Waste Management 73 (2018) 301–306

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Highly efficient combustion with low excess air in a modern energy-from-waste (EfW) plant

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A R T I C L E I N F O

Article history:
Received 10 February 2017
Revised 6 June 2017
Accepted 27 June 2017
Available online 8 July 2017

Keywords:
Energy-from-waste
Grate incineration
Low excess air
Nitrogen oxides
Carbon monoxide
Combustion control

A B S T R A C T

The effect of low excess air and high adiabatic combustion temperatures on CO and NOx formation has been investigated on a commercially operated energy-from-waste plant. With optimal combination of low O_2 levels and stable combustion control, uncontrolled NOx levels could be lowered to 100–150 mg/Nm^3 (dry, at 11% O_2) while keeping CO emissions at low levels. Even at adiabatic temperatures above 1400 °C thermal NOx hardly contributed to the total NOx emissions in a grate-fired EfW plant. An advanced combustion control system allowed continuous operation with very little excess air ($\lambda < 1.2$) while keeping CO and NOx at levels well below the legal emission limits.

1. Introduction

The investigated grate-fired energy-from-waste (EfW) plant Renergia is located close to Lucerne, Switzerland and started operation in 2015. Hitachi Zosen Inova (HZI) delivered the complete combustion system including the boiler, as well as the flue gas treatment system. The plant reaches high energy efficiency by exporting process steam to a nearby paper factory and by using an efficient combustion system based on the latest technology available for EfW plants.

After more than a year of operation, optimization, and monitoring, we have been able to gain new insights into the waste combustion process under highly energy-efficient conditions with low excess air. Today the plant runs with a the lowest O_2 concentrations within the original design range of 3–7 vol% (wet) at the boiler exit. For comparison, traditional EfW plants operate with oxygen concentrations above 5 vol% (wet) corresponding to excess air ratios above 40% (Niessen, 2010).

One benefit of lower excess air ratios is the reduction of uncontrolled nitrogen oxides (NOx) formation during waste incineration. NOx in the flue gas can stem from three different sources (Villani et al., 2012). Most NOx in EfW plants is formed by oxidation of nitrogen species in the waste fuel (fuel NOx). At high temperatures (typically above 1450 °C) also thermal NOx can occur, while prompt NOx is hardly relevant in waste fired combustion processes (Sørum et al., 2001). It is generally assumed that thermal NOx is only of minor significance in EfW plants (Jørgensen and Madsen, 2000). However, EfW plants are usually designed for and operated at moderate adiabatic temperatures (<1300 °C), while little knowledge is available regarding potential NOx formation at higher adiabatic temperatures (>1400 °C).

Most NOx emissions in EfW plant arises from fuel NOx. Its precursors such as HCN or NH_3 are released directly from the waste and oxidized into nitrogen monoxide (NO). The formed NO can be decomposed again by hydrocarbon radicals into HCN (Visona and Stanmore, 1996). This equilibrium is controlled by the presence of oxidising and reducing species. With less air taking part in the combustion process, the equilibrium is shifted away from NO resulting in lower NOx emissions (Streibel et al., 2006; Miyagoshi et al., 2007; Waldner et al., 2013).

Other well-known primary measures for NOx reduction (Houshfar et al., 2012) include staged injection of secondary air (Martin et al., 2015; Speth et al., 2016) as well as the use of recirculated flue gas (Liuzzo et al., 2007).

An additional benefit of operating the plant with low excess air is the improved plant efficiency. Thermal losses associated with the flue gas flow are reduced (Miyagoshi et al., 2007) and less power is consumed by the air fans (primary and secondary air as well as the induced draught fan). Due to the reduced exhaust gas flow rate, the gas velocities within the combustion chamber and

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http://dx.doi.org/10.1016/j.wasman.2017.06.049
0956-053X/

boiler are reduced as well, resulting in less fly ash, which saves landfill costs.

However, the reduction of excess air is limited by the occurrence of significant amounts of unburnt species such as carbon monoxide at very low air-fuel ratios (Rogaume et al., 2002). Even with an improved intermixing of the fuel-rich flue gas with secondary air, a perfect mixing is not realistic (Waldner et al., 2013). At certain locations in the combustion chamber and within the turbulent eddies, too little oxygen will be available for complete oxidation of the fuel, leading to unacceptable emissions of CO and other compounds.

