RECENT DEVELOPMENTS AND APPLICATIONS OF FLAMELESS OXIDATION

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1 INTRODUCTION

The European energy strategy, the future shape of the energy system and market, the development and improvement of technologies for an efficient use of energy are among the most relevant and discussed issues of our time.
Within a low-carbon strategy a step-wise process fixing two main milestones was defined by the European Council in 2007: the first step has been set for 2020 with the goal of 20% less greenhouse gas emissions together with 20% increase in the share of renewable energies and 20% improvement in energy efficiency. Then, a second step refers to 2050 and aims at 80 to 95% cut in emissions. In the particular case of the German energy policy the fulfilment of these objectives is made even more challenging due to the ratification of the so-called "*Energiewende*" which phases out nuclear power in Germany by 2022.
The scope of the present publication is to illustrate how the application of flameless oxidation can actually represent a significant contribution to the achievement of the goals addressed by the European energy strategy for the future decades.
The benefits and opportunities related to the utilization of the flameless oxidation technology still have large potential not only on the industrial field, but also in the private and domestic energy sector as well as in power generation plants.
Basically, two methods can be addressed for the achievement of the goals set by the Energy 2020 strategy: on one hand the CO_2-free power generation, on the other hand the energy conservation through higher efficiency. It can be shown how the implementation of these latter measures implies much more contained economical efforts.

2 ENERGY SAVINGS ENABLED THROUGH *FLOX*® TECHNOLOGY

2.1 Recent developments of burner design

Extensive application of waste heat recovery for preheating combustion air, with consequent energy savings, has been carried out in high temperature furnaces, mainly for the steel industry. Flameless oxidation (*FLOX*® – registered trademark of WS GmbH, Renningen) enables NO_x-emissions at a minimal level despite high combustion air temperatures [1,2,3].
The two FLOX® burners shown below in **Figure 1**, are the result of recent developments in burner design aimed at the optimization of the integrated heat exchangers both in terms of efficiency and costs.

Figure 1 a): self regenerative FLOX® burner: Regemat® M250

Figure 1 b): self recuperative FLOX® burner: Rekumat® S150

Figure 1: High efficiency gas burners for industrial furnaces

Figure 2 shows the improvement in the performance of innovative burner designs for a typical operating condition with 1000°C process temperature. State of the art heat exchanger designs for self-recuperative gas burners are characterized by values of NTU (number of transfer units) around or slightly above 1.
With regenerative and "gap-flow" recuperative heat exchangers, NTU values from approximately 3 to 5 can be achieved mainly due to much larger heat transfer surfaces and, in the case of the gap-flow burner, also due to enhanced heat transfer in the laminar channels configuration.
The heat exchanger design translates into higher air preheating and lower exhaust gas losses that are about halved if compared to the standard designs.

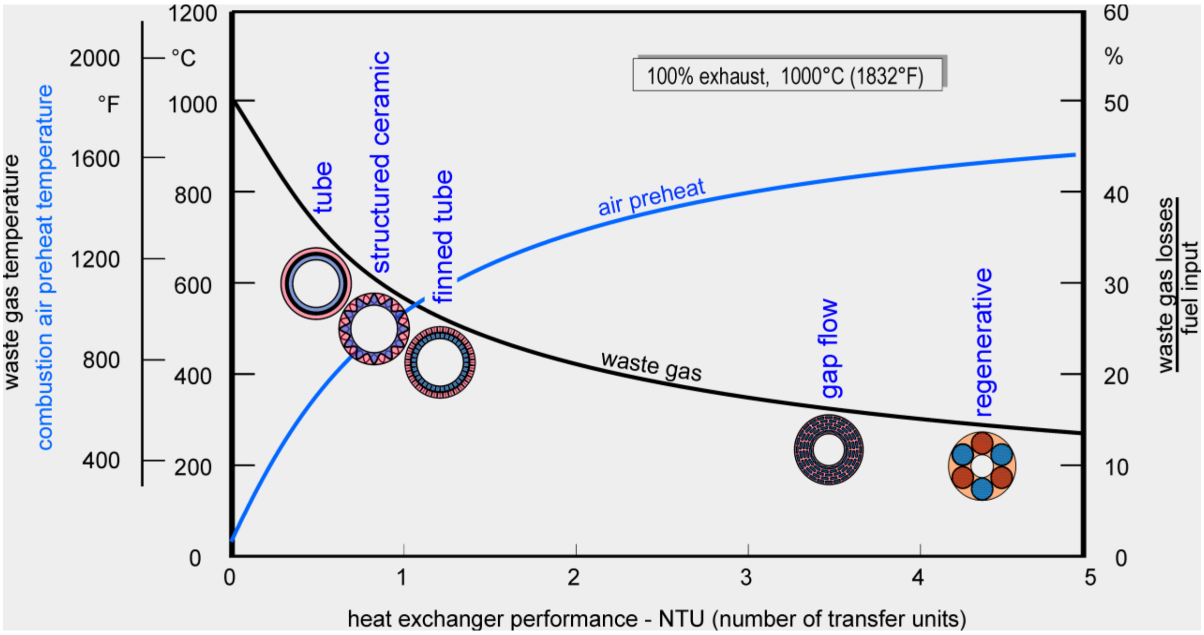

Figure 2 – Effect of heat exchanger design on air preheating and exhaust gas losses

