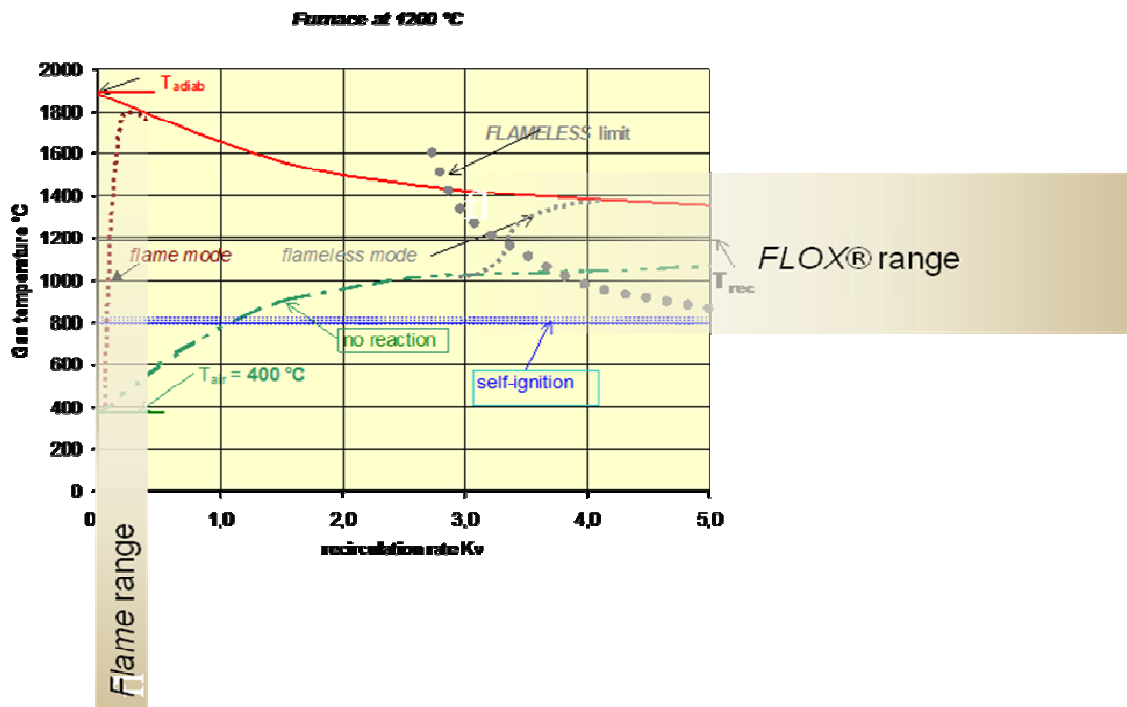


Figure 4 - Temperature vs K_v diagram

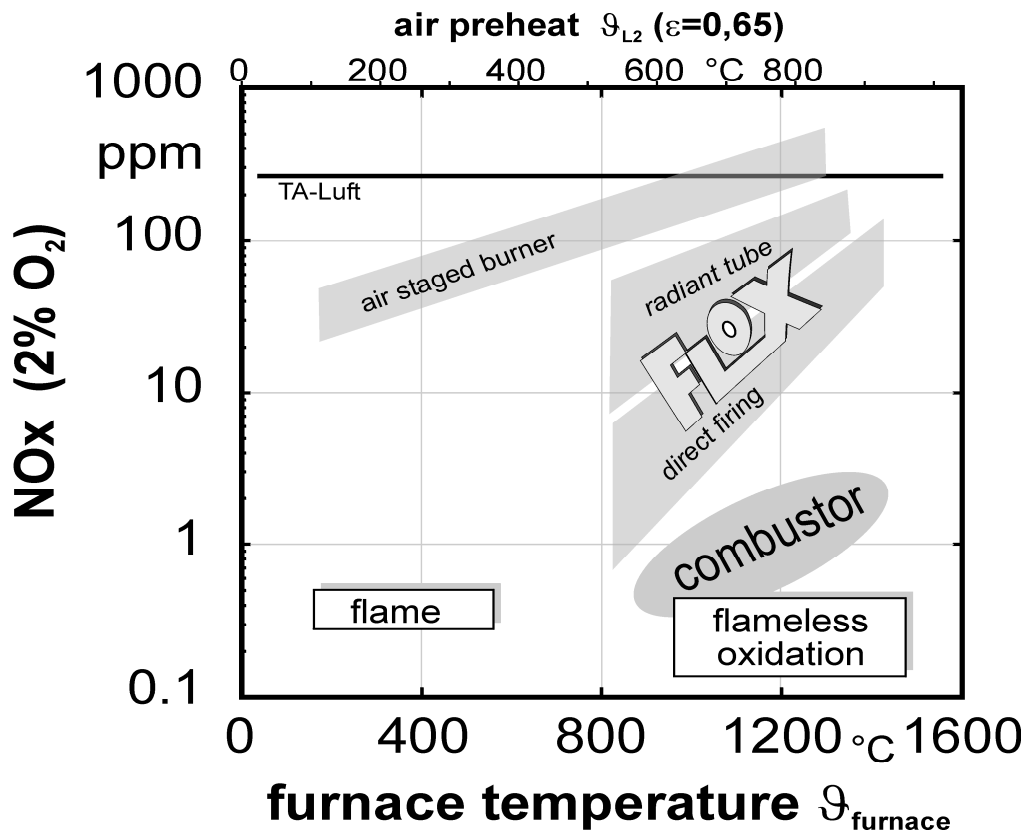
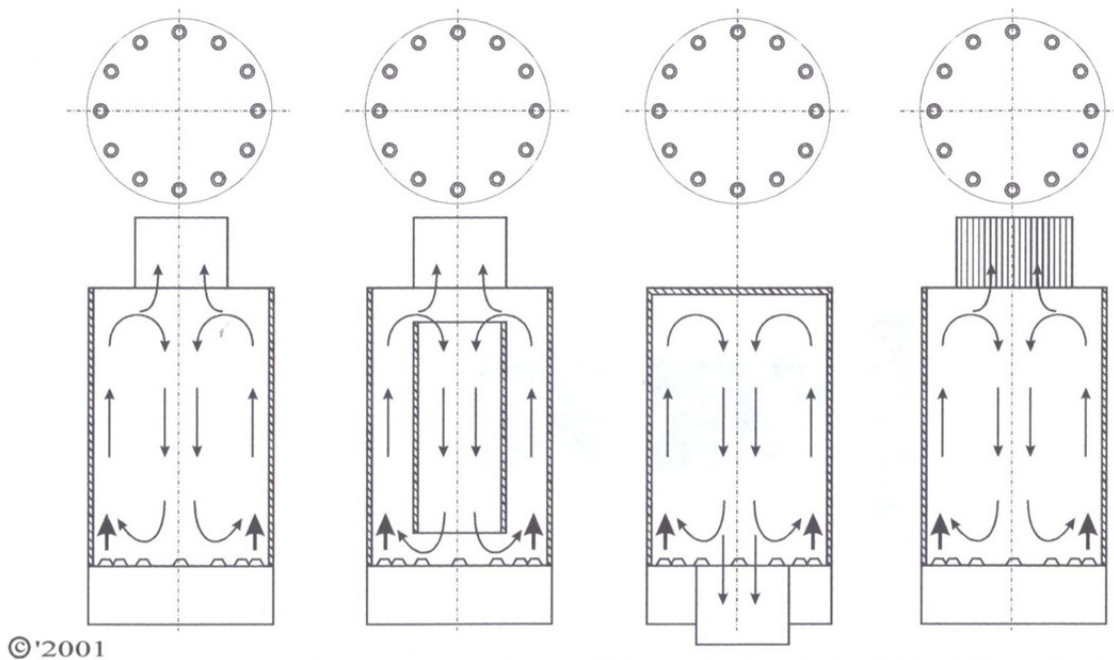