Here, the limits of low excess air operation have been elucidated on a modern, commercially operated EfW plant with a focus on reduction of NOx formation and stable operation of the plant.

2. Material and methods

2.1. Plant description

The EfW plant Renergia in Lucerne, Switzerland comprises a grate fired combustion process and a dry flue gas treatment system. It consists of two identical lines with a total annual waste throughput of 200,000 tonnes and a thermal capacity of 47 MW per line. The plant has been designed for waste net calorific values (NCV) between 9 and 16 MJ/kg. The combusted solid waste mixture originates from municipal and industrial sources and exhibits a typical waste NCV between 10 and 15 MJ/kg as derived from a thermal and mass balance. A longitudinal cut of the plant is shown in Fig. 1. The boiler is fully cladded in the first pass without any refractories. The plant is operated with moderate live steam parameters of 410 °C at 40 bars. The grate (INOVA grate) consists of two lanes, each having four individually controlled grate elements. The primary air is preheated and its flow rate through the individual grate elements is fully controlled with dampers and measured with venturis. The primary air control system assures an energetically optimized operation of the fan and dampers. The secondary air enters the combustion chamber together with recirculated flue gas through concentrical nozzles. The nozzles are placed on two levels, each with an array of nozzles on the boiler and bunker side. Recirculated flue gas is extracted after the electrostatic precipitator. The distribution of secondary air and recirculated flue gas to the individual nozzle arrays is controlled with dampers.

The flue gas treatment section (see Fig. 1) was designed for a gradual decrease of the flue temperature and comprises a first reactor and fabric filter operating with $NaHCO_3$ for removal of HCl and SO_2 followed by an SCR catalyst that reduces the NOx emissions down to 35 mg/Nm^3 (at 11% O_2). After a first extraction of heat from the flue gas by an external economizer the flue gas is further treated by $Ca(OH)_2$ and lignite coke for polishing the remaining acids from the flue gas and removal of VOCs and heavy metals. After a last temperature reduction with the aid of a condensate preheater the flue gas leaves the plant through the stack.

2.2. Flue gas analysis

An extractive raw gas analyser (Sick, MCS 300 P) installed after the electrostatic precipitator (ESP) was used to monitor the uncontrolled NOx and CO concentrations. The amount of uncontrolled NOx was cross-checked by reverse calculation from the flue-gas flow and the NOx concentration at the stack, as well as the amount of ammonia solution consumed for the selective catalytic reduction (SCR) of the NOx according to Equation (1).

$$4\ NH_3 + 4\ NO + O_2 \rightarrow 4\ N_2 + 6\ H_2O \qquad (1)$$

The NOx concentrations obtained by this reverse calculation were in excellent agreement (see Fig. 2).

O_2 concentration in the flue gas was measured in-situ upstream the ESP (Sick, Zirkor 302E). Excess air in terms of lambda (λ) was roughly estimated using the O_2 concentration in the dry flue gas according to Eq. (2).

$$\lambda = \frac{21}{21 - O_{2,dry}} \qquad (2)$$

2.3. Combustion control system

When strongly reducing the amount of air being present in the combustion process it is more likely that CO is formed, especially in situations, when the combustion intensity is higher than required. A deviation of the O_2 concentration below its design setpoint acts as an indicator for increased combustion intensity. When only little O_2 is available for complete oxidation, strong deviations of the O_2 concentration need to be avoided.

As a consequence, an excellent combustion control system (CCS) is required when operating an EfW plant at very low O_2 concentrations right at the optimum point regarding CO and NOx formation. Therefore a new HZI CCS has been implemented, that adjusts the different air flows, the grate movement and the ram feeder speed according to the measured live steam flow and O_2 concentration at the boiler exit. The CCS is further supported by additional sensors and logic:

