Flue-gas coupling of a waste incinerator with a lignite-fired coal boiler: assessment of the best-suited injection concept by computational and experimental methods

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Abstract

The work presented in this paper focuses on the combustion behaviour of the coupled UPSWING (Unification of power plant and solid waste incineration on the grate.) process as well as on the reduction and destruction of pollutants like NOₓ and PCDD/F. The concept, which has been developed by the Forschungszentrum Karlsruhe, describes the coupling of a waste incinerator to a coal-fired power plant for heat and/or electricity generation, both on the steam and on the flue gas side. Possible injection concepts for the incinerator flue gases were investigated by large-scale CFD simulation in order to evaluate the impact of a wet, NOₓ-rich flue gas stream on the overall combustion behaviour of a pulverised coal-fired boiler. The necessary input data for the large-scale simulation was elaborated in various experiments at a semi-technical combustion reactor. The acquired data was used to validate the reliability of the coal combustion model as a prerequisite for the large-scale simulation. The results of both experimental and theoretical work are used to determine the best-suited coupling concept.

Keywords: sustainable waste management, pollutant destruction, CFD, NOₓ.
1 Introduction

The UPSWING process is proposed to use the economic advantages of coupling a waste incinerator with a power plant while avoiding the risks of additional emissions and the deterioration of power plant residue quality. The idea is to inject partly cleaned flue gases from a municipal solid waste incinerator (MSWI) into the furnace of a conventional pulverised coal-fired power plant (Fig. 1). In this context different options for flue gas injection are discussed (1-4). A further option is the utilisation of the flue-gases as carrier gas and drying medium in the coal mills (I). The concept also combines the steam circuit of both facilities (II).

A simple acid scrubbing stage removes more than 95% HCl and approx. 90% of Hg. Other heavy metals are removed by a common filter system (ESP or bag filter), whereas the pollutants NOx, SO2 and PCDD/F (Poly-chlorinated di-benzo dioxins and furanes) are introduced into the power plant process. One of the main tasks of the UPSWING project, funded by the EC within the 5th Framework Programme, is to prove that these pollutants are reduced/destroyed in the power plant process [2].

The benefits of the concept are an improved efficiency of waste-to-energy conversion and a reduction of specific investment costs compared to a same-size waste incinerator. The concept solves environmental deficits of direct co-combustion, such as high- and low-temperature chlorine corrosion and deterioration of power plant residues, and maintains environmental standards while utilising waste as renewable energy source. The concept contributes to environmental and social aspects such as alleviating waste disposal problems, CO2 emission reduction and an improved control of pollutants.

An import factor within the concept is that the composition and the amount of flue gases generated by a waste incinerator change during operation as a consequence of the inhomogeneity of the waste incinerated. This means load changes (mass flow), variable flue gas composition (O2, CO2, water content) and pollutant load (SO2, NOx, PCDD/F) [3]. As a consequence, the location of flue

Figure 1: The UPSWING process: Coupling of a waste incinerator to a coal fired power plant.
gas injection—or the injection concept—is of great importance for the overall performance of the process. With the scope of the project, the following questions have to be answered:

1. Is the ductwork/are the suction devices/are the flue gas de-dusting (ESP)/is the flue gas de-sulpheration (FGD) capable to handle the increase flow? What are the effects on the overall residence time of the flue gases in the furnace in terms of emission reduction (NO\textsubscript{x}) and destruction (PCDD/F)?
2. What are the effects of dilution on the total emissions limits, especially in terms of SO\textsubscript{2} and the overall reduction efficiency of the FGD?
3. What are the effects on the temperature distribution in the furnace? Is the combustion efficiency/fuel burnout reduced?

The work presented in this paper focuses on the evaluation of the effects of coupling on combustion and emission behaviour. This includes the determination of the favourable injection concept and optimised process parameters for coupling in terms of fuel burnout, emission behaviour and residence time of the flue gases in the furnace, which is highly relevant for PCDD/F destruction. Four different alternatives have been identified and were investigated in detail (Fig. 1): The vapour inlets (1) for lignite fired plants, the burner air system (2), the injection via additional injection nozzles above the burner level (3) and the injection into the ash hopper (4).