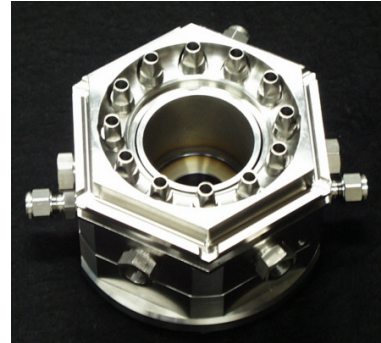
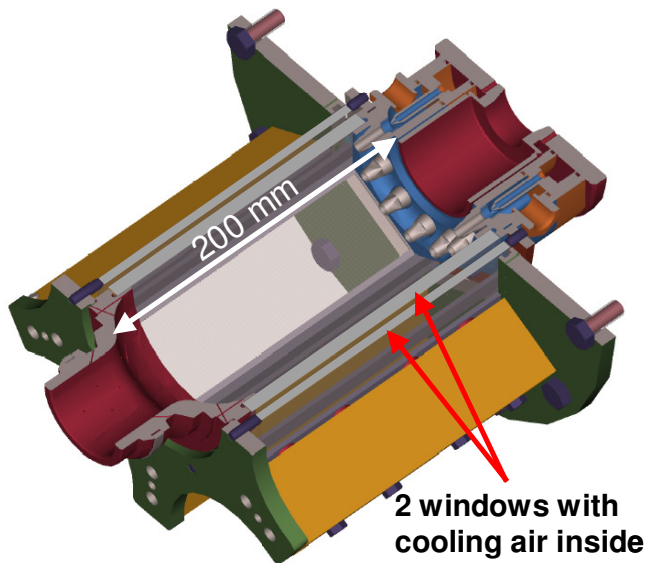
Figure 5 - NOx emissions from high temperature furnaces



