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Final report: Improved electrical efficiency and bottom ash quality on waste combustion plants

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Abstract

Investigations making it possible to evaluate and further develop concepts to improve electrical efficiency in a waste combustion plant were performed. Furthermore, one objective of the study was to investigate the possibilities of improving waste bottom ash leaching properties by use of a rotary kiln treatment. The project work included construction of a bench-scale rotary kiln, performing ash rotary kiln treatment experiments, conducting gas suction probe measurements on a waste incineration plant and making some concept evaluations. The influence of the rotary kiln thermal treatment on the leaching of Ca, Al, Si, Mg, Ba, Sr, Cl, Cu, Pb, Zn, Cr, Mo, sulfate, DOC and carbonate was determined. As a result of these tests, the rotary kiln thermal treatment of bottom ashes can be recommended for reducing the leaching of Cu, Pb, Cl, Zn and DOC; however, an increased leaching of Cr and Mo should be expected. The combustion conditions above the grate of a waste incineration plant were investigated and the release and concentration of volatile ash species in the flue gas such as Cl, Na, K, Ca, Pb, Zn and S were measured. The conducted measurements show that flue gas from grate sections 3 and 4 can produce a sufficiently hot flue gas that contains only low concentrations of corrosive species, and therefore can be used to increase superheater temperatures. Implementation of the so-called flue gas split concept together with other steam circle modifications on a waste combustion plant, and using a reasonable increase in final steam temperature from 400 to 500°C, have the potential to increase electrical efficiency from 24 to 30% (with respect to lower fuel heating value) in a waste combustion plant.

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A2. Report: Design, construction and commissioning of rotary kiln facility. Erhardt Mogensen, Peter Arendt Jensen, Henrik Kløft, Martin Bøjer.

A3. Report: Manual to Rotary kiln experiments. Igor Nesterov, Peter Arendt Jensen, Kim Dam-Johansen.

A4. Report: Tilvejebringelse af slagge til roterovnsforsøg. Henrik Kløft, Erhardt Mogensen, Peter Arendt Jensen.

A5. Report: Overview of the Thermal Treatment Experiments (Phase I). Igor Nesterov, Peter Arendt Jensen.

A6. Journal paper, to be submitted to Science of the Total Environment: Quantification of leaching from waste incineration bottom ash treated in a rotary kiln. Jiri Hyks, Igor Nesterov, Erhardt Mogensen, Peter A. Jensen, Thomas Astrup.

A7. Report: Thermal Treatment Experiments (Phase I) – The influence of kiln treatment on incineration bottom ash leaching properties. Jiri Hyks, Thomas Astrup, Peter Arendt Jensen.

A8. Report: Thermal Treatment Experiments (Phase II) – The influence of kiln treatment on corrosive species in deposits. Igor Nesterov, Peter Arendt Jensen.

A9. Report: Driftsstrategi for roterovn. Erhardt Mogensen.

A10. Journal paper, Fuel Processing Technology (2008) 525 – 539: Alkali/Chloride release during refuse incineration on a grate: Full-scale experimental findings. Martin Bøjer, Peter Arendt Jensen, Flemming Frandsen, Kim Dam-Johansen, Ole Hedegaard Madsen, Kasper Lundtorp.

A11. Conference paper, Proceedings of NAWTEC16, 16th Annual North American Waste-to-Energy Conference, May 19-21, 2008, Philadelphia, Pennsylvania, USA: High Electrical Efficiency by Dividing the Combustion Products. Ole Hedegaard Madsen, Martin Bøjer, Peter Arendt Jensen, Kim Dam-Johansen.

A12. Report: Release of Potentially Corrosive Constituents from the Grate of a Waste-to-Energy Boiler – Measurements July 2007. Martin Bøjer.

A13. Journal paper, accepted for publication in Energy and Fuels: Release of Corrosive Species above the Grate in a Waste Boiler and the Implication for Improved Electrical Efficiency. Martin Bøjer, Peter Arendt Jensen, Kim Dam-Johansen, Ole Hedegaard Madsen, Kasper Lundtorp.

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1.0 Introduction

A high proportion of Danish domestic waste is used as fuel in waste combustion plants, and thereby contributes to the production of heat and electricity. Through the combustion and flue gas cleaning processes, raw waste is transferred into bottom ash, fly ash and a reasonably clean exit flue gas, the largest solid residual fraction of which is bottom ash. A modern waste-to-energy plant therefore provides energy and reduces the amount of waste. However, for society to obtain maximum benefits from waste combustion technology, some parts of the process should be improved. The possible utilisation of waste combustion bottom ash is determined by ash heavy metal leaching. Depending on the leaching properties, bottom ash can be utilised for road construction, noise barriers, etc. If the metal leaching of waste bottom ash could be reduced, the harmful environmental impact of the ash would be in turn reduced and open more possibilities for ash utilisation. The maximum electrical efficiency of a modern waste combustion plant is approximately 24%, which is relatively low compared to a coal combustion power plant that may obtain an electrical efficiency of 45%. The main reason for this is that superheaters in a waste combustion plant are typically limited to a steam temperature of 400°C and a steam pressure of 45 bars. The steam temperature limitation prevents high corrosion rates and the consequent destruction of the superheaters. Ash deposits in a waste combustion boiler are very corrosive and often contain relatively high concentrations of the elements Cl, K, Na, Zn and Pb. If superheater temperature could be raised, the electrical efficiency of the plant could be increased.

Before this project began, a brainstorming workshop was conducted with participants from the DTU Department of Chemical Engineering and Babcock & Wilcox Vølund A/S. The objective was to provide ideas on how a waste combustion plant could be improved, in order to obtain higher electrical efficiency and improve bottom ash leaching properties. This work resulted in a patent (reference 1), which proposed two different concepts that could potentially increase the plant's electrical efficiency. The first possible concept is shown in Figure 2 and is termed the 'flue gas split concept'. In essence, part of the flue gas from the grate combustion zone that is hot, but contains low amounts of corrosive ash species, is directed towards an extra high temperature superheater. A wall is inserted into the boiler chamber, which then leads part of the grate flue gas to a superheater that subsequently boosts steam temperature.

The second patented concept is shown in Figure 2. The objective of this concept is to use a rotary kiln that could be heated by a gas burner to improve slag quality. At the same time, the hot flue gas leaving the rotary kiln may be used to superheat the steam to a high temperature, and thereby increase the plant's electrical efficiency. For several reasons the thermal rotary kiln treatment is seen as a promising technique in improving the leaching quality of bottom ashes. Thermal treatment can be carried out directly at the waste incineration plant, thereby reducing the costs compared to a stand-alone treatment facility. Rotary kiln ash treatment combines high temperature conditions, long retention time and good material mixing. The high temperature treatment induces changes in the bottom ash matrix, which generally result in both physical and chemical fixation of some metals and therefore lower heavy metal leaching. The combustion of residual organic matter, and the consequent lower leaching of soluble organic carbon (DOC), may cause a decrease in the leaching of elements that are mobilised by organic complexation (e.g. Cu and Pb).