2 Approach

The basic approach includes an experimental and a theoretical part, whereas the theoretical approach bases on the results of the experimental part and is done by large-scale CFD boiler simulation. The experimental approach describes the evaluation of different injection concepts using a defined incinerator flue gas composition at a semi-technical combustion reactor [7] and the determination of favourable injection concepts.

The theoretical approach includes the modelling of a semi-technical combustion reactor and the improvement and adaptation of an existing NO\textsubscript{x} model based on the results from semi-technical experiments for a specific lignite, the modelling and NO\textsubscript{x} optimisation of a pulverised coal fired lignite boiler and the simulation of different injection concepts and load settings as well as the application of the adapted NO\textsubscript{x} model.

2.1 Experimental approach and results

The experimental work performed and presented in this paper focuses on the evaluation of different injection concepts and the provision of data as initial input for the adaptation of an existing NO\textsubscript{x}-model. The coal combusted during the experiments is comparable to the coal fired in the investigated industrial boiler and was milled/dried using a fan beater mill. All experiments were performed with an excess air ratio of 1.20, corresponding to 3.5% O\textsubscript{2} in the flue
gas at the reactor exit. Combustion air was injected via the primary air duct of the pilot-scale burner. Two different air-staging configurations were investigated during the trials. Burnout air was injected at two different positions into the reactor in order to realise different residence times in reducing atmosphere. The experiments were performed with a fixed wall temperature of 1100°C.

2.1.1 **Flue gas generation and injection**

Artificial incinerator flue gases were generated using a digitally controlled gas-mixing device (HOVACAL digital calibration gas generators 311/111). Using a basic flue gas composition of 80% nitrogen, 10% oxygen and 10% carbon dioxide, NO₂ was added by evaporation of HNO₃(aq). The volume of incinerator flue gases in relation to the flue gas volume from coal combustion was adjusted to 10% [1], which corresponds to 0.40m³N/h(dry) for a coal mass stream of 1kg/h. As full saturation of the flue gases can be assumed after an acid scrubbing step (φ = 1), a quantity of 0.30 kg/m³ was added to the flue gas stream, calculated according equation 1.1 for a scrubber temperature of 70°C:

\[
X[kg_{H₂,O} / kg_{dry}] = 0.622 \cdot \frac{p \cdot \varphi}{p - p \cdot \varphi}
\]  

(1.1)

The temperature of the injected flue gases was 200°C as the installation of a recuperative or regenerative heat exchanger is planned after the scrubbing step for flue-gas reheating [1].

![Injection configuration at the combustion reactor.](image)

The first option investigated was the injection via the secondary air duct of the pilot-scale burner, corresponding to the injection of incinerator flue gases via the air system/vapour inlets of the power plant (Fig. 2 - A.1/B.1). The second option investigated was the staged injection in a distance of 0.9m from the burner, corresponding to the injection of incinerator flue gases via injection nozzles above the burner level (Fig. 2 - A.2/B.2). The concept of incinerator flue gas injection into the ash hopper could not be investigated at the test facility.
because this option would imply an injection “above the burner level”, which is not feasible at this unit. Nevertheless this option was investigated as case C in large-scale simulation.

Aside from baseline operation, i.e. without injection of incinerator flue gases, two primary options were investigated during the trials:

**Case A: Additional injection of MSWI flue gases**
Flue gases were injected via the secondary air duct of the burner [A.1], or injected at 0.9m distance from the burner below the flame [A.2], respectively. The coupled flue gases are therefore diluted and the overall exit oxygen content increases to 4.1 vol.-%.