©'2001

Figure 6 - Principle of the FLOX® combustor

Optical Combustion Chamber with FLOX® combustor



- 5 - 30 bar
- $\lambda = 2 - 3$
- 1.5 - 9 g/s natural gas, 300 K
- 50 - 350 g/s air, up to 690 K

Figure 7 - FLOX® combustor for gas turbines

FLOX® Burner

Axial Velocity and Streamlines (Numerical Simulation)

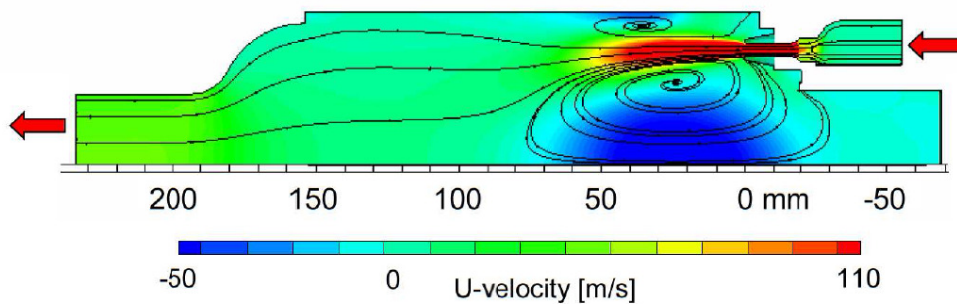
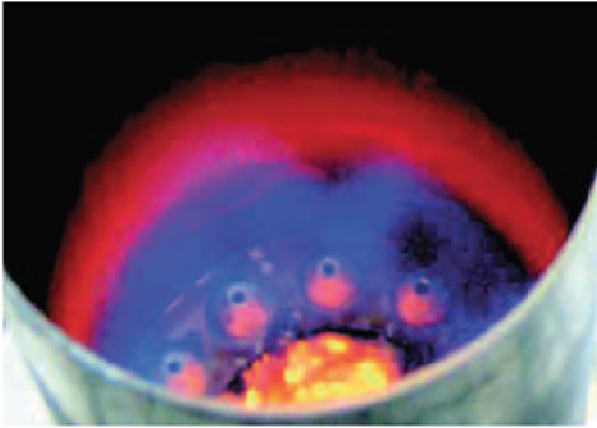
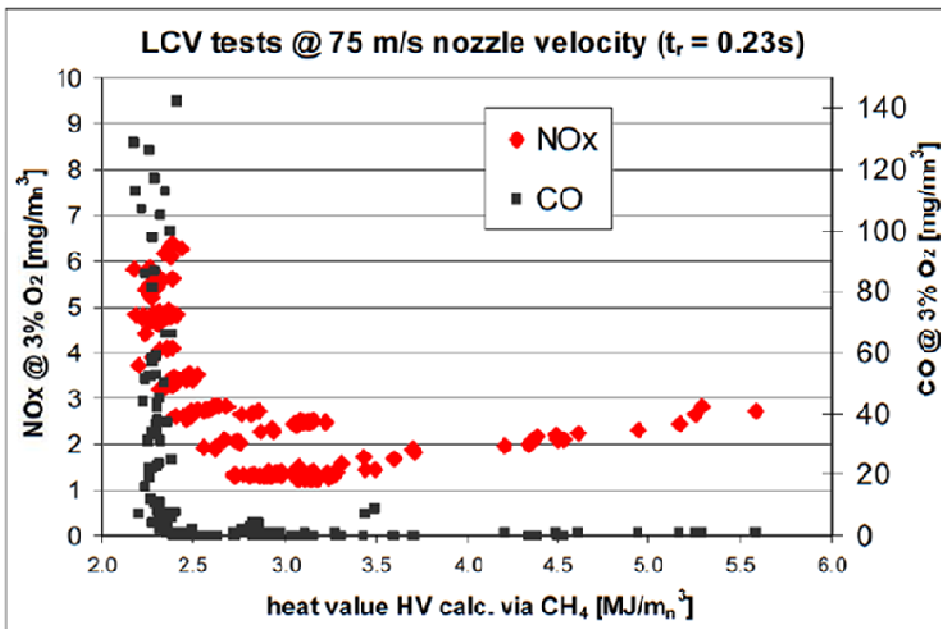