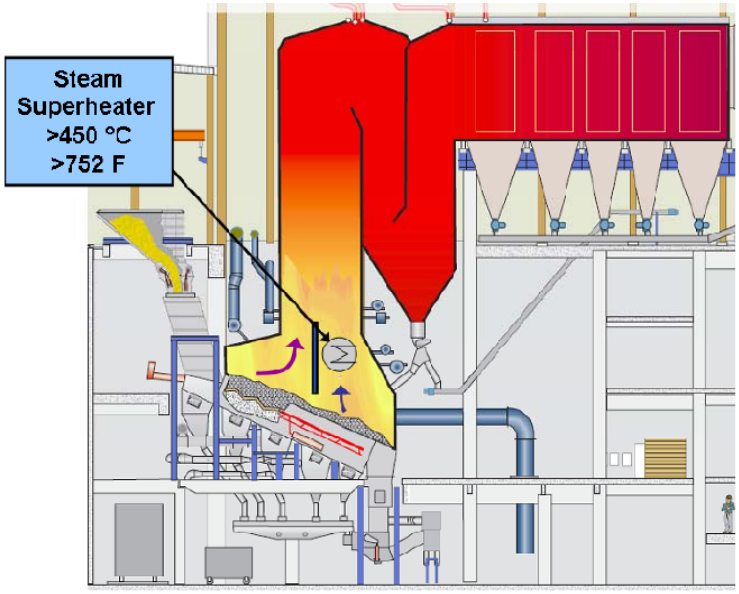

Figure 1. Possible set up of the flue gas split concept.

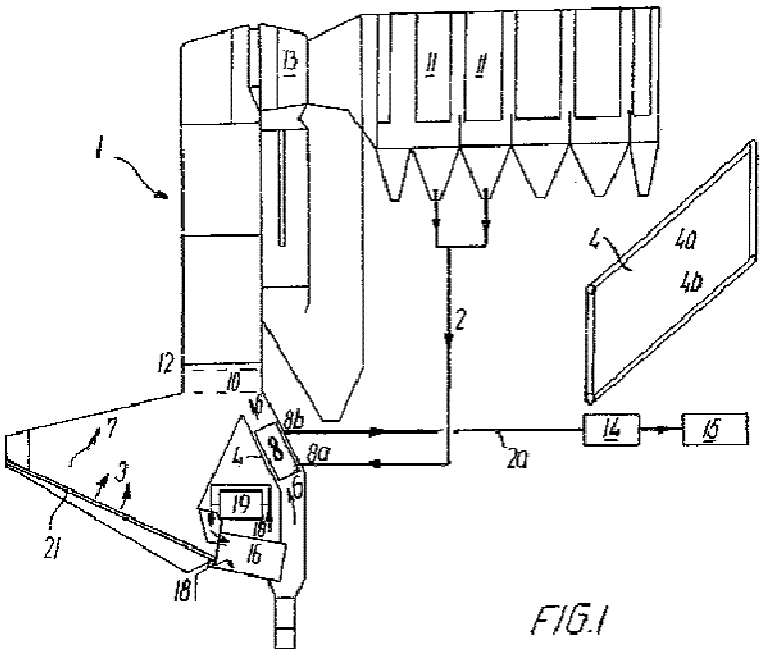

Figure 2. Concept of inserting a rotary kiln into a waste incineration plant. Figure 2 illustrates one possible method for integrating a rotary kiln in a grate waste combustion plant. The rotary kiln ensures improved slag quality and provides a flue gas that can be used for extra steam superheating. Number explanations: 16: rotary kiln; 8: extra superheater; 19: gas burner.

This project was conducted through the collaboration of Babcock & Wilcox Vølund A/S, the Department of Environmental Engineering DTU, I/S Vestforbrænding and the Department of Chemical and Biochemical Engineering DTU. The main objective of the Energy.dk-funded project was to perform investigations that would make it possible to evaluate and further develop the concepts described in the patent. A further objective involved investigating the possibility of improving waste bottom ash leaching properties by using the rotary kiln treatment. The main project activities were performed in the following working areas:

- Design and construction of a pilot-scale experimental gas fired rotary kiln.
- Conducting kiln facility experiments to study the influence of kiln ash treatment on leaching, and performing an investigation of kiln flue gas corrosivity.
- Measurements were made above the grate at Vestforbrænding to study the release of ash species and combustibles above the grate fuel layer.
- Conducting CFD and thermodynamic calculations to evaluate the patented flue gas split concept.

The final documentation for the project results consist of this résumé's report as well as other reports and papers, all of which can be found in the appendices (10 reports, one conference paper and three journal papers in total).

2.0 Literature review

As a basis for the project work and the experiments carried out on the pilot-scale rotary kiln, a literature review was performed regarding the influence of thermal treatment on ash leaching properties (Appendix A1). A large portion of Danish municipal waste is combusted in waste incineration plants, which generates different types of ash residues. The largest residue amount is bottom ash, of which approximately 600 thousand tonnes is produced yearly in Denmark. Waste combustion bottom ash is often utilised as construction material in roads and ramps or as noise barriers etc. How a specific type of ash can be utilised is determined by the composition and the heavy metal leaching properties of the ash. High leaching release levels may mean that the ash has to be disposed in a controlled and expensive landfill. One of the objectives of this research project is to investigate the possibility of reducing the leaching of heavy metals from the incineration bottom ash by a thermal treatment of the slag in a rotary kiln.

Bottom ash from municipal solid waste incineration (MSWI) plants is highly inhomogeneous and is often dominated by the elements Si, Ca, Al, Fe, Na, Mg and K. Furthermore, a very broad range of heavy metals also appear in the ash. The utilisation of MSWI residues is split into three categories, according to the specification of incineration residues as described in the Danish statutory order no. 1480 (Reference 2).

Category 1: To fulfill category 1, an ash must be limited with respect to both the content of some heavy metal species and the leaching of heavy metals from the ash. Category 1 residues can be used without any limitation. However, in practice all municipal waste incineration bottom ashes exceed some of the specified heavy metal content concentrations.

Category 2: Maximum leaching of different heavy metals in the range of 0.1 µg/l (Hg) up to 300 µg/l (Ba) is specified. This bottom ash can be utilised for roads, noise barriers, foundations, etc.