**Case B: Substitution of combustion air**
Flue gases were injected via the secondary air duct of the burner [B.1], or injected at 0.9m distance from the burner below the flame [B.2], respectively. Combustion air was partly reduced - or substituted - using the remaining 10 vol.-% oxygen in the incinerator flue gases for coal combustion. Although the flue gas amount increases slightly, the overall exit oxygen content remained constant.

### 2.1.2 Experimental results and discussion

**Case A: Additional injection of incinerator flue gases**
Fig. 3 and Fig. 4 illustrate the NOx results for flue gas injection via the secondary air system [A.1] at 0m for unstaged combustion and for two staging configurations ($\lambda_{\text{coal}} = 0.95$ and 0.85). Additional flue gases (FG) were injected at a load ratio of 10%, increasing the available oxygen in the main combustion zone. The NOx concentration in the flue gases was increased from 0 to 400ppm. Residence time of the flue gases in the reduction zone was 1s for burnout air injection at 0.9m and 2s for burnout air injection at 1.4m.

![Figure 3: A.1 - FG residence time 1s (0/0.9m).](image)

For unstaged combustion, the results indicate no major influence of the incinerator flue gases as well as the NOx load compared to the baseline case. For staged combustion however, the emissions are significantly higher compared to
the baseline case as a consequence of the increased oxygen level in the reduction zone (Fig. 4). The influence of the additional NO\textsubscript{x} load (200/400ppm) is generally low, which indicates that the coal reduces the additional NO\textsubscript{x} load aside from dilution effects.

Fig. 5 shows the NO\textsubscript{x} results for flue gas injection via the lateral injection port at 0.9m [A.2]. The residence time in the reduction zone is 2s for the coal and 1s for the incinerator flue gases. Staging settings and composition of the incinerator flue gases are similar to the injection at burner level.

![Figure 5: A.2 - FG residence time 1s (0.9/1.4m).](image)

The overall emissions are significantly lower compared to the results found in [A.1]. The point of injection at 0.9m is well below the flame, resulting in lower oxygen concentration and efficient reducing conditions in the main combustion zone. In case of additional flue gases injection, this concept seems to be preferable in any case.

![Figure 6: B.1 - FG residence time 1s (0/0.9m).](image)

![Figure 7: B.1 - FG residence time 2s (0/1.4m).](image)

**Case B: Substitution of combustion air**

Fig. 6 and Fig. 7 illustrate the NO\textsubscript{x} results for flue gas injection via the secondary air system [B.1]. Flue gases (FG) were injected on a load ratio of 10%, whereas
the NO\textsubscript{x} concentration in the flue gases was increased from 0 to 400ppm comparable to Case A. Combustion air was reduced - or substituted - in order to keep the oxygen level comparable to the baseline case.

The NO\textsubscript{x} emissions are generally lower compared to [A.1], Fig. 6 shows even lower results compared to baseline. Fig. 8 shows the NO\textsubscript{x} results for flue gas injection via the lateral injection port at 0.9m [B.2]. Staging settings and composition of the incinerator flue gases are similar to the injection via the secondary air inlets. Combustion air was substituted consequently. The residence time in the reduction zone is 2s for the coal and 1s for the incinerator flue gases.

![Figure 8: B.2 - FG residence time 1s (0.9/1.4m).](image)

Substitution of combustion air leads to lower emissions of the coupled process compared to additional injection of flue gases. This can be well explained with the remaining oxygen of the flue gases. In case of injection via the secondary air system [B.1], the emissions are comparable to baseline operation for longer residence times and an air ratio of 0.85 (Fig. 7). In case of lateral injection (Fig. 8), lower emission levels can be determined for staged combustion at $\lambda_{\text{coal}} = 0.95$. The results for $\lambda_{\text{coal}} = 0.85$ are comparable to baseline operation as well as to the injection via the secondary air system.

Considering both basic options, the additional injection of incinerator flue gases and the substitution of combustion air, the second option seems to be preferable. Nonetheless the efforts for control and regulation at the power plant have to be taken into account as a consequence of fluctuations in the flue gas composition of the waste incinerator.