The potential of the technologies mentioned above can be well recognized through a comparison in terms of energy savings between different solutions for high temperature heat treatment applications as shown in **Table 1**. All figures refer to a quite representative application with 1000°C process temperature while the values of primary energy consumptions as well as the related CO_2 emissions are normalized with respect to the energy delivered to the process.
The assumptions on the characteristics of the electric power generation system are related to the German energy mix.
The first case taken into account is the less efficient solution using natural gas heating systems with no heat recovery through air preheat. The efficiency will be approximately 50% and therefore the normalized primary energy consumption equals 2. The same consideration applies to normalized amount of CO_2 emissions.

Table 1 – Comparison on the energy and CO_2 savings potential offered by different technological solutions in industrial heat treatment applications

heating system	natural gas, no air preheat	natural gas, stand. preheat	natural gas, opt. preheat	natural gas, O_2***	electric heating
waste gas losses*	50%	30%	15%	15%	-
losses in the power plant	-	-	-	7%	58%
primary energy** (norm.)	2	1,4	1,2	1,3	2,4
CO_2-emissions (norm.)	2	1,4	1,2	1,6	2,6

* 1000°C furnace temperature
** german energy mix (Source: BMWi)
*** O2: 0,5 kWh_{el} / m^3

The second case represents what can be considered the state of the art in the high temperature thermal treatment industry: burners with integrated recuperative heat exchanges for air preheat with an exhaust outlet temperature of about 600 °C corresponding to a waste gas loss of 30%.
Using natural gas burners with innovative design and optimized air preheating, such as with the WS self-regenerative and gap-flow self-recuperative *FLOX*® burners shown in Figure 1, reduces the waste gas losses by a factor of 2 with respect to the standard heating solution, that is 15% instead of 30 % energy loss.
This is reflected in the lower energy consumption and CO_2 emissions: switching from the current operating heating systems (which is basically a mix of state of the art, electric and no preheat heating technologies) to the innovative natural gas burners designs would represent the achievement of the goals set for 2020 by the European energy strategy.
The comparison with oxy-combustion of natural gas shows how this solution does not represent a real step ahead with respect to the current state of the art since the primary energy consumption is significantly affected by the power consumption of the air separation units.
Finally, the use of an electric heating system in the heat treatment industry is by far the least efficient solution originating the largest impact in terms of primary energy consumption and CO_2 emissions.
The previous analysis shows that the utilization of high efficiency *FLOX*® burners represents an important and profitable contribution to the goals of the European energy policy of the next decade.

2.2 Middle and long term

As far as these innovative gas burner designs are taken into account each saved kW on the gross capacity compared to the state of the art solutions implies additional costs in the range of 50 to a few hundred €uro/kW_{th}. In contrast, the cost for CO_2 free power generating utilities, whether CCS coal, nuclear, solar or wind, would be typically in a range of few to several thousands €uro/kW_{el}. Energy conservation is so far the most economical solution to reduce primary energy consumption and CO_2 emissions.

However, looking further to the long term objectives set by the European Council for 2050 it becomes clear that the huge step represented by the 80-95% reduction in CO_2 emissions will require much bigger efforts and must also include new methods for energy generation. Therefore, it is now crucial to identify and investigate the technological solutions in the energy generation field where the integration of the *FLOX*® technology can play a key role.

3 ENERGY GENERATION USING *FLOX*® TECHNOLOGY

In this section several energy generation solutions will be shortly reviewed to address alternative fields of application for flameless oxidation in addition to the more commonly established use in industry.

3.1 *FLOX Coal II*

Since the 1970s primary measures in pulverized coal combustion have been developed to satisfy the demand of low NOx emissions, e.g. swirl burners and air staging. Nevertheless, high cost flue gas treatment systems like SCR are still necessary to fulfil the legal requirements. With respect to even lower emission limits in the future, new measures are necessary to match the requirements and to reduce the costs of power generation.
Since flameless oxidation is already a mature technology for gaseous fuels, the application to solid fuels still needs to be further developed.
The EU-funded projects "*FloxCoal*" have shown the feasibility and the potential of NOx reduction using pulverized coal in flameless oxidation in bench scale and pilot scale (0.3 MW_{th}) [4].
Now, the project "*FLOXCoal II*" aims to develop scale-up methodology and simulation tools which are required for the implementation of pulverized coal flameless oxidation (*PC-FLOX*) burners in utility plants.

3.2 Gas Turbines

In gas turbines the use of *FLOX*® combustors can help to undercut the NO_x figures of lean premixed combustors even when modifications of the fuel composition occur, for instance introduction of H_2,, made from excess wind power, in the methane grid.