Category 3: Maximum leaching of different heavy metals in the range of 1 µg/l (Hg) up to 4000 µg/l (Ba) is specified. This category includes some of the same utilisations as found in category 2, but not for squares, cable shuts and noise barriers.

Outside of category: Material has to be disposed in a carefully controlled landfill facility.

The statutory order regarding categories 2 and 3 specifies limits for the leaching of the heavy metals As, Ba, Pb, Cd, Cr, Cu, Hg, Mn, Ni, Zn and somewhat higher limits for the leaching of Na, chloride and sulphate. In practice, it is not possible to determine the leaching from an actual site, so the leaching properties of a given bottom ash residue are determined by laboratory testing. Batch leaching tests are presently used as part of a standard compliance test that attributes material to categories 2, 3 or 'out of category'. A water to solid ratio of 2 is employed, along with a leaching time of six hours. Typically, fresh municipal incineration bottom ash exceeds even category 3 with respect to the leaching limits of several metals (Pb, Zn, Cd Cu, Cr). However, after the ash has been weathered (stored in open air) for typically three months, most of it complies with category 3 limitations. The natural pH of fresh bottom ash is typically 10.5 – 11.0, while after weathering, values of 8.5 – 9.5 are observed. After weathering, most bottom ashes comply with category 3 rules. Excess leaching limits for some ashes are mainly seen in the form of the elements Cu and Pb. Ashes rarely comply with category 2 specifications. The largest deviations are seen for Cu, Cr and Pb, but some ashes also exceed the leaching limits of Cl, Na, As, Ni and Zn.

The control of heavy metal leaching is a complicated process. Leaching is controlled by phase precipitation/dissolution, molecular species sorption/desorption and transport processes occurring through the interaction of the material with percolating water. The pH of the interacting system is often considered a main parameter and has a strong influence on leaching. According to present knowledge, some of the controlling mechanisms for leaching of different elements can be somewhat simplified be summarised by the following statements:

- The leaching of Al, Fe, Zn, Cu and Pb follows typically a u-shaped curve as a function of pH. Minimum leaching is observed at intermediate pH. However, for Zn, Cu and Pb, only a moderate increase in leaching at high pH levels can be observed, while at low pH the leaching increases significantly.
- The leaching of Ca, Mg, Cr, Na, Cd and Ni generally decreases with increased pH level.
- Organic slag matter content influences the leaching of Cu, Zn and Pb. The oxidation of organic matter can lead to the decreased leaching of Cu, Zn and Pb. Cu leaching ability is controlled mostly by organic acids such as fulvic acid.

For several years, the thermal treatment of bottom ashes has been known to be capable of reducing the leaching of some elements from ashes. The bulk of thermal laboratory treatment studies have used treatment temperatures from 900 to 1100°C, the results of which can be summarised in the following statements:

- A decreased leaching with thermal treatment has been observed for most studies for the following elements: Cu, Ca, Mg, K, Pb, Zn and Ni. In some cases, the reduced leaching of Zn and Pb has only been observed at low pH (below 6). In a single case, Cu leaching was increased by high temperature treatment (1100°C).
- Cd and Cr leaching have been reduced mainly by high temperature treatment (1100°C).
- A reduced leaching of Al is seen mainly at high pH levels (above 5).

It is not known exactly how treatment operation conditions and the variable composition and structure of raw bottom ash affect the leaching properties of treated ash products. Several laboratory-scale fixed bed studies on the heat treatment influence on bottom ash leaching properties have been performed; however, only very limited studies have been carried out using an actual rotary kiln treatment.

3.0 Design, construction and commissioning of the rotary kiln test facility

To make it possible to test the patented concept of integration of a rotary kiln with a grate waste combustion plant, a bench-scale rotary kiln reactor was constructed. The kiln used the already generated bottom ash from a grate waste combustion plant. The objectives were to make a rotary kiln facility where the influence of heat treatment on bottom ash leaching could be investigated, and to ensure that the concept of using the exit flue gas from the kiln to provide extra superheating could be tested. Measuring changes in slag leaching properties can be carried out by comparing treated and non-treated bottom ashes. The corrosivity of the kiln exit flue gas can be tested after being collected by a small deposit probe that simulates a superheater. Through chemical analysis of the probe deposit, the corrosivity of the flue gas can be estimated. It was decided to attempt to simulate the conditions in a full-sized rotary kiln as well as possible. Therefore, a continuous kiln process was used and slag particles up to a size of 15-20 mm to be treated in the kiln. The particle size meant that a minimum inner kiln diameter of 200 mm had to be used.

The main components of the rotary kiln facility are shown in Figure 3. A vibration feeder preheats and sends the slag to the rotary kiln through an intermediate chamber. The rotary kiln angle and rotation speed can be changed, and the kiln is heated by a gas burner with an input power of 5 to 30 kW. The flue gas flows in the opposite direction of the slag in the kiln. Heat-treated bottom ash is collected in a 70-litre water-cooled closed slag silo. The outer diameter of the kiln is approximately 700 mm and the inner size a diameter of 200 mm and a length of 2 metres. The feeder can provide from 1 to 18 kg/h of bottom ash to the rotary kiln. Five thermocouples are placed in the kiln refractory to measure the temperature of the inner surface of the kiln, which can vary between 800 and 1200°C. Further documentation on the design, construction and operation of the rotary kiln facility can be seen in appendices A2 and A3.