Although comparable emission levels are achievable for the coupled process, it has to be emphasised that the total flue gas volume is increased by 10% for the additional injection (Case A) and 5% for the substitution of combustion air (Case B). Considering comparable emission levels for the coupled process, the total amount of emitted pollutants will be increased.

### 2.1.3 Burnout level of the coal in the combustion reactor

During the experiments fly ash was sampled at the reactor exit and analysed towards carbon (C), hydrogen (H), nitrogen (N) and sulphur (S) content. In order to compare the results from the different experiments it had to be assured that the
particle bound nitrogen was completely released into the gas phase. Several of the fly ash samples were analysed and it became obvious that the burnout level of all samples - even in air staging configuration - was higher than 99% (less than 1% C in the ash). No remaining nitrogen, sulphur or hydrogen could be determined in any sample.

### 2.2 Theoretical approach and results

#### 2.2.1 Simulation of semi-technical combustion reactor

The acquired data from the experiments described above were used to validate the reliability of the coal/NO\textsubscript{x} combustion model of the 3D-CFD code AIOLOS as a prerequisite for the large-scale simulation. AIOLOS, developed by the Institute of Process Engineering and Power Plant Technology (IVD) at University of Stuttgart, mainly deals with pulverized coal combustion. AIOLOS is based on a conservative finite-volume formulation, using the SIMPLEC- or SIMPLE-method for velocity-pressure coupling, standard k-\(\varepsilon\)-model or differential Reynolds stress model for turbulence. Prior to the modifications in the present work, the program included a four-step-reaction scheme, two for heterogeneous reactions of pyrolysis and char combustion and two for the gas phase reactions. Radiative heat transfer is calculated either by a Discrete-Ordinates-method or 5 other different radiation models [4]. More detailed information about the code AIOLOS can be drawn from [5].

![Scheme of the NO model.](image)

The applied global NO\textsubscript{x} model allows the prediction of NO\textsubscript{x} emissions from unstaged and staged combustion of pulverised coal. The main gaseous nitrogenous species are HCN, NO, N\textsubscript{2} and the highly reactive intermediate NH\textsubscript{3}. HCN is considered to be released from coal during devolatilisation which is either oxidised to NH\textsubscript{3}, which again can either be oxidised to NO or reduced to N\textsubscript{2} by NO. Also a recycle reaction, describing the destruction of NO by CH\textsubscript{4} to HCN is implemented. In order to account for the differences in coal rank, the distribution of nitrogen in the products of primary pyrolysis (HCN, NH\textsubscript{3}, tar-N and char-N) is estimated in a pre-processing step, prior to the CFD calculation. A more detailed description of the model, e.g. reaction rates and parameters, can be found in [6].
Adaptation of existing coal/NO model
For the simulation of the semi-technical combustion reactor a 2D numerical grid was generated, formulated in cylindrical coordinates. In a first step simulations were carried out in order to correctly depict the coal combustion properties at the furnace exit. Therefore for each experimental setup in case of changing boundary conditions, e.g. air-to-fuel ratio, the modelled particle size distribution of the coal was adapted to guarantee a complete coal/char burnout and the secondary air was fine-tuned to correctly predict the measured O₂/CO₂-concentrations at the furnace exit.

In a second step the NOₓ model was applied as a post-processor to determine the NOₓ-formation in the combustor. The above mentioned distribution of nitrogen in the products of primary pyrolysis (HCN, NH₃, tar-N and char-N) as an initial boundary condition for the NOₓ model appears to have a major influence on the model predictions. Hence variations of these parameters have been used to adapt the predictions of the model for every experimental setup to the measured values, in order to gain model parameters for the later application of the large-scale power plant.

Results
The NOₓ simulations show a good correspondence of predicted and measured results as displayed in Fig.10 and 11.