Figure 8 - Modeling of the FLOX® burner



courtesy  ökozentrum langenbruck

Figure 9 - Details of the FLOX® burner for lean landfill gases



courtesy  ökozentrum langenbruck

Figure 10 - Performance of very lean gas firing

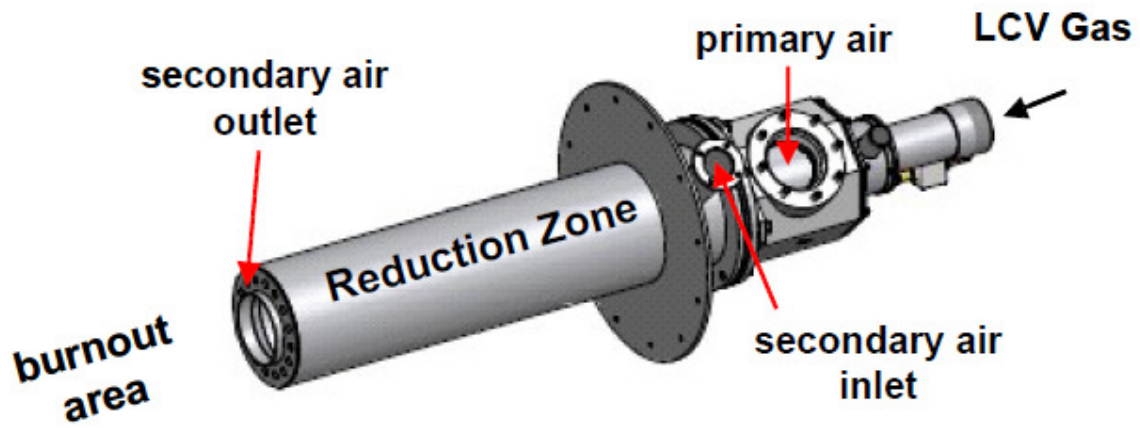


Figure 11 - Developments of the lean gas burner (air staging)

OXYCOAL-AC-Process III

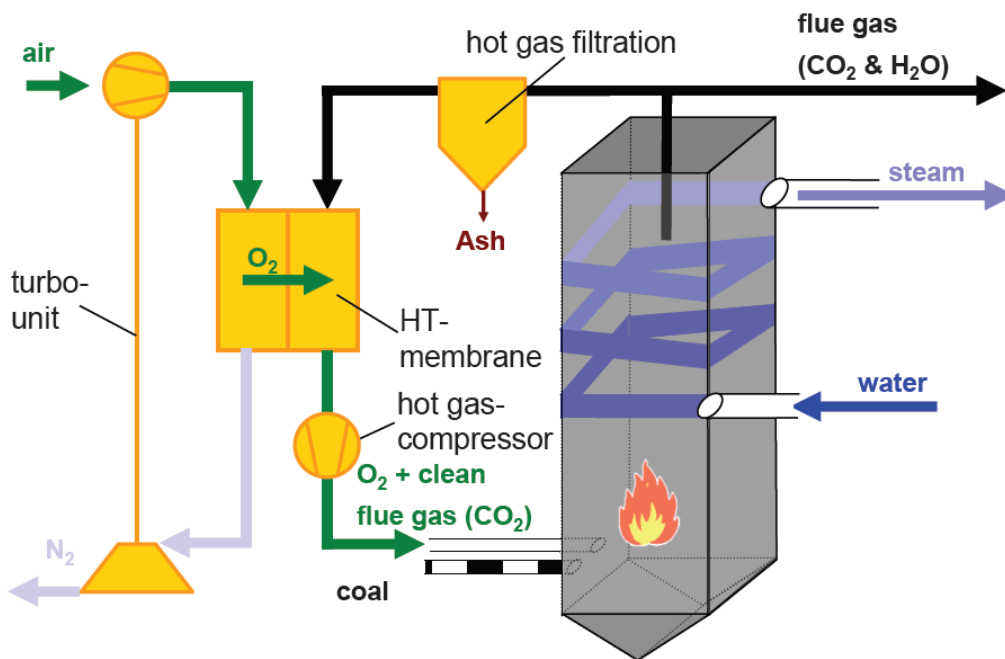


Figure 12 - Diagram of the OXYCOAL-AC project