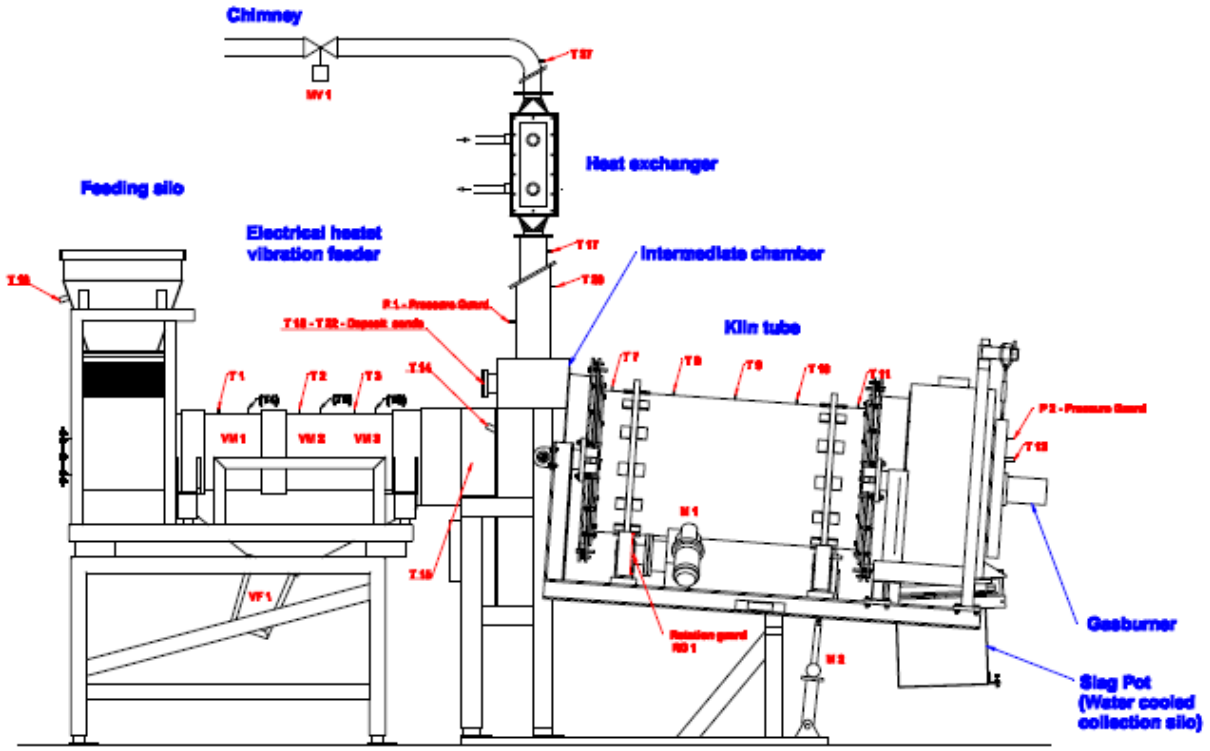

Figure 3. Sketch of rotary kiln experimental facility

4.0 Provision of bottom ash for experiments

Untreated bottom ashes were collected at the I/S Nordforbrænding MSW incineration plant, which has a nominal capacity of 19 tonnes/h at a thermal load of 10.5 GJ/tonne. The plant receives typical Danish combustible waste: residual MSW from households after source separation (47%), commercial and institutional waste (26%) and "other non-household waste" (27%). No hazardous waste was included. During the sampling process, bottom ash from three consecutive discharges was shovelled directly from a lamella conveyor, resulting in three bulk samples of 60-70 kg (w/w) each. The bulk samples were mixed on-site, pre-crushed with a shovel and passed through a 40 mm sieve; oversized metal pieces were removed from the mixed sample, which was then moved to the laboratory, air-dried and passed though a 15 mm sieve (for further details, see Appendix A4).

5.0 Rotary kiln studies

Before hot waste incineration experiments were conducted, cold flow tests were performed to determine residence time and feeder characteristics. All hot experiments were conducted according to the detailed descriptions in the operation manual (Appendix A3).

5.1 Rotary kiln treatment influence on slag leaching

Experiments were carried out on the rotary kiln facility to study the influence of the thermal treatment of municipal solid waste incineration (MSWI) bottom ash on the leaching abilities of heavy metals, and to observe if the treatment could lead to a better utilisation of bottom ash. Additionally, experiments were conducted to investigate if the flue gas from the kiln could be used to obtain an increased superheater temperature (see section 5.2).

In a series of rotary kiln experiments, incineration bottom ashes were treated at temperatures ranging from approximately 800 to 1100°C and at oven residence times of 20 to 120 minutes. In total, 13 kiln ash samples were fabricated, and some visible changes depending on treatment temperature could be observed. For sample temperatures below 950 ^{o}C, no changes in bottom ash structure were observed. At temperatures higher than 950 ^{o}C, partial melting of bottom ash and formation of glass began, while at temperatures higher than 1080 ^{o}C, larger pieces of molten ash were formed. Further discussions of the kiln treatment can be seen in Appendix A5. The particle sizes of both the treated and non-treated samples were determined by sieve analysis. Thermal treatment at 1080°C resulted in bottom ash agglomeration, as the residues generated at this temperature contained the highest percentage of particles unable to pass through a 20 mm sieve.

The leaching properties of bottom ashes treated in the rotary kiln were investigated by using a combination of lab-scale leaching experiments and geochemical modelling. Quantification of leaching on all samples was achieved by compliance leaching tests (natural pH), and additional pH-static leaching tests were carried out on samples treated in the kiln for approximately 1 hour at temperatures of 930 and 1080°C. The study is described in detail in Appendices A6 and A7. The natural pH of the compliance leaching tests, using an S/L ratio of 2, showed pH levels of treated samples from 11.8 to 12.4, while the lowest pH was observed for samples treated at the highest temperatures. The pH-static tests were conducted at pH levels from 9 to 12.

The applied waste bottom ash was dominated by high concentrations of Al, Ca and Fe (and probably Si) and had intermediate levels of Cu, K, Mg, Na, P, S and Ti. Similar elemental composition of raw and treated

samples indicated that only minor fractions of the inorganic species evaporated (the exception may be Cl). Bottom ash Total Organic Carbon (TOC) was reduced by the kiln treatment, measuring 0.5 and 3.0 wt% for the untreated samples, and at 930°C approximately 0.1 wt% and at 1080°C 0.06 wt% for the treated samples. Figure 4 shows TOC in the bottom ash as a function of treatment temperature.

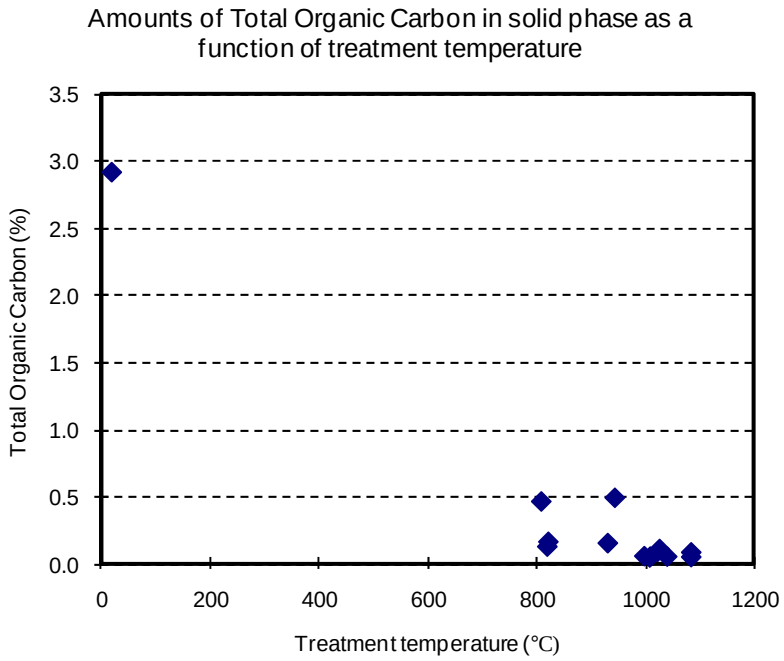

Figure 4. Amounts of Total Organic Carbon (TOC) determined in solid residues (% of dry matter) as a function of treatment temperature.