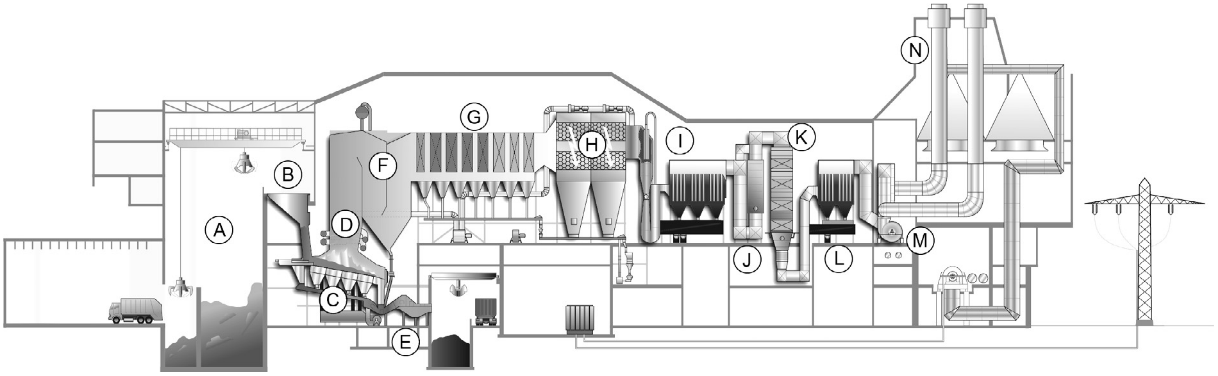

Fig. 1. Longitudinal cut of the Renergia energy-from-waste plant. (A) bunker with segregated compartments; (B) feed hopper; (C) combustion grate; (D) staged injection of secondary air and recirculated flue gas; (E) ram bottom ash extractor; (F) boiler; (G) horizontal pass with super heaters and economizers; (H) electrostatic precipitator; (I) dry flue gas treatment with $NaHCO_3$; (J) SCR catalyst; (K) external economizer; (L) flue gas treatment with $Ca(OH)_2$ and lignite coke; (M) induced draught fan; (N) stack.

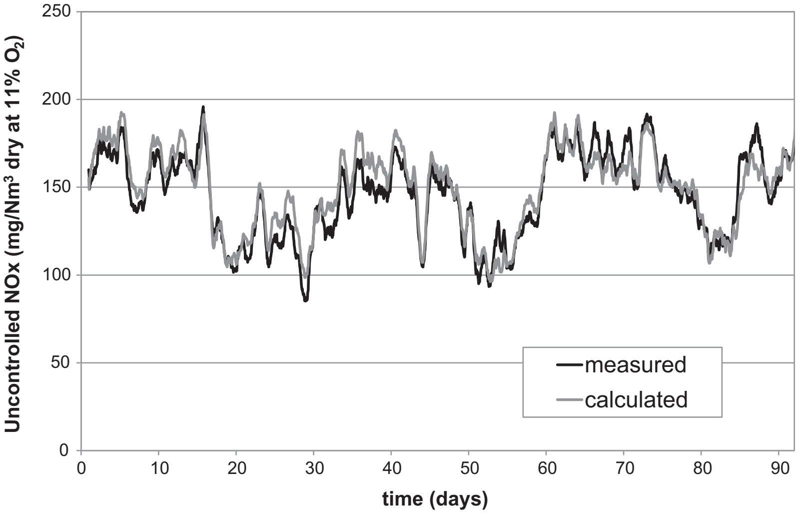

Fig. 2. Comparison of directly measured uncontrolled NOx concentrations with the ones obtained from reverse calculation over a time period of 3 months. The values are in excellent agreement.

- A 3D laser scanner mounted above the feed hopper provides information on the type of waste entering the combustion chamber.
- The waste net calorific value is estimated from the flue gas composition.
- The pressure difference across the grate indicates the waste bed height and its compactness.
- Video analysis is used to derive the position and curvature of the fire end line from the combustion chamber camera image.

2.4. Test campaigns

Several tests have been carried out between summer 2015 and 2016, while the combustion process was continuously optimised. In the course of the test campaign, the excess air was lowered from an initial design value of 5 vol% O_2 at the boiler exit down to less than 3 vol% O_2 (wet). This was achieved by reducing the amount of primary and secondary air and adjusting their distribution as well as by optimising the parameters and logic of the combustion control system. The adiabatic temperature was controlled by altering the amount of recirculated flue gas entering the combustion chamber. The test periods shown in the results section were selected based on continuous operation at full load (without altering the combustion parameters) and reliable data from flue gas analyser.