![Figure 10: NOₓ simulation results compared to measured data (0% flue gases).](image1)

![Figure 11: NOₓ simulation results compared to measured data (λ=0.85;add. flue gases/substituted).](image2)

The model should be able to be applied to large-scale.

2.2.2 Simulation of flue gas coupling in large-scale applications
Modelling of PF boiler
The numerical grid of an existing lignite-fired power plant with 1.865.555 calculated cells, including 11 domains was created. In Fig. 12, the whole grid and a zoomed-in burner domain, showing the arrangement of the burners are shown. Feasible access for the incinerator flue gases are the hopper air inlet, the vapours nozzles and the over fire air nozzles (see Fig.12). The latter possibility was counted out because of the expected too short residence time of the flue gas injected through the over fire nozzles in terms of PCDD/F destruction.
To find the best suited injection mode for the incinerator flue-gases in a large-scale application a parameter study was carried out. Besides the vapours and hopper air inlets additional virtual nozzles were taken into account as possible locations. The virtual nozzles were designed at 20.0m and 24.0m, respectively, located between the vapours and over fire air nozzles (see Fig. 12). The second parameter besides the location is, following the approach of the experimental work, an additional flow of flue gases from MSWI through the discussed inlets, or flue gases from MSWI that partly replace the combustion (secondary) air.

The memory demand of approx. 3GB together with the big number of internal calculated cells necessitates to run the simulations on a supercomputer to gain results for the six variants in an acceptable timeframe. The simulations were performed each on one node (8 processors) on the NEC-SX6 platform at the HLRS (High Performance Computing Center) Stuttgart.

Set-up of the parameter study
The following table 1 characterises the different simulated variants of the parameter study.

The NO\textsubscript{x} content of the flue gases was kept constant at 400ppm and the water content of the flue gases remained at a constant level of 0.37 m\textsuperscript{3}/(m\textsuperscript{3} flue gas) for the different variants (except baseline).

NO\textsubscript{x}-optimisation of the baseline case
Besides the attempt to find the best-suited injection concept for the incinerator flue gases, it was an objective to find an optimal operation mode of the PF-boiler in terms of reduced NO\textsubscript{x} emissions. Since the experiments showed the biggest reduction potential at a burner air-to-fuel ratio of 0.85 (see 4.3), the coal-dust and air distribution of the original burner settings were modified in such a way that secondary air was partly reduced in the burner section and added to the over-fire air and the additionally designed injection nozzles (at 24.0m) to maintain the total air-to-fuel-ratio.

Figure 12: Discretisation of the industrial boiler.
Table 1: Characterisation of different simulated variants.

<table>
<thead>
<tr>
<th>Variant</th>
<th>Operation mode</th>
<th>Baseline</th>
<th>A.1</th>
<th>A.2</th>
<th>B.1</th>
<th>B.2</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mills in operation</td>
<td>7 of 8</td>
<td>7 of 8</td>
<td>7 of 8</td>
<td>7 of 8</td>
<td>7 of 8</td>
<td>7 of 8</td>
<td>7 of 8</td>
</tr>
<tr>
<td>Injection location of the flue gases via</td>
<td>-</td>
<td>vapours inlets of the burner @15.96m</td>
<td>virtual nozzles @ 20.0m</td>
<td>vapours inlets of the burner @15.96m</td>
<td>virtual nozzles @ 20.0m</td>
<td>hopper air inlet @5.90m</td>
<td></td>
</tr>
<tr>
<td>Amount of injected flue gases [% of total flue gas of PF boiler]</td>
<td>-</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Flue gas replaces partly combustion air</td>
<td>-</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td></td>
</tr>
</tbody>
</table>

Results
The results of the different variants in terms of the furnace exit values of temperature, NOx and unburned fuel (C in ash) and also the radiative and convective heat to the furnace walls, represented by Heat to walls, are displayed in Fig. 13.