Leaching of Cd, Co, Ni, Ti, Be, Bi and Sn from both untreated and treated residues was found close to or below their detection limits; hence, the effects of thermal treatment on leach ability could not be quantified. Thermal treatment had no significant effect on the leaching of Ca, sulfate, Al, Si, Mg, carbonate, Ba and Sr. The leaching of these elements from the treated residues remained unchanged and was, in most cases, controlled by the same minerals as in case of the untreated residues.

The leaching of some elements (Cl, Cu, Pb, DOC (Dissolved Organic Carbon) and Zn) decreased as a consequence of thermal treatment. An increased treatment temperature caused increased Cl evaporation, and thereby a decreased Cl leaching. Increased leaching temperature caused a small decrease in Zn leaching. For DOC, Cu and Pb, a similar trend was observed, i.e. leaching was significantly decreased with an increase in the treatment temperature. It can be concluded that higher treatment temperature caused the higher burnout of organic carbon in the solid phase (Figure 4), which in turn caused lower leaching of DOC. Since the leaching of DOC controls the leaching of Cu (and to some extent also Pb) via complexation, lower leaching of DOC causes lower leaching of Cu and Pb.

After thermal treatment, Mo and Cr leaching increased by a factor of 4 and more than two orders of magnitude, respectively. The increase in Mo leaching could be likely explained by the thermally-induced transformation of Fe/Al-(hydr)oxides from the amorphous state to more a thermodynamically stable crystalline state, which has less surface sorption sites available. Therefore, thermal treatment reduces the sorption capacity of Al and increases the amount of Mo that can be dissolved.

Current EU compliance leaching limits (see Appendix A7) divide waste slag into three waste categories: A. inert, B non-hazardous and C. hazardous. For all elements determined accurately, untreated slag complied with the inert classification (A), although some of the treated samples had an increase in Cr leaching Consequently, regarding EU limits, no thermal treatment was actually required. However, even after reducing the leaching of some elements by using the rotary kiln treatment (Cl, Cu, Pb, DOC and Zn), the increased leaching of other elements (Cr, Mo) changed the classification of the residues from “inert”(A) to “non-hazardous”(B).

Rotary kiln thermal treatment of bottom ashes can be recommended for reducing the leaching of Cu, Pb, Cl, Zn and DOC; however, an increased leaching of Cr and Mo should be expected. The obtained rotary kiln leaching data agree with previously conducted fixed bed laboratory studies for several elements (Zn, Cu, Pb, Cl and DOC) (Section 2.0 and Appendix A1). In some of the laboratory studies reported in the literature, reduced leaching was observed for elements that in the rotary kiln studies were below detection limits or observed to be stable (Cd, Ca, Ni, Mg). Only limited data is available for Cr and Mo, while just one study has reported reduced Cr leaching at treatment temperatures above 1100°C.

5.2 Properties of flue gas from kiln treatment

If kiln exit flue gas is used to increase steam temperature, and thereby increase electrical efficiency, the corrosivity of the fly ash released from the kiln needs to be low. The rotary kiln pilot plant was used to conduct experiments in which (see Appendix A8) flue gas fly ash properties were tested by use of a small hot air-cooled deposit probe. The flue gas generated in the kiln when treating incineration bottom ash was observed to form deposits at a relatively high rate (28 to 102 g/m^2/h), and the deposits contained high Cl levels (6 to 32 wt%). The measuring data shows that the flue gas generated by the heat treatment of incineration bottom ash in the pilot scale rotary kiln was relatively rich in Cl, S, K and Na, and probably also in Zn and Pb. The measuring data indicated that the flue gas from a rotary kiln slag treatment process is not well suited for increasing superheater steam temperature in a waste combustion plant.

5.3 Rotary kiln control strategy

Based on the pilot-scale kiln experiments and previous full-scale experiences, a possible rotary kiln control strategy has been proposed (for further details, see Appendix A9), which will be integrated with the waste combustion plant control system. A possible physical integration of the kiln with the boiler is shown in Figure 2, while some of the important features of the kiln control concept are listed below:

- Kiln rotation is manually controlled and based on a kiln residence time calculation. A typical residence time of 45 to 60 minutes is recommended to obtain a good burnout.
- The feeding of waste onto the grate is regulated according to an objective to obtain the last 15-20% burnout in the rotary kiln. This could minimise the need for a support fuel.
- The flu gas flow lead to the final superheater (the superheater placed in the kiln exit flue gas) may have to be regulated to obtain adequate exit steam temperature.
- The load of the burner in the rotary kiln can be controlled using exit rotary kiln flue gas temperature as a reference.

6.0 Measurements of release in an incineration boiler

During the combustion of waste on the grate in a waste combustion boiler a significant fraction of volatile ash forming elements such as Cl, Na, K, Pb, Zn and S is released to the gas phase. Some minor amounts of ash particles (often rich in Si, Ca, Al and Fe) are also provided by entraining ash particles from the bed combustion. Further downstream in the boiler chamber, aerosols may be formed by condensation, and deposit formation on boiler coils happens by direct condensation and particle impaction. Deposits with high contents of Cl are relatively corrosive, which is the main reason for limiting maximum superheater temperature. The volatilisation of chlorine increases rapidly with temperature, and is nearly fully achieved at 900 °C. This temperature is typically lower than the maximum temperature in the active burning zone. The major parts of the corrosive species are therefore released on the first part of the combustion grate and thereby at the front of the furnace. The rear parts of the grate are characterised by the burnout of a relatively clean char (most Cl, K and Na is released near the fuel entrance), thereby releasing relatively clean and far less corrosive combustion products. This phenomenon may be applied to split up the flue gases from the grate into two fractions, one of which supplies sufficient heat flux and a low chlorine gas concentration and may then be used in a high temperature superheater to increase steam temperature and thereby the electricity efficiency of a waste-fired power plant (see Figure 1).

Babcock & Wilcox Vølund (BWV) has received a world patent on the flue gas split concept (reference 1). To investigate the applicability of the concept in a boiler two measuring campaigns were conducted at Vestforbrænding boiler unit 5. It was the objective to determine the release of the volatile ash forming elements along the grate, as well as the energy content of the released flue gas. The measurements made it possible to determine the optimal position of the flue gas dividing wall.