3. Results and discussion

3.1. Uncontrolled NOx

3.1.1. Effect of excess air

Uncontrolled NOx formation strongly depends on the amount of O_2 being present in the combustion process (Waldner et al., 2013). Here we could reproduce these results for extended continuous operation periods. The influence of the O_2 setpoint on uncontrolled NOx is shown in Fig. 3 for the region between 2.33 and 5 vol% O_2 (wet). The measured O_2 concentration at the boiler exit fluctuates around this setpoint (see also Figs 7 and 8). Taking 5 vol% O_2 as a reference, the amount of uncontrolled NOx is reduced from above

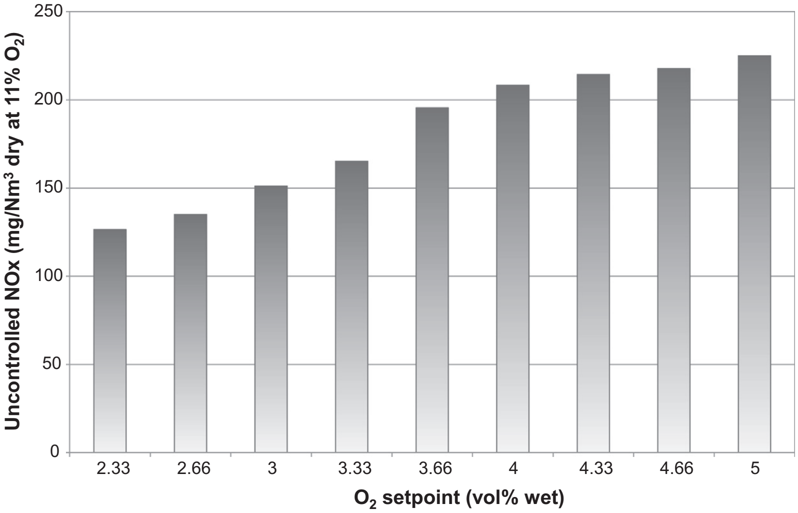

Fig. 3. Uncontrolled NOx concentration as a function of the O_2 setpoint. Uncontrolled NOx is markedly reduced to below 150 mg/Nm^3 (at 11% O_2) when reducing the excess air to less than 3 vol% O_2.

200 mg/Nm^3 to below 150 mg/Nm^3 (at 11% $O_{2,\ dry}$) when lowering the O_2 setpoint to 3 vol% (wet) or even lower.

In Switzerland, all emission limits are referenced to 11 vol% $O_{2,\ dry}$. As a consequence, by lowering the O_2 in the combustion process, e.g. from 5 to 4 vol%, the corrected concentrations at 11 vol % $O_{2,dry}$ are reduced by 5.9%. However, the lower corrected NOx concentrations do not only originate from this mathematical correction, but also from the combustion process itself, as derived from the difference between the measured NOx emissions and the calculated contribution of the correction to 11 vol% $O_{2,dry}$. Fig. 4 visualises the contribution of the two effects when lowering the O_2 setpoint from 5.0 down to 2.33 vol% (wet). A setpoint of 5 vol% O_2 was used as reference. Fig. 4 reveals that the correction to 11% $O_{2,dry}$ is not the main driver for the NOx reduction but rather the reduction of O_2 taking part in the combustion process shifting the equilibrium away from NO (Visona and Stanmore, 1996).

3.1.2. Adiabatic temperature

The significance of thermal NOx formation was investigated up to adiabatic temperatures of 1450 °C. The Renergia plant is equipped with a recirculating flue gas (RFG) system that allows adjusting of the adiabatic combustion temperature while keeping O_2 concentrations stable. The adiabatic temperature was calculated iteratively using a thermal balance.

Fig. 5 exemplarily shows the resulting uncontrolled NOx concentrations while increasing the adiabatic temperature from about 1300 °C to above 1400 °C. To increase the adiabatic temperature, the RFG flow rate was reduced in combination with a slight reduction of the average O_2 setpoint from 3.5 to 3.2 vol% (wet) for a test period of 10 days. For comparison, the preceding 15 days are shown in Fig. 5. No increase of NOx was observed with higher adiabatic temperatures. This demonstrates that contribution of thermal NOx is not significant in EfW plants for adiabatic