3.3 Biogas plants

If fuel gas is so lean and of varying composition (examples are landfill recovery, blast furnace gas etc) that the gas cannot be burnt in regular burners or flares, then preheating by means of heat recovery is required and flameless oxidation looks like the natural solution. One example is the application of *FLOX*® burners on biogas plants where the low calorific residual gas from the gas separation unit can be safely burnt and used to provide the required thermal power to the plant.

3.4 CHP (Combined Heat and Power generation)

Different types of technologies can be applied where it is meaningful to foresee the utilization of flameless oxidation technology:

- *Cogeneration with Stirling Engines*. The efficiency of the process is narrowly restricted by the Carnot cycle, which depends on the temperature difference between hot and cold reservoir. Flameless oxidation enables to achieve very low pollutant emissions even at high combustion chamber and air preheat temperatures and by doing so allows higher efficiencies with low impact on the environment.

- *Micro Turbines Cogeneration*. Micro turbine cogeneration can also benefit from the use of flameless combustion especially because of the intrinsic adaptability of this technology to different fuel compositions and fuel-to-air ratios.
- *Fuel Cells Modules*. *FLOX*®-Steam-Reforming of methane for hydrogen production combined with fuel cells can be implemented with overall efficiencies of well over 90% (electric >30%) and low emissions in modules for CHP in the class of few kW of electric and thermal power. This range of power can be ideally exploited at the private scale for decentralized power generation and storage without feeding-in the electric grid and contribute to reshape the short- and medium-distance mobility (up to 100 km/day) in agreement with the energy strategy for 2050.

Table 2 – Comparison of fuel costs and CO_2 emissions for different mobility and energy scenarios

comparison of fuel cost and CO2-emissions	fuel cost per 100 km			CO_2 in g / km		
	gasoline	grid power	CHP	gasoline	grid power	CHP
car with internal combustion engine compact car: 6l /100km	10 €			130		
car with electric engine compact car: 20kWh/100km		5 €	1,50 €		110	40
car with electric engine light-weight car: 8kWh/100km		2 €	0,50 €		44	16

all figures rounded:
cost: gasoline 1,70 €/Liter, grid power 0,25 €/kWh, natural gas 0,065 €/kWh
CO2-emissions for grid power in Germany: 550 g/kWh
subsidies, capital cost, etc not considered

Table 2 shows a comparison in terms of fuel costs and CO_2 emissions with 3 different types of vehicles already available on the market: a compact car with internal combustion engine, an electric car of the same size and a light-weight electric car.
The figures show that combining decentralized CHP with light-weight electric mobility can represent a reduction in the CO_2 emissions (from 130 to 16 g/km) that would even fulfil the energy and environmental requirements for 2050 on a fossil fuel based system. Another highly beneficial effect is the reduction of fuel costs for the user.

4 *FLOX*® MODELING: FROM "5 MINUTES CFD" TO "REAL TIME CFD"

The development of new products in the burner technology requires know-how and experience, experimental efforts and the understanding of the complex and interdependent physics that take place within combustion processes. Numerical modeling is considered today an essential tool to improve this understanding.
Recently, a workshop took place in Hinterstein, Germany, in order to realize the idea of fast numerical simulation of flameless oxidation (*5 minutes CFD*) using an open source CFD software package.
Scientists and engineers from WS GmbH and the Universities of Stuttgart, Aachen and Brussels were involved.

The goal of the work was to build a common basic platform for fast flameless oxidation simulations to be used, checked and improved by the participants in a continuous exchange of knowledge and results.
The workshop was quite successful with respect to the downsizing of the calculation times to few minutes and the results obtained from the simulations were showing good agreement with measured data and observation from practical experience.
Certainly, further efforts are planned to check the trustworthiness of the models under a wider set of boundary conditions and to validate them against detailed models and further experimental data.
However, the next target to be pursued would be the development and implementation of “real time - CFD”, i.e. to simplify and fasten the calculations to such a degree that the time required for the simulation would match the physical time of the combustion process.
Based on the results obtained during the workshop, it seems realistic that such goals will be reached in the near future.

5 CONCLUSIONS

Flameless oxidation is successfully applied in the industrial high temperature processes, especially in the steel industry. Further improvements in terms of energy savings are made possible by this combustion technology which allows to combine high air preheating with very low NOx emissions. This led recently to the development of innovative *FLOX*® gas burners with very high efficiencies for industrial applications. The utilization of such burners represents a significant contribution in terms of energy savings and reduction of CO_2 emissions in the frame of the German *Energiewende* and European energy policy for 2020.
The challenging goals in the energy and environmental strategy for 2050 call for much bigger and structural efforts in the energy generation systems in which *FLOX*® can express an even more significant potential.

REFERENCES

[1] Wuenning J.G. – Handbook of Burner Technology for Industrial Furnaces – Vulkan Verlag – ISBN 978-3-8027-2950-8

[2] Baukal C.E. Editor – Industrial Combustion Testing – Chap 23 – CRC Press – ISBN 978-1-4200-8528-0

[3] IFRF Online Combustion Handbook – Files 171-175 – www.ifrf.net

[4] http://floxcoal2.eu-projects.de