In the initial measuring campaign measurements of gas concentrations (O_2, CO and CO_2), volatile element concentrations (Cl, Na, K, Ca, Pb, Zn and S) and gas suction pyrometer temperatures were conducted along the grate. The Vestforbrænding boiler unit 5 had six ports equally distributed along the grate, and it was possible to measure at last five of these ports; port L1 was near the fuel inlet and port L6 near the bottom ash outlet. Accurate temperature data was obtained and a temperature profile seen with a maximum temperature of 1140 °C±71 °C at port L3. The sampling system used for collecting the volatile species was not ideal for measurements in the early sections of the grate (L2–L4) due to tar that condensed in the tubes and filters. Most of the Cl, Na, K and Ca elements were released at port L2 and a gradual decrease in concentration was observed at ports L3 and L4. The measured concentrations at port L2 were 177, 71, 44 and 42 ppmv for Cl, Na, K and Ca, respectively. Combustion took place primarily at grate Sections 2 and 3. This first measuring campaign had some important limitations. It was not possible to conduct probe measurements in port 1, large amounts of tar were collected in ports L2 – L4 making the concentration determinations very uncertain, and repeated measurements were not conducted.

In the second measuring campaign, local gas concentrations (CO, CO_2, O_2, NO and SO_2), volatile constituents (Cl, S, Na, K, Ca, Pb, Zn, Cu and Sn) and gas temperature measurements were conducted along Vestforbrænding boiler unit 5's grate (Appendices A12 and A13). Measurements were performed in the first five ports of the six ports along the grate. Measurements were also performed in a port at the top of the first draught in the fully mixed flue gas. Video recordings of the grate were used to document the location of the visible flames during the experiments. A new gas extraction probe was designed to conduct measurements in flue gas with high tar content. An oxygen injection in the tip of the probe was used to combust the tar. The

newly designed probe with added oxygen reliably produced extraction samples that could be analysed directly by ICP-OES, and samples extracted from the same port yielded reasonably similar concentrations. The position of the flame front on the grate may influence local probe measurements. In some of the measurements, it was intended to make a long grate fire; however, a long flame appeared somewhat randomly during the measuring campaign, so the video recordings of the grate were used to determine the flame's front position. The division between a short and a long flame was chosen at the middle of grate section 3.

Local temperature was measured using a closed tube containing a thermocouple. Figure 5 shows the measured temperatures along the grate. Closed symbols are used for the long flame and open symbols for the short flame. The flame length impact on temperature is observed at port L2, where the shorter length of flames yields higher temperatures. In contrast, longer flames yield higher temperatures at port L4. No short flame temperature measurements were carried out at port L3, although lower temperatures would have been expected. The temperatures at ports L1 and L2 were 824±148 °C and 900±212 °C, and the maximum temperature was measured at port L3 at 1006±152 °C. At the port in the top of the first draught (EBK1), a temperature of 840±43 °C was measured.

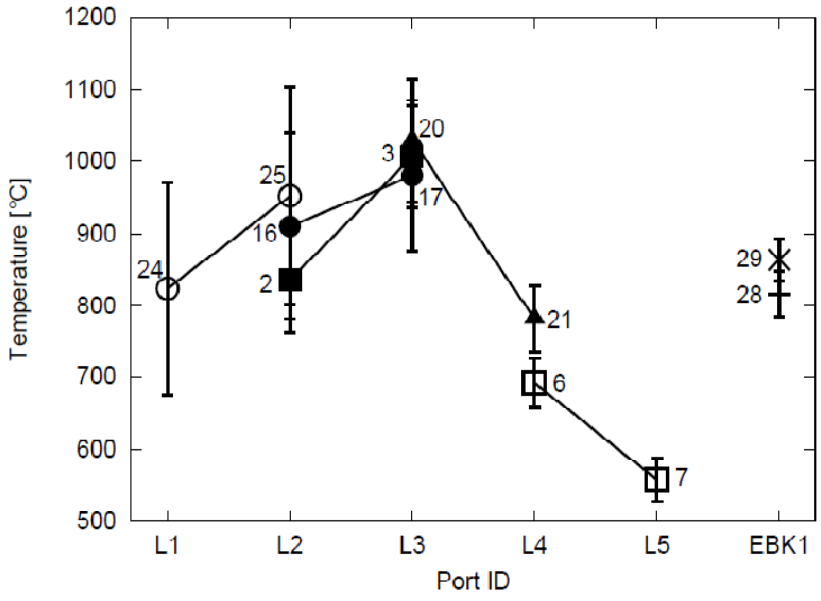

Figure 5. Average temperature measurements and corresponding standard deviations. Filled symbols correspond to a long fire, while non-filled symbols correspond to a short fire.

Gas concentration measurements showed nearly no oxygen in the flue gas at ports L1 and L2 (0.3 vol.% and 0.5 vol.%), some at port L3 (8.5 vol.%) and approximately 21 vol.% at ports L4 and L5. Likewise, CO concentrations at ports L1, L2 and L3 were 8.6 vol.%, 8.3 vol.% and 2.5 vol.%, respectively, and below 0.3 vol.% at ports L4 and L5. Primary air rises vertically through the grate waste, where different stages of combustion occur. Early on, the grate produces a large amount of CO due to substoichiometric conditions with drying and pyrolysis as the prevailing processes. At port L3, char combustion is the prevailing process with little pyrolysis, which was also indicated by the highest temperatures measured at port L3 as well as a surplus of oxygen. At ports L4 and L5, O_2 is higher than 20 vol.%, indicating that the gas above the grate is heated mainly by cooling of the hot slag on the grate and that combustion is limited at grate sections 4 and 5.

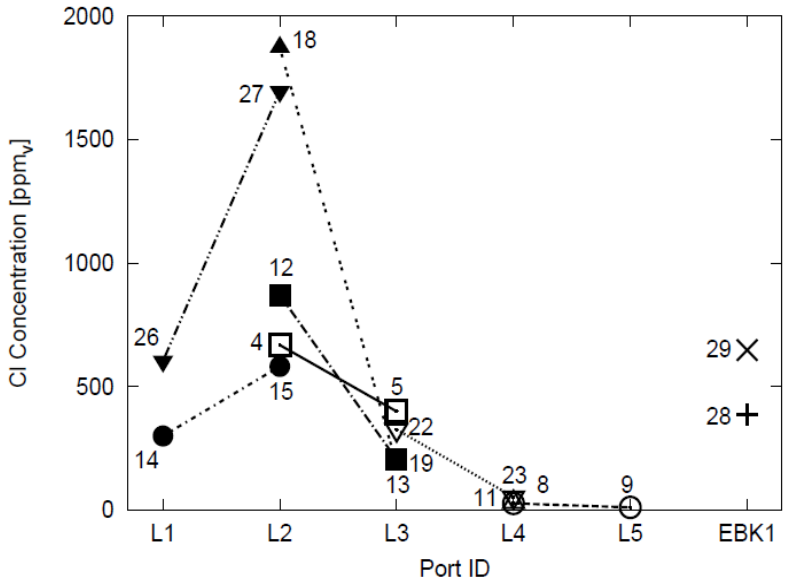

Figure 6. Measured Cl concentrations above the grate. Filled symbols correspond to a long fire, while non-filled symbols correspond to a short fire.

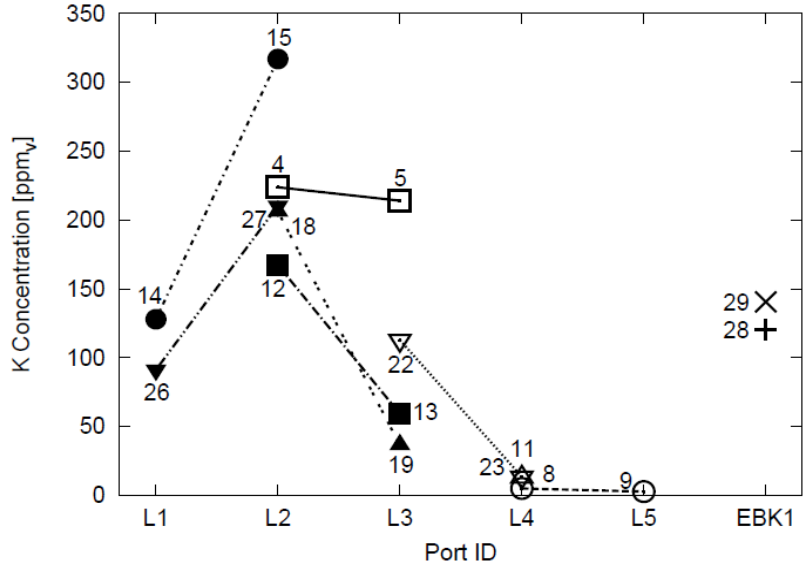

Figure 7. Measured K concentrations above the grate. Filled symbols correspond to a long fire, while non-filled symbols correspond to a short fire.

An important objective of this study was to quantify the release of Cl, S, Na and K along the grate. The length of the flames did not seem to make a significant difference between the concentration measurements of corrosive species. For all these elements, the maximum concentrations were measured at port L2, followed by a steep decrease at ports L3 and L4. The measured maximum concentrations of Cl (Figure 6), S, Na and K (Figure 7) were approximately 1800 ppmv, 800 ppmv, 350 ppmv and 250 ppmv, respectively. The patented flue gas split concept propose to utilise a part of the flue gas from the grate that has low concentrations of corrosive constituents and a sufficient enthalpy to make high temperature steam superheating possible. The conducted measurements show that flue gas from grate sections 3 and 4 can

produce a sufficiently hot flue gas that only contains low concentrations of corrosive species. It will, however, require steady control of the position of the grate fire.

7.0 CFD calculations

To realise the flue gas split concept (Figure 1), it will probably be necessary to insert a wall in the boiler chamber, whereby the part of the flue gas with a low Cl content is directed towards a superheater that can increase steam temperature. To investigate the effects of inserting such a flue gas dividing wall into the furnace chamber, CFD calculations were performed (for further documentation, see Appendix A14). The CFD calculations of the furnace chamber flow and temperature pattern were carried out on an empty furnace chamber and on a furnace chamber mounted with different flue gas splitting walls. A general rule used for the design of waste combustion furnace chambers are that the flue gas shall have a residence time of a minimum two seconds at flue gas temperatures above 850°C, in order to ensure complete burn out. Inserting an un-isolated water-cooled wall into the furnace chamber could cool the flue gas down, such that the requisite two seconds above 850°C are no longer obtained, so the influence of the wall on local flue gas temperature was investigated through CFD calculations. Some of the conclusions based on the results of the CFD calculations are as follows:

- The secondary air injection system has to be redesigned to ensure adequate furnace chamber flows when the flue gas dividing wall is mounted.
- Control of the grate combustion process has to be improved to ensure an accurate control of the flame front position.
- The flue gas dividing wall needs some degree of refractory lining to prevent the flue gas from cooling too much.

8.0 Electrical efficiency

Several process parameters have an impact on steam turbine performance, and thereby the electrical efficiency of a waste combustion plant. Some of the most important of these parameters are steam temperature and pressure. A study on some of the possible modifications of the steam cycle that can improve plant electrical efficiency is documented in Appendix A11. Typically, new combined power and heat waste combustion plants use steam data of 400°C and 50 bar and can obtain an electrical efficiency of approximately 24% (with respect to a lower fuel heating value). When using an extra superheater, as proposed in the patented concepts, a first step could be to increase the steam data to 500°C and 50 bar, thereby increasing efficiency by 3%. A classic method used to improve efficiency is to reheat a part of the steam after the high-pressure turbine, which can increase electrical efficiency by approximately 3 to 4%. In order to gain maximum effect from this setup, though, steam pressure has to be increased to 120 bar. Implementation of the proposed technologies on a waste combustion plant, and using a reasonable increase in final steam temperature from 400 to 500°C, has the potential to increase electrical efficiency from 24 to 30% (with respect to a lower fuel heating value).

9.0 Comparison with the results from project PSO 5784

A previous Energinet.dk funded project (PSO-5784, reference 3) has dealt with the influence of ash composition and operation conditions on ash formation and ash leaching properties on a grate waste combustion plant. Generally the PSO-5784 projects deal with other subjects than the present investigation, however, a few conclusions from PSO-5784 shall be mentioned:

- The waste input composition characteristics significantly influenced the characteristics of the generated ash residues.
- The grate combustion operational conditions did not influence the ash residues characteristics. This meant that bottom ash leaching properties could not be changed by changing the grate combustion conditions.

The conducted projects indicate that a rotary kiln slag treatment is needed if bottom ash leaching properties shall be changed.

10.0 Conclusions

One objective of this project was to perform investigations, which would make it possible to evaluate and further develop the concepts described in a patent that deals with obtaining improved electrical efficiency in a waste combustion plant. A further objective was to investigate the possibility of improving waste bottom ash leaching properties by using a rotary kiln treatment.

The patent proposes two methods to improve a plant's electrical production efficiency. The first concept (The flue gas split concept) utilises a part of the flue gas from the grate combustion zone that is hot, but contains relatively high amounts of chlorine rich corrosive ash species. Therefore, a wall can be inserted into the boiler chamber, which leads a part of the grate flue gas to a superheater that boosts steam temperature. The method of the second concept involves using a rotary kiln that can be heated by a gas burner to improve slag quality, and simultaneously uses kiln exit flue gas to increase superheater temperature.

The project has provided the following unique scientific results:

- The influence of rotary kiln thermal treatment on the leaching of Ca, Al, Si, Mg, Ba, Sr, Cl, Cu, Pb, Zn, Cr, Mo, sulfate, DOC and carbonate has been determined.
- Combustion conditions just above the grate of a waste incineration plant with respect to temperature, hydrocarbon release and concentration of O_2, CO_2 and CO have been determined.
- The release and concentration of volatile ash species as Cl, Na, K, Ca, Pb, Zn and S just above the grate in a waste combustion plant have been determined.

Some of the important technical results obtained in the project are listed below:

- A flexible bench-scale gas-heated rotary kiln experimental facility was constructed, and experiments with bottom ash treatment and flue gas fly ash deposit formation were conducted.
- The rotary kiln thermal treatment of bottom ashes can be recommended to reduce the leaching of Cu, Pb, Cl, Zn and DOC; however, an increased leaching of Cr and Mo should be expected.
- Deposit probe measuring data indicate that the flue gas from a rotary kiln slag treatment process is not well suited for increasing superheater steam temperature in a waste combustion plant.

- For the volatile elements Cl, S, Na and K measured along the grate of a waste boiler at Vestforbrænding, the maximum concentrations were measured a few metres after the fuel inlet, while the concentrations decreased strongly further downstream of the grate. The conducted measurements show that flue gas from grate sections 3 and 4 can produce a sufficiently hot flue gas that only contains low concentrations of corrosive species. It will, however, require a steady control of the position of the grate fire.
- CFD calculations indicate the flue gas-dividing wall in the flue gas split concept needs some degree of refractory lining to prevent flue gas cooling too much.
- Implementation of the patented flue gas split concept on a waste combustion plant, and using a reasonable increase in final steam temperature from 400 to 500°C, has the potential to increase electrical efficiency from 24 to 30% (with respect to lower fuel heating value). The 30% electrical efficiency can probably be obtained by using the flue gas split concept combined with other known steam cycle improvements.

As a result of the conducted studies, some recommendations regarding future work are provided:

- The use of additives in the form of clay minerals mixed with the bottom ash in a kiln treatment process may significantly improve both the properties of the flue gas (less corrosive) and the leaching properties of the treated ash.
- The conducted experimental leaching determinations in this project were carried out on pulverised material. The kiln treatment caused some melting and sintering that reduced leaching, so in future studies leaching determinations should also be performed on non-pulverized samples.
- To lead the way for the flue gas split concept, probe deposit measurements in the near grate zone should be conducted in a full-scale plant. The next step should be to insert an extra pilot superheater in a full-size waste combustion plant.
- Further rotary kiln treatment studies are needed to determine how all the changes in operating conditions influence changed ash leaching properties.

Danish Resumé

Et formål med dette projekt var at udføre undersøgelser, der kan bedømme og udvikle nogle patenterede metoder til forøgelse af elvirkningsgraden på affaldsfyrede kedler. Herudover var det et formål, at undersøge mulighederne for at forbedre tungmetal udvaskningsegenskaberne for bundaske fra affaldsfyrede anlæg via en behandling i en roterovn.

Det omtalte patent beskriver to metoder til at forbedre elvirkningsgraden. I det første koncept tænkes en andel af røggassen fra risteforbrændingslaget, som indeholder en lav mængde klor, anvendt til at forøge overhedningen, og dermed forøge elvirkningsgraden. Der foreslås anvendt en ekstra væg i fyrrummet, og en ekstra højtemperatur overheder for at realisere konceptet. I det andet koncept foreslås anvendt en roterovn til at forbedre bundaskens udvaskningsegenskaber, og den dannede røggas fra roterovnen kan så anvendes til at forøge overhednings temperaturen.

Projektets hovedaktiviteter har været udført indenfor følgende områder:

- Der er designet og konstrueret en pilotskala gasfyret roterovn.

- Der er udført roterovns forsøg, med henblik på at belyse indflydelsen på tungmetal udvaskning fra slagge, og undersøge afgangsrøggassens indhold af korroderende aske bestanddele.
- Der er udført målinger lige over risteforbrændingslaget på en affaldskedel på Vestforbrænding, for at undersøge afgivelsen af askedannende elementer og de lokale forbrændingsforhold.
- Der er udført CFD og termodynamiske beregninger med henblik på at undersøge det første af de to foreslåede koncepter.

På grundlag af de udførte projektaktiviteter kan uddrages følgende konklusioner:

- Indflydelsen af roterovns behandling af bundaske på udvaskningen af Ca, Al, Si, Mg, Ba, Sr, Cl, Cu, Pb, Zn, Cr, Mo, sulfat, DOC og karbonat fra er bestemt. Roterovnsbehandling med henblik på at reducere udvaskningen af Cu, Pb, Cl, Zn og DOC kan anbefales. Der er dog observeret en forøget udvaskning af Cr og Mo som følge af roterovnsbehandlingen.
- Udførelsen af belægningsprobe målinger ved roterovnsforsøg har vist at den dannede røggas er rig på en aske med et højt indhold af klor og alkali metaller, der giver en korrosiv belægning på overhedere. Dette indikerer, at afgangsrøggassen fra roterovnsprocessen ikke umiddelbart er anvendelig, til at forøge overhedertemperaturen på at affaldsfyret anlæg.
- For de flygtige askedannende elementer Cl, S, Na og K målt langs med risten på vestforbrænding blev den maksimale koncentration målt nogle få meter fra brændselsindfødningen. De udførte undersøgelser viser, at på et sådant anlæg vil den røggas der passende kan anvendes til forøget overhedning skulle udtages fra 3 og 4 sektion på forbrændingsristen.
- CFD beregninger har vist, at den væg der skal lede røggassen til en ekstra overheder, bør være udmuret, for at undgå for høje varmetab i fyrrummet.
- Realiseringen af det patenterede koncept med indførelse af en ekstra væg i fyrrummet og indsættelse af en højtemperatur overheder der kan forøge damptemperaturen fra 400 til 500°C vil potentielt kunne øge elvirkningsgraden fra 24 til 30% (med hensyn til brændslets nedre brændværdi). De 30% virkningsgrad er baseret på anvendelse af en ekstra overheder kombineret med anvendelse af andre kendte modifikationer af dampkredsen.

Acknowledgment

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