![Figure 13: Simulation results of the industrial boiler.](image)

A method to estimate the residence times of the flue gases in the boiler at certain temperatures without a kinetic model in order to study the destruction of PCDD/F was developed. The residence time $\tau$ of the flue gases in the boiler is calculated as shown in eq. (1.2). Therefore, the single averaged residence time of the flue gases in every vertical cell layer $i$ from the individual inlet of the flue gases to the furnace exit (Fig. 13) are summed up. $\bar{v}_i$ is the mean vertical velocity, and $h_i$ the furnace height in the cell layer $i$, respectively.
The mean temperature $T_m$, of the flue gases can be calculated by expression (1.3), whereby the temperatures are weighted with their individual residence time in every cell layer $i$ from the individual inlet of the flue gases to the furnace exit and the product is summed up.

$$T_m = \frac{\sum T_i \cdot \tau_i}{\tau}$$

Figure 14: Residence time of the flue gases > 850°C.

In Fig. 14 the flue gas residence time of the different variants together with their mean temperatures are compared.

A reason for the short residence time in this boiler is the strong diminution of the boiler at the combustion chamber exit and the subsequent acceleration of the flue gases from approximately 20m/s at a furnace height of 30.0m up to 60m/s at 40.0m.

3 Conclusion

The work presented in this paper focuses on the effects of flue gas coupling on combustion and emission behaviour, including the determination of the favourable injection concept. This was done by an integrated experimental and theoretical approach, using the results of the experimental part as validation data for a global NO$_x$ model. The different concepts for flue gas coupling were investigated by large-scale boiler simulation of an industrial furnace. The following parameters were determined to evaluate the theoretical results:

- Temperature in comparison to baseline. Higher mean temperatures improve fuel burnout. The mean temperature does not imply maximum temperatures in the flame in terms of thermal NO production (lower -, comparable +, higher ++);
- Residence time of the incinerator flue gases in the furnace. Longer residence time are considered beneficial in terms of pollutant destruction (< 1s : -, > 1s : +);
- NO\textsubscript{x} emission compared to baseline. Increased total emission are considered negatively (higher -, comparable +, lower ++);
- C in ash: An increase carbon content at the reactor exit is worse in terms of combustion efficiency (higher -, comparable +, lower ++);
- Heat to walls: The radiative and convective heat to the furnace walls compared to baseline operation (higher ++, similar +, lower -)

Table 2 summarises the evaluation of the investigated coupling concepts according to the parameters defined:

<table>
<thead>
<tr>
<th></th>
<th>A.1</th>
<th>A.2</th>
<th>B.1</th>
<th>B.2</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>add, vapours</td>
<td>add, nozzles</td>
<td>subst, vapours</td>
<td>subst, nozzles</td>
<td>subst, hopper</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>-</td>
<td>--</td>
<td>-</td>
<td>--</td>
<td>+</td>
</tr>
<tr>
<td>Residence time</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>NO\textsubscript{x}</td>
<td>++</td>
<td>-</td>
<td>--</td>
<td>+</td>
<td>--</td>
</tr>
<tr>
<td>C in Ash</td>
<td>-</td>
<td>--</td>
<td>-</td>
<td>--</td>
<td>-</td>
</tr>
<tr>
<td>Heat to walls</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

It has to be stated that all investigated injection concepts have a more or less negative impact on the coal boiler, i.e. in terms of emissions, temperature reduction of the flame or fuel burnout. This could be expected, as the injection of relatively cold and wet flue gases does not seem beneficial in terms of boiler efficiency. Nevertheless when considering the concept with the modest effects on combustion behaviour and boiler performance, option A.1, the additional injection of the incinerator flue gases via the vapours inlets is the best solution for the investigated industrial boiler. The benefits of this coupling concept are

- the lowest NO\textsubscript{x} emission of all investigated concepts including the baseline case;
- the heat flux to furnace walls is comparable to baseline operation (boiler performance);
- the minimum efforts in terms of control and regulation, especially in comparison to the substitution of (coal) combustion air.
Acknowledgements

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