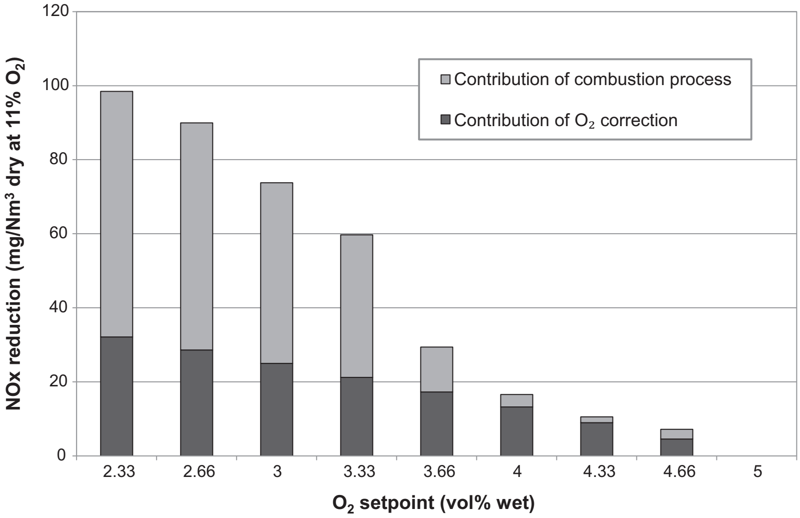

Fig. 4. Contribution of the combustion process and the correction to 11% O_2 to the reduction of uncontrolled NOx as a function of the O_2 setpoint. An O_2 setpoint of 5 vol% O_2 was chosen as reference.

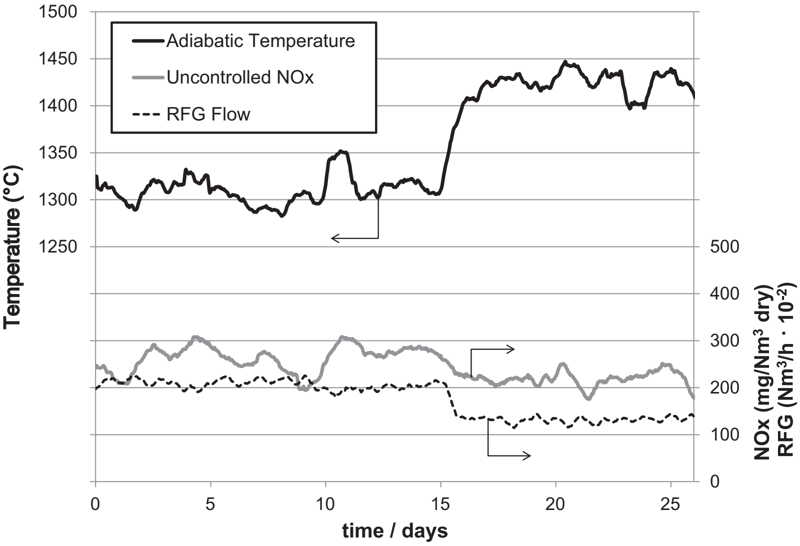

Fig. 5. Half day moving average values for the adiabatic temperature (top), uncontrolled NOx (bottom) and flow rate of recirculated flue gas (bottom). The adiabatic temperature was increased from 1300 to above 1400 °C by reducing the RFG flow rate without significantly affecting NOx concentration.

temperatures up to 1450 °C, if local peak temperatures can be avoided within the flame itself. In this plant, this was realised with the combination of RFG technology, the injection on two stages and fully cladded boiler walls. The absence of refractories in the combustion chamber might help in keeping thermal NOx low, as the thermal energy is faster transferred from the flue gas to the boiler, thus reducing the peak temperatures in the combustion chamber.

3.1.3. Carbon monoxide

When reducing the amount of O_2 in the combustion process the formation of unburnt species, i.e. carbon monoxide (CO) becomes more significant. Thus, a good combustion control system is required when operating EfW plants at very low O_2 setpoints (see chapter 3.2).

Fig. 6 shows the correlation of CO with uncontrolled NOx. NOx decreased with less excess air, but at a certain limit not all CO was completely oxidised to CO_2 (Eskilsson et al., 2004). The correlation of CO with NOx is even more pronounced than expected considering only the O_2 concentrations. Very low NOx concentrations below 100 mg/Nm^3 were usually accompanied with higher CO emissions. Above 100 mg/Nm^3 NOx (dry at 11% O_2) the remaining CO measured with the raw gas analyser was stable around 20 mg/Nm^3. The optimum point of operation is therefore a trade-off between preventing oxidation of NOx precursors and full oxidation of CO. On the Renergia plant this optimum is located between 100 and 150 mg/Nm^3 uncontrolled NOx, which was achieved with an O_2 setpoint between 2 and 3 vol% (wet) corresponding to λ values below 1.2

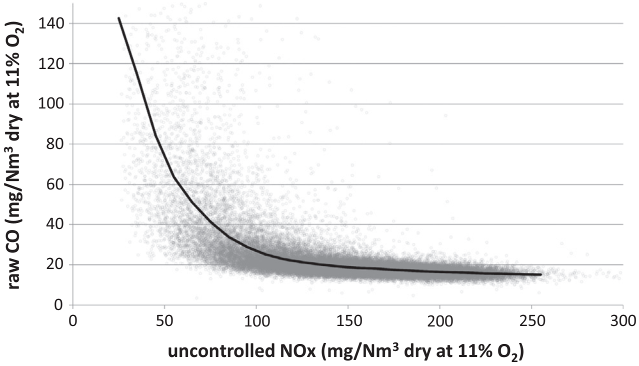

Fig. 6. Amount of CO as a function of NOx concentration. The dots represent one minute averaged values over a time period of one month. The black line is a trend line for visualisation purpose.

To assure operation of the plant at this optimum point, the combustion control system was modified for continuous and automatic adjustment of the O_2 setpoint according to the current CO emission level (see Fig. 7). With this control active, the amount of uncontrolled NOx could be further reduced to nearly 100 mg/Nm^3 while CO emissions slightly increased. Interestingly on the Renergia plant this optimal operation point is very low with respect to O_2 concentrations (about 2.3 vol% wet in average). The next chapter briefly explains what is needed to assure stable operation at such low O_2 concentrations without formation of significant amounts of CO.

3.2. Combustion control

A good combustion control system is essential when operating an EfW plant at such low excess air ratios while keeping CO emissions within the legal limits. The stable operation is shown in Fig. 8 depicting the live steam flow and O_2 concentrations at the boiler exit. The data points are based on 1 min averaged values. It can be seen that the live steam fluctuations are very small with only little deviation from the setpoint. In fact, the live steam flow hardly exceeds a control band of ±3%. As a directly related process value, the measured O_2 concentration at the boiler exit is also very stable, remaining most of the time within a control band of ±1 vol% around its setpoint of 3 vol% (wet). It should also be noted that the O_2 concentration never falls below 1.5 vol% where significant amounts of CO might be formed.

In addition to Fig. 8, the probability density function of the O_2 concentration at the boiler exit and of the live steam flow deviation from its setpoint is shown in Fig. 9. For these calculations, 1 min average values have been used over a time period of 1 month. Based on 1 min averaged values, the typical live steam standard deviation is below 1%. The plant runs more than 98% of the time with a live steam flow within a deviation of ±3% from the setpoint.

Besides the optimised combustion control system in combination with additional sensors other factors might contribute to this

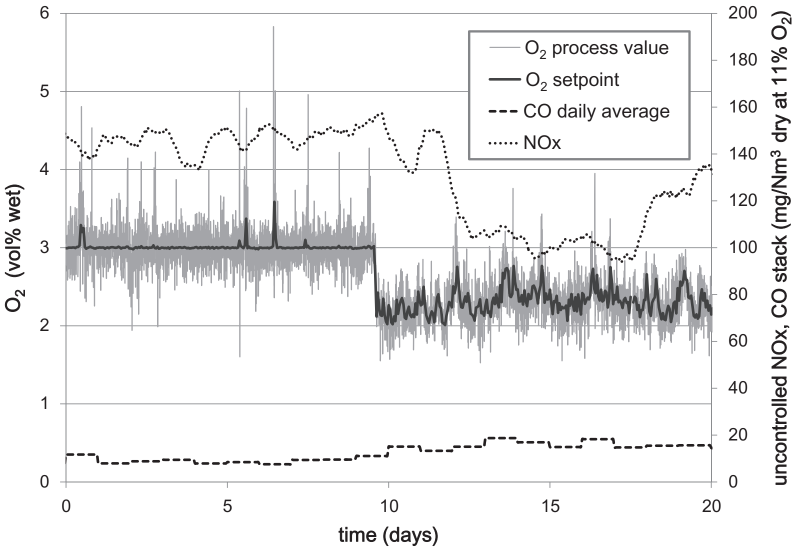

Fig. 7. Operation of the plant with constant O_2 setpoint of 3 vol% (up to day 10) and with variable O_2 setpoint below 3 vol% (wet). O_2 setpoint was automatically adjusted to the lowest possible O_2 content, while keeping CO emissions below 20 mg/Nm^3 (daily average, dry at 11% O_2). The measured O_2 process value follows its setpoint.

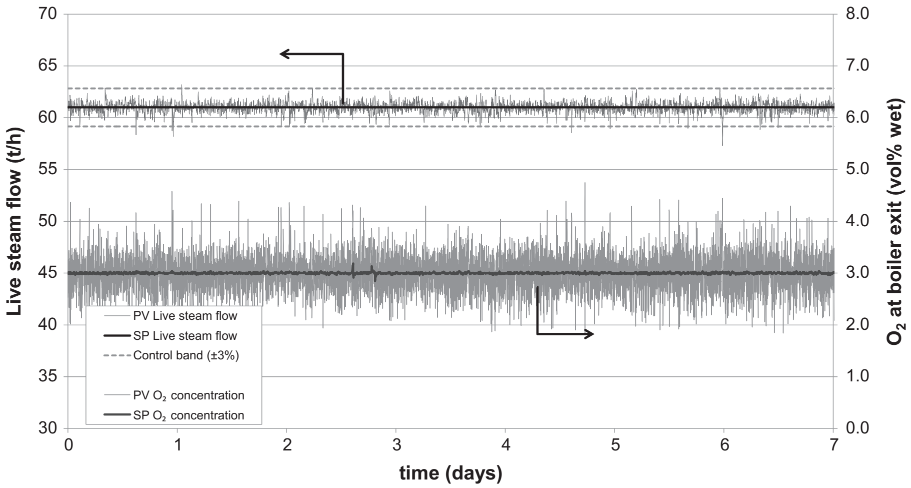

Fig. 8. Live steam flow (top, left axis) with setpoint (black) and control band of ±3% (dashed lines) as well as O_2 concentration at the boiler exit (bottom, right axis) with setpoint at 3 vol% (minute average values are shown).

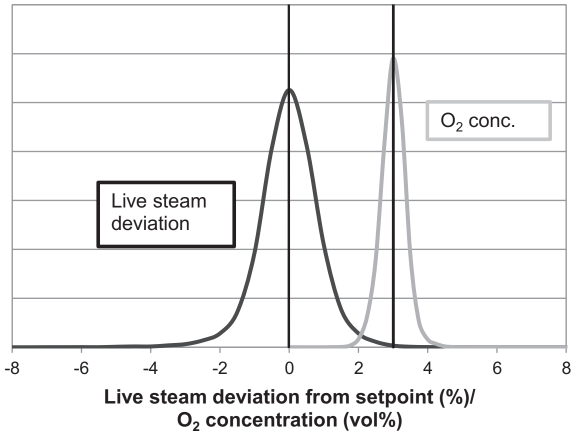

Fig. 9. Probability density functions of the live steam flow deviation from its setpoint as well as of the O_2 concentration at the boiler exit. The probability density functions have been derived from 1 min average values recorded over 1 month of continuous operation at 3 vol% O_2 (wet).

very stable operation. First, the bunker management, where Renergia relies on an automated crane system and physically segregated bunker compartments. Second, a relatively high net calorific value of the waste (typically 10–15 MJ/kg) that facilitates keeping the fire intensity stable. Third, the absence of refractories in the first pass provides a fast response of the measured live steam flow to changes in combustion intensity and thus allows a fast counteraction by the CCS. The thermal buffer effect from the refractories is absent and thus changes in the fire intensity are quickly detected in the live steam flow.

4. Conclusions

It was successfully demonstrated that a commercial EfW plant can run with very little excess air. ($\lambda < 1.20$). Continuous operation at 3 vol% O_2 or even lower was possible without exceeding CO emission limits or lowering steam flow stability. Reducing the excess air markedly lowered the amount of NOx being formed in the combustion process, and uncontrolled NOx concentrations around 100–150 mg/Nm^3 (dry at 11% O_2) could be reached. Two main reasons for this achievement have been identified. On the one hand a proper design of the combustion chamber in combination with good intermixing of the flue gases by injection of secondary air and recirculated flue gas. On the other hand an optimized combustion control system allowing very stable combustion conditions with little fluctuations in live steam flow, waste bed height and O_2 concentrations.

Acknowledgements

We thank Renergia and especially Mr. Ruedi Kummer and Mr. Felix Bolli for giving us the possibilities to investigate and optimize the waste combustion process.

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