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High efficient waste-to-energy in Amsterdam: getting ready for the next steps

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Abstract

Waste-to-energy (WtE) plants are traditionally designed for clean and economical disposal of waste. Design for output on the other hand was the guideline when projecting the HRC (HoogRendement Centrale) block of Afval Energie Bedrijf Amsterdam. Since commissioning of the plant in 2007, operation has continuously improved. In December 2010, the block's running average subsidy efficiency for one year exceeded 30% for the first time. The plant can increase its efficiency even further by raising the steam temperature to 480°C. In addition, the plant throughput can be increased by 10% to reduce the total cost of ownership. In order to take these steps, good preparation is required in areas such as change in heat transfer in the boiler and the resulting higher temperature upstream of the super heaters. A solution was found in the form of combining measured data with a computational fluid dynamics (CFD) model. Suction and acoustic pyrometers are used to obtain a clear picture of the temperature distribution in the first boiler pass. With the help of the CFD model, the change in heat transfer and vertical temperature distribution was predicted. For the increased load, the temperature is increased by 100°C; this implies a higher heat transfer in the first and second boiler passes. Even though the new block was designed beyond state-of-the art in waste-to-energy technology, margins remain for pushing energy efficiency and economy even further.

Keywords

Waste-to-energy, waste incineration, energy efficiency, Amsterdam, computational fluid dynamics (CFD), furnace, suction pyrometer, acoustic pyrometer

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Introduction

The concept of waste-to-energy (WtE) as a sustainable alternative to land filling of household or residual waste is increasingly gaining acceptance. In ecologically advanced European countries such as The Netherlands, Switzerland or Scandinavia grate-based WtE plants achieve high recovery rates and produce electricity, process steam and steam for district heating. The Amsterdam plant with its two new lines in the HRC (HoogRendement Centrale, High Efficiency WtE) block was designed for particularly high energy recovery with respect to electricity generation. The challenge of achieving this goal was considerable, since to date, boilers of 40 bar at 400°C were deemed to be the most suitable for WtE given the constraints posed by corrosion in the furnace and boiler. Increasing live steam temperature creates super heater corrosion and increasing boiler pressure with a given live steam temperature is limited by acceptable steam wetness in the low-pressure turbine. The new HRC lines with a total waste treatment capacity of 530 000 t year^{-1} based on a lower calorific value of 10 MJ kg^{-1} were commissioned in 2007 using a very efficient energy concept consisting of a 130 bar boiler operating with

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superheated steam at 440°C and intermediate reheater (AEB, 2006). The steam–steam reheater allows a strong increase in steam pressure with moderate live steam temperature. This enables a new range of steam parameters and a new flexibility in shifting boiler load from super heaters to the radiation part. This allows for gross electrical efficiency of 34.5% and a net design efficiency of just over 30%, the difference, 4.5% of the gross heat input, is needed as on-site power. Over the year 2010 the annual average of the performance indicator, the so called 'subsidy-efficiency', has exceeded 30%. This is the Dutch Milieukwaliteit Elektriciteitsproductie (MEP, Environmental Quality in Electricity Production) subsidy-efficiency and it is equivalent to about 28.5% net electrical efficiency plus 2% heat delivery. This annual average includes all operational variations and is still rising.

The study described herein comprises the determination of the furnace conditions based on suction and acoustic pyrometer measurements as well as CFD analyses. The basic idea is to obtain comprehensive knowledge and understanding of the actual operation and furnace conditions. This will facilitate further optimization of the process in terms of

- reduction of ammonia consumption for selective non-catalytic reduction (SNCR) NO_x-reduction
- possible minimisation of fouling and corrosion
- energy efficiency (by an increase of live steam temperature to 480°C)
- total cost of ownership (by an increase of waste throughput and boiler load to 110%).

The new HRC block of Afval Energie Bedrijf Amsterdam

The new HRC block of AEB Amsterdam was commissioned in 2007. The design concept for this enlargement was focused on the principle 'Design for output', thus recovering as much energy and materials from every tonne of incinerated waste as possible. To achieve this goal new ideas and approaches had to be implemented.

HRC concept

The new block has a total combustion capacity of 530 000 t year^{-1} based on the design lower calorific value of 10 MJ kg^{-1} and consists of two lines equipped with a MARTIN horizontal grate and combustion system.

It is well known that steam power plants yield greater efficiency when the pressure and temperature of the live steam is increased. The limiting factor is that high live steam temperature increases the risk of super heater corrosion. In Amsterdam the steam pressure is increased from the typical 40 bar to 130 bar. Another new component is the intermediate reheater: saturated steam from the drum reheats the wet 14 bar steam from the first stage of the turbine to 320°C (Figure 1). A water separator avoids re-evaporation of the condensed fraction, which would lead to a decrease in efficiency. A further key element is the live steam temperature of 440°C at the outlet of the super heater. The advantage of this concept is its high energy efficiency due to the high pressure and the reheating combined with still modest super heater temperatures of 440°C. The membrane walls in the furnace are protected by Inconel (increased steam saturation temperatures due to higher pressure), whereas the super heater is made of carbon steel without any particular coating (AEB, 2006). The corrosion experience with the super heaters is very positive with no pipe changes after 30 000 operational hours per boiler, which is attributed to the design of the combustion system and boiler: Low flue gas velocities and long retention time of fly ash particles before hitting the super heater. Also the Inconel on the membrane wall has behaved as designed. There is a marginal corrosion with average rates of about 0.1 mm year^{-1} which will result in a lifetime of >10 years. More information on corrosion studies in the HRC block can be found in Zahn et al. (2010).

The combustion takes place at an excess air ratio of 1.4, reducing the flue gas losses. Some of the flue gas is recirculated back into the lower part of the boiler which reduces the temperature and improves mixing in the post combustion zone. Additional combustion air is injected above this flue gas recirculation level (so called tertiary air level).

As the plant is located directly at the Amsterdam harbour, sea water can be used in the main condenser, which allows a condensing pressure of 0.03 bar. A further measure for increasing the energy efficiency of the new block is the recovery of various available heats at different temperature levels. The flue gas temperature at the boiler exit is 180°C. Through a second economizer, where the heat is shifted directly to the condensate, the flue gas is further cooled down to 130°C, where the heat is shifted directly to preheat the condensate (from approximately 80 to 105°C). After the last stage of the flue gas treatment, a condensing scrubber uses the condensing heat of the moisture in the flue gas of about 59°C to preheat the condensate from condensation temperature (from approximately 25 to 50°C in economizer 3.

Operational data of energy efficiency

In 1999 the 'Energy from waste' agreement was concluded between the Dutch government and the operators of WtE plants. The idea was to give WtE operators a tax advantage (REB, regulating energy tax) to improve the energy efficiency. In a reaction to this, AEB initiated a massive programme to optimize energy efficiency. One of the many projects was the initiation of a district-heating network in Amsterdam-West. Later on in 2003 the Dutch Ministry of Economic Affairs introduced an incentive subsidy to

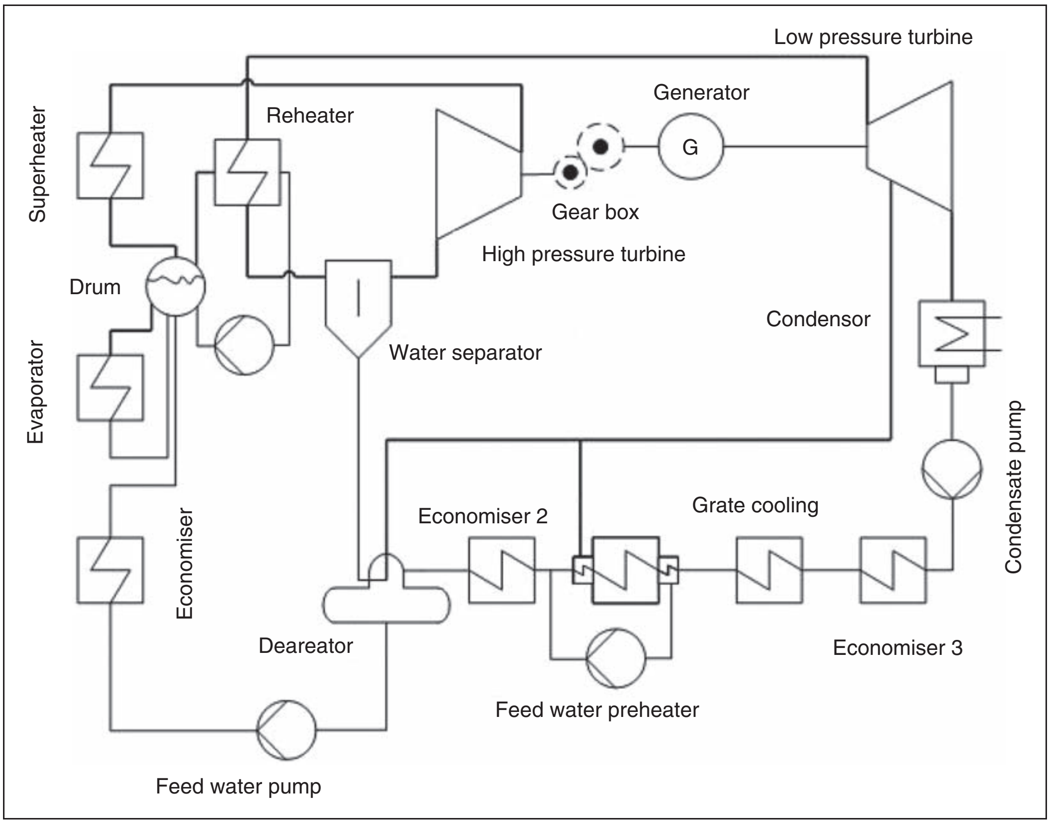

Figure 1. Water–steam cycle showing the turbine and the various heat transfer surfaces in one line. The reheater operates with saturated steam from the drum. The condensate is pumped directly back into the drum.

stimulate the use of energy from renewable sources (Minister van Economische Zaken 2003). The idea was to have a subsidy scheme which increased with efforts made towards getting the plants to run above the then state-of-the-art efficiency of 22%. The subsidies are paid only for the produced electricity attributed to the biogenic portion of the waste (47–51%, reviewed yearly by the Dutch authorities) and increase incrementally up to 30% efficiency. Efficient plants gain twice from this approach, because they get a higher subsidy while at the same time they produce more electricity due to the higher efficiency. The combined use of heat and power (CHP) is promoted by including delivered heat with a relatively high factor of two-thirds to the energy efficiency indicator (see Equation (1)), which will be referred to in this paper as 'subsidy-efficiency':

$$subsidy\text{-}efficiency = \frac{delivered\ electricity + (2/3)\ delivered\ heat}{gross\ heat\ (energy)\ of\ the\ processed\ waste} \quad (1)$$

The calculation of the subsidy-efficiency is done on a monthly basis with the net exported values for electricity and heat. Equation (1) is simplified for the case of the Amsterdam HRC plant, where no auxiliary burners are installed. The heat for start up is provided by the other boilers in operation at the side. The subsidy is re-evaluated every month, depending on the running average of the 'subsidy efficiency' for the last 12 months. The subsidy is limited to the first 10 years of commercial operations. The rating of heat at 67% (2/3) of electricity is relatively high in comparison with performance criteria like R1 (42%) and exergy (16–23%). AEB had focused on increasing electrical efficiency for the new project because the existing plant had sufficient capacity for the district-heating network. Therefore AEB concluded that optimization of electrical efficiency was the only possibility for improvement of the environmental performance. The high rating of the heat in respect to its equivalent quantity of electricity is the reason that a heat exchanger was added directly after the construction. This shows that high electrical efficiency can well be combined with heat delivery and that for evaluating the performance of WtE plants the use of fixed equivalence factors between heat and electricity is problematic. More on this discussion and the use of 'exergy' for evaluating plant performance can be found in Murer et al. (2009).

Permanent sensors are installed at the HRC block to measure the relevant data for the efficiency calculation continuously. The heat balance and heating value calculation is done according to the FDBR guideline (FDBR, 2000). Every month the subsidy-efficiency as well as the electric efficiency, boiler efficiency and gross heat input are calculated based on data from more than 170 measuring devices. The trends are also studied to identify effects on operational changes and plant behaviour.

The annual moving average in Figure 2 shows a steady increase due to improved operation and maintenance strategies. Stable monthly average subsidy-efficiencies in the range of 30 to 32% can be achieved. The lengthy overhaul conducted in January 2010 with an inspection of the Inconel cladding in the first boiler pass as well as changes made to the turbine adversely affected efficiency. In June and August 2010 shorter inspection downtimes also caused a decrease in efficiency. The conversion efficiency of the common steam turbine is reduced when it operates at half of its design load during periods when overhauls are carried out on one combustion line. The graph shows clearly that the major part of the efficiency is achieved by high net electricity production, while only a small fraction (2–3%) is attributed to the heat delivery.

Objective: increased throughput and live steam temperature

Waste-to-energy plants may have life times of 30 to 40 years or even above. Technologies and environmental requirements evolve during these time spans necessitating continuous adaptations and retrofits. In the 1990 s and 2000 s improved flue gas treatment systems were implemented in older plants to meet new regulations. In the case of HRC plants, the potential for further improvement investigated in the study described herein lies in a further increase in energy efficiency (by increased live steam temperature to 480°C) and reduced total cost of ownership (by increased waste throughput and boiler load).

As already mentioned, typical live steam temperatures for WTE plants of 400°C are already exceeded by the actual operation of the HRC plants using 440°C. Further increase of the super heater temperature was already foreseen during the design phase of the plant, but not implemented for daily operation up to now due to the corrosion risk. An empty slot between the last super heater bundle and the economizer was prepared in the horizontal pass of the boilers to accommodate an additional super heater bundle to achieve increased live steam temperatures. In addition, the turbine specifications allow increased live steam temperatures up to 480°C. With this modification an increase in net electric efficiency by almost 0.2%-points could be achieved.

Another important area of improvement is increasing the waste throughput and consequently the boiler load. The aim would be to reduce the total cost of ownership by increasing the boiler load to 110%, based on steam production, combining live steam and steam for the reheater. The main sources of income for a WtE plant are the tipping fee for the waste and the revenue for electricity and heat delivery. In the HRC, income from electricity has shifted from less then 30% for most plants to about 50% of total income. Financing the investment and maintenance constitute the

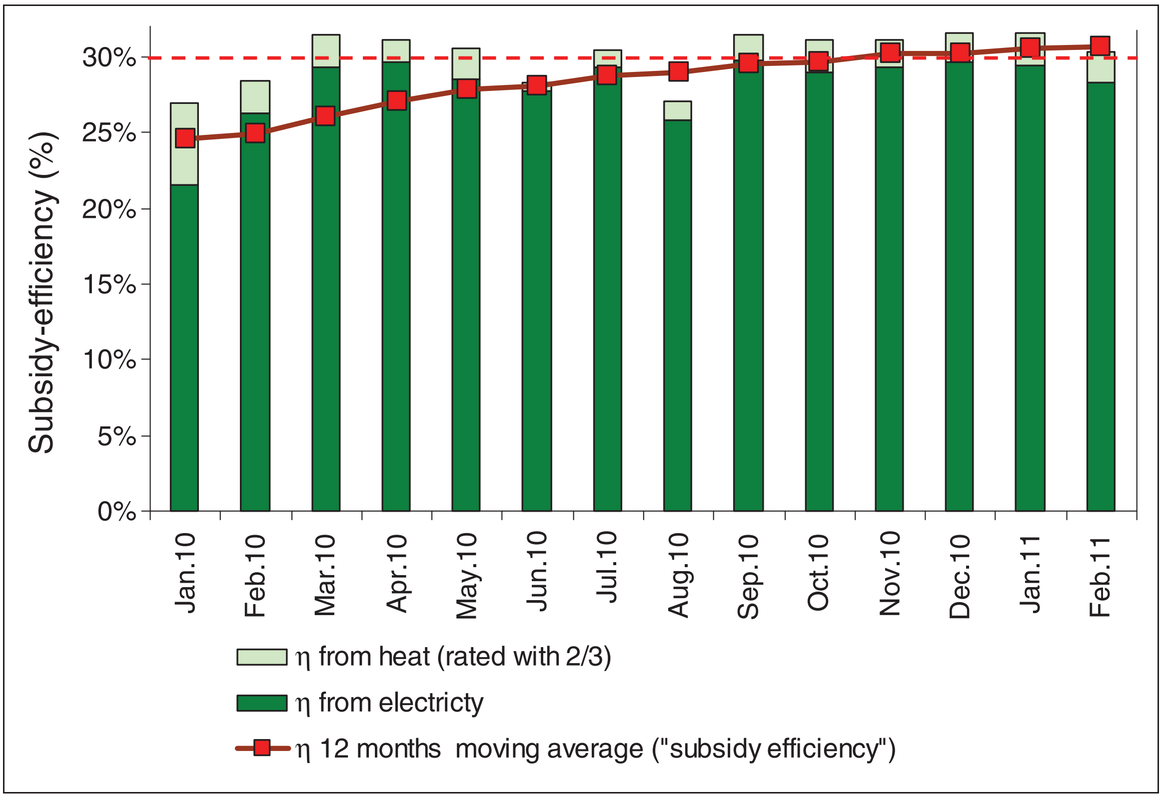

Figure 2. Trend for subsidy-efficiency of the HRC block, showing monthly average values which are split into an electric and a heat contribution. Due to continuous improvement of operation and availability, the moving average for one year exceeded 30% in December 2010.

greatest cost factors. Increasing the boiler load obviously leads to a respective increase in income, whereas the cost of investment remains unaffected (as long as the cost of retrofit is marginal compared to the total investment).

The difficulty of the project lies in achieving these improvements (of live steam temperature and boiler load) without losses in availability or incurring additional maintenance costs. That is why a systematic and research and development-based approach which includes extensive corrosion research and a precise knowledge of the actual conditions of the combustion, furnace and boiler is necessary. Especially the validated computational fluid dynamics (CFD) analyses allow predictions for safe operation in these conditions at 480°C live steam temperature and 110% boiler load.

A potential political argument against these objectives is that treating more waste necessitates acquiring the waste from further afield. A study by Otten and Bergsma (2010) showed that in terms of avoided CO_2 emissions and energetic efficiency, it is beneficial to transport the waste from further afield and burn it in a more efficient WtE plant. The calculated distance is about 200 km per percent higher efficiency. The outstanding energy efficiency of the Amsterdam HRC plant makes transportation of additional waste ecologically justifiable for distances of over 1000 km.

Measurement of furnace conditions with suction and acoustic pyrometers

In order to assess possibilities relating to changing operation conditions, it is crucial to have a complete understanding of the actual operation conditions and more particularly the conditions in the furnace. Over and above the large number of sensors installed in the plant for continuous gathering and processing of data for operational purposes, various additional measurement and observation devices were installed for a measurement campaign in December 2010.

Figure 3 shows the approach used for the measuring campaign. An acoustic pyrometer using eight horns for sending and receiving was installed in the first pass. On the levels above and below, openings were used to insert suction pyrometers to validate the data collected by the acoustic pyrometer. The suction pyrometers were used at three different openings with three different insertion depths per boiler side. The temperature and oxygen concentration in each position is measured over a 25 min period. The gas from the lower suction pyrometer was further analysed for CO, CO_2 and NO_x. An endoscopic furnace camera was used to look into the boiler from the centre of the left and right boiler wall in the first pass.

Two horns of the acoustic pyrometer were installed at the front wall while three horns were installed at the left and right boiler wall, respectively. A grid of acoustic paths was formed from this configuration. On each path the average temperature was calculated from the time of flight of a sound signal propagated from one horn to the horn at the end of the respective path. A temperature profile can be generated with the information from all paths. The accuracy of the temperature profile increases in the part of the boiler cross-section where the number of paths is high and where there are many intersections between paths. By implication, the calculated temperature in the front of the cross-section is more accurate than the temperature in the rear.

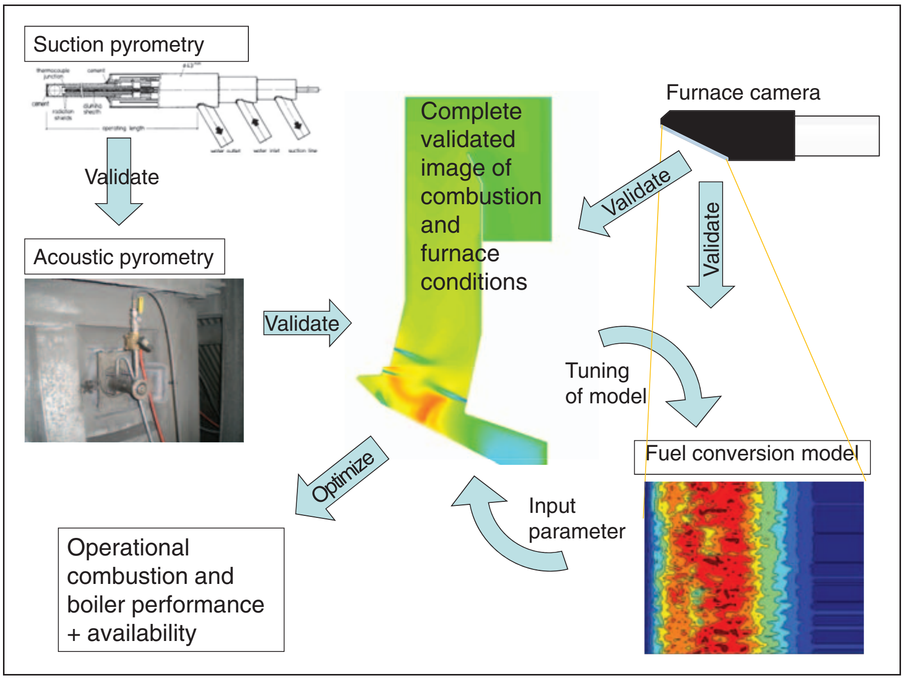

Figure 3. Approach for generating improved understanding of the plant: various measurement techniques and devices are used to obtain a reliable picture.

The acoustic pyrometer software calculates an average area temperature for 16 evenly distributed squares in the cross-sections. The registered temperature trend of these areas was compared with the temperature measured by the suction pyrometer 2.8 m above and 3 m below. As can be seen in Figure 4 at more than 13 m, the boiler is so large that the suction pyrometers were able to cover only one-quarter of the total boiler width from one side. The temperature trend from the acoustic pyrometer in the rear part of the boiler was not able to reproduce the fluctuation seen in the trends of the suction pyrometer from openings 5 left and 5 right, due to the low availability of information in this region. The temperature measured by the suction pyrometers at the openings 1 and 3 on both sides was represented well by the acoustic pyrometer as can be seen in Figure 5. The sampling time for the temperature measured by the suction pyrometer is 5 s. The acoustic pyrometer works in sequence; this implies all paths are measured one after another, resulting in an average sampling time of 92 s for the whole measuring campaign. Therefore, only long-term combustion perturbations lasting a few minutes can be seen in the graphs of the acoustic pyrometer.

The suction pyrometer measurements were performed over a 3-day period. The acoustic pyrometer remained installed for three more months to gather additional data and investigate different combustion settings. During this period a 2-day load increase to the planned level of 110% was performed. Primary air, recirculated flue gas and tertiary air were increased proportionally to the load, so that the flue gas composition did not change. The bottom ash burnout will be investigated during planned long-term operation at 110% load during 2011, and combustion settings can be adjusted if necessary. At 110% load, depending on live steam and reheater mass flow, the boiler load fluctuations remained in the same range as at 100% load. The fluctuations in the average temperatures measured by the acoustic pyrometer were increased with the higher load case (Figure 6). Furthermore the average acoustic pyrometer temperature itself increased slightly.

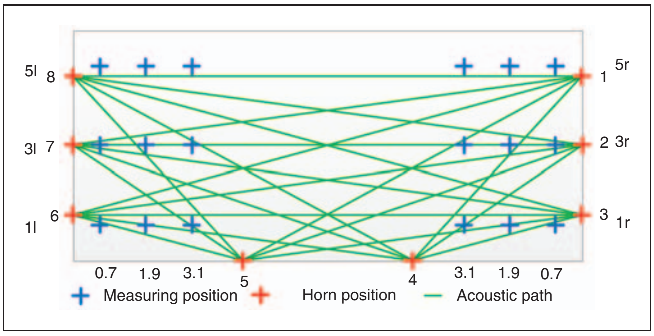

Figure 4. Boiler cross section of the first pass showing measuring positions of the suction pyrometer for the three openings on the left and right side of the boiler, the positions of the horn for the acoustic pyrometer and the resulting grid of acoustic paths.

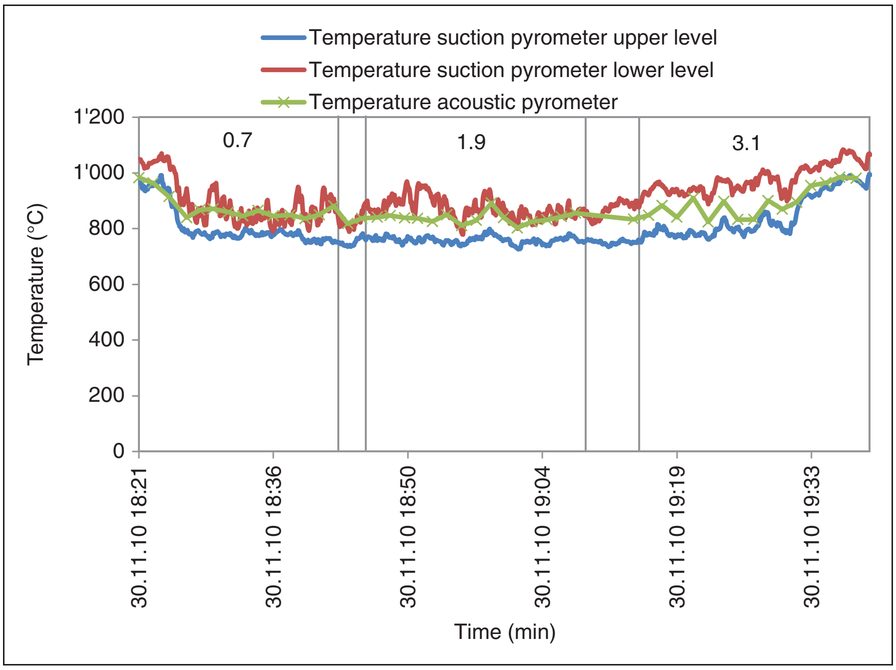

Figure 5. Validation of the temperature calculated from the acoustic pyrometer with the temperature trends from the suction pyrometers (three insertion depths 0.7, 1.9 and 3.1 m) installed in the first opening on the left side of the boiler one level above and below the acoustic pyrometer.

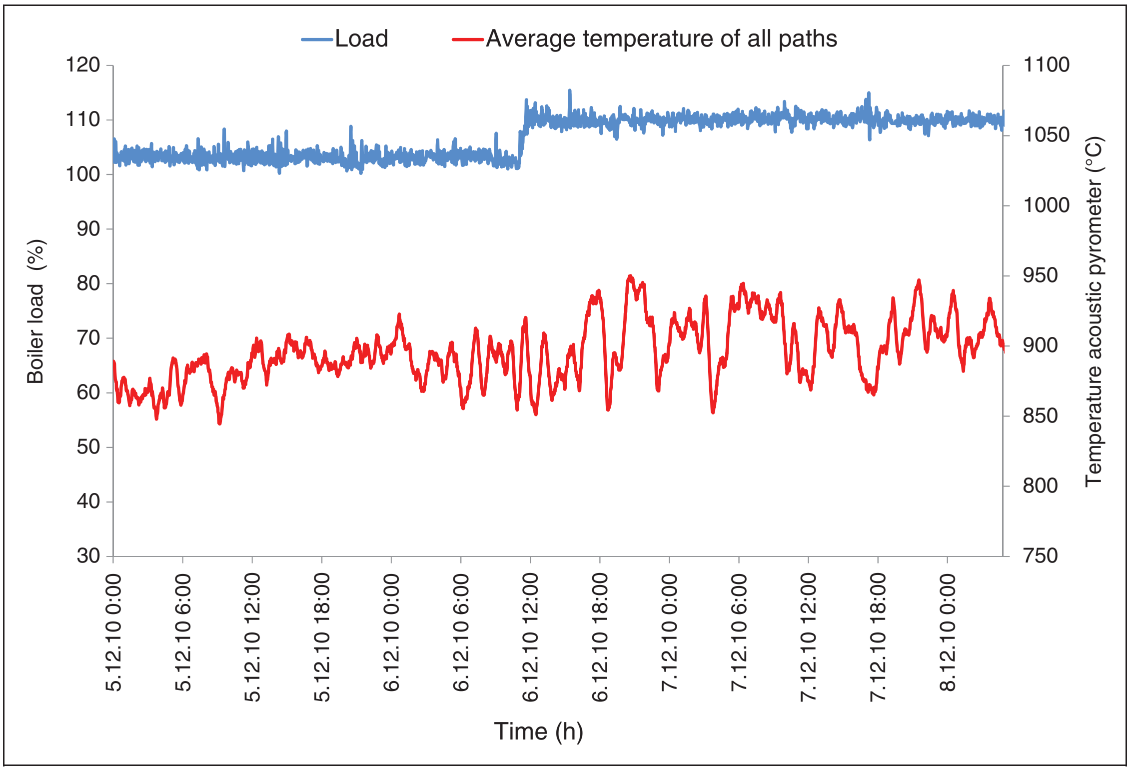

Figure 6. Load compared with average temperature of the acoustic pyrometer. The temperature level at this height also increases with load. The combustion becomes more unstable resulting in higher temperature fluctuations, while the fluctuations for the load are not affected.

Computational fluid dynamics model

Method

Computational fluid dynamics calculations of the plant were made to get an insight into the current combustion condition and to ascertain the additional stress the boiler is subjected to at 110% load. One consideration being: How does unevenly distributed combustion affect the temperature distribution in front of the horizontal pass? For this investigation the first pass and the upper section of the second pass of the boiler were modelled, to see the main effects of combustion as well as the performance of the SNCR system. It was necessary to model the whole width of the boiler to investigate uneven combustion. In order to compare the results of the 100 and 110% load cases, the vertical temperature distribution and the amount of heat transferred in the different boiler sections is compared.

The CFD calculation was performed with ANSYS Fluent 13.0 (ANSYS Inc., Canonsburg, PA, USA). Using ANSYS Workbench three different meshes were produced. The modelled geometry represents a total volume of 3100 m^3. A coarse mesh with 620 000 cells was used to get good start values for the finer meshes. A mesh with 3.5 million cells was used as intermediate step to obtain preliminary results. The fine mesh used in this investigation had 15.9 million cells, where the biggest cell is about 0.0007 m^3. The mesh was refined above the grate up to the end of the post-combustion zone and at the SNCR injections (Figure 7). A newly developed model involving the injection of ammonia water along with pressurized air was applied for the first time.

In addition, an empirical model which allows for stochastic waste composition and air distribution has been used for grate-based combustion. A special feature of the model is its ability to generate profiles of different combustion conditions which can then be combined to produce a larger profile. It is a key feature of the model that the large local differences arising from the statistical properties of the waste will result in similarly large local variations of the combustion and its gases. This allows for a better insight into the quality of the mixing of the inhomogeneous gas composition and the reactions taking place. In particular, there will be more local areas with oxygen surplus and others with large CO contents and the reactions in these distinct mixtures will be different from the case in which more averaged waste and flue gas compositions are used (Table 1).

The calculated temperature at the level of the acoustic pyrometer is compared with the average, minimum and maximum temperature registered by the acoustic pyrometer during an investigation period of 2 h of stable operation. The average temperature in this cross-section is 870°C with shorter local peaks reaching up to 1000°C. The temperature of the CFD calculation in this cross-section varies from 850 to 990°C, which is the right range (Figure 8). However, the temperature profile calculated by the acoustic pyrometer software could only be reproduced roughly: further work has to be put into the modelling of the grate-based combustion.

Temperature profile (vertical)

The temperature distribution inside the boiler is an important way of comparing different load cases. The temperatures on 48 lines spaced evenly in the boiler were averaged in order to obtain a temperature profile which represents the whole boiler cross-section. The different combustion stages can be seen clearly due to changes in temperature.

The gas temperature released from the centre of the waste bed decreases slightly at the constriction of the boiler due to colder gas coming from both the waste drying zone and the end of the grate. The next change in temperature is caused by the recirculated flue gas, which is used for better mixing in the start of the post-combustion zone. The oxygen in the recirculated flue gas as well as the still unused oxygen, now mixed with the rest of the flue gas, promotes effective post combustion. Tertiary air is introduced into the post-combustion zone approximately 1.5 m above the injection level of recirculated flue gas, which leads to a sudden decrease in temperature of about 80 to 100°C. The oxygen delivered with the tertiary air is only needed to ensure good burnout of the unburned components in the flue gas. The main heat is already released at the level of the recirculated flue gas.

An increase in temperature of more than 50°C was seen for a load increase from about 104 to 110% during the test with the acoustic pyrometer. In the represented calculation cases, the waste input was adjusted to the calculated heat release during two test periods. For the 100% load case, the measured data was registered during a period when the primary air heaters were switched off. This fact plus the increased temperature due to the higher load are responsible for the total flue gas temperature difference of about 100°C for both load cases (Figure 9). The higher flue gas temperature has an effect on the SNCR system. Therefore additional SNCR tests were performed at a higher level. These tests are not described herein.

An important point for comparing both load cases is to compare the amount of transferred heat in different sections

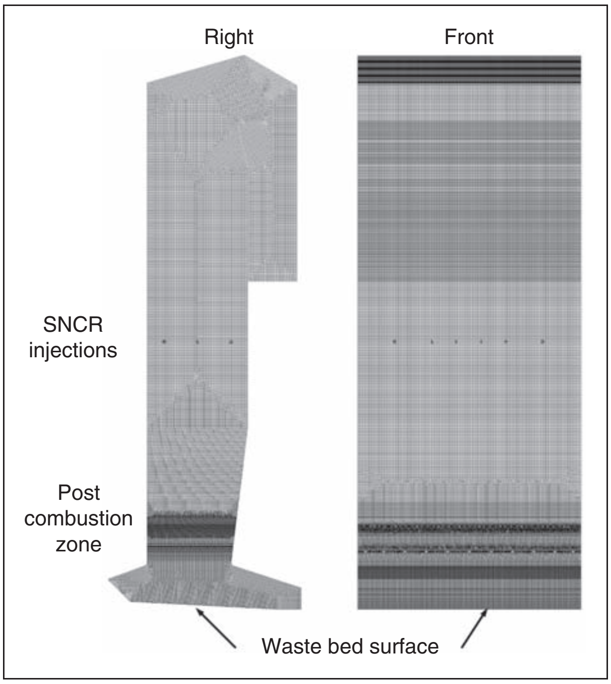

Figure 7. The 15 million cell mesh of the right and front wall of the boiler, refinements are made at the post combustion zone. For the SNCR injections the mesh is refined twice depending on the ammonia concentrations. More cells are refined at this level inside the SNCR reaction zone.

Table 1. CFD model detailed information

Turbulence model	*k*–epsilon realizable model
Reaction model	Eddy dissipation model, accurate enough for calculating temperature and heat release when compared with temperature fluctuations in Figure 5
Radiation model	P1 radiation model
Gas emission coefficient	Domain based weighted sum of grey gases
Inlet conditions waste bed	Empirical statistical waste bed model, generating profiles from under fire air distribution, waste throughput and waste composition
	Respecting mass, species and energy balances Temperature – radiation coupling implemented via user defined function (UDF)
Inlet conditions recirculated flue gas	Composition from boiler outlet, considering only O_2, CO_2, H_2O and N_2
Thermal wall boundary conditions	Saturation temperature of evaporating water at 135 bar and average thermal resistivity formed by refractory (where applied), metal and some deposits
Time settings	Steady state
Iterations	Coarse mesh: 3500
	Medium fine mesh: 2500 Fine mesh: 4000

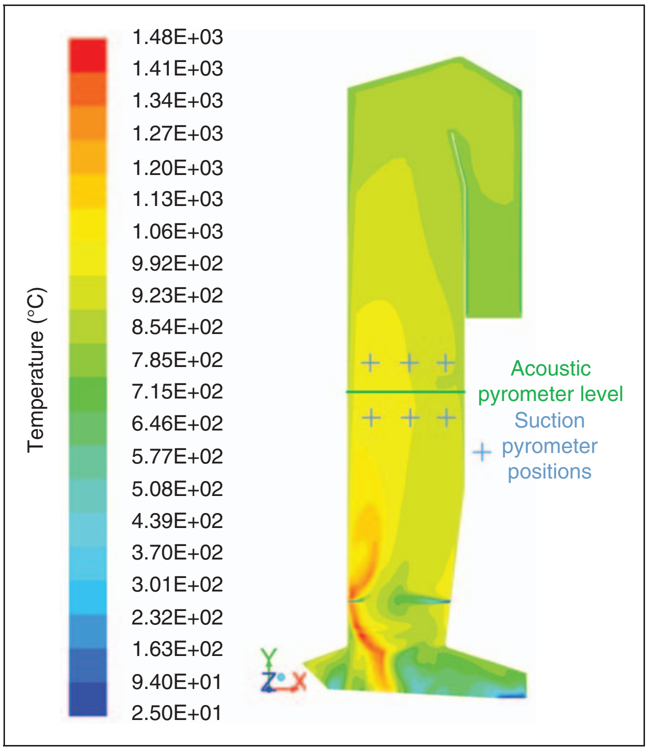

Figure 8. Temperature distribution with highlighted level of the acoustic pyrometer. The measured temperature in this position ranges between 850 and 925°C for the 100% load case.

of the boiler. For this reason the modelled part of the boiler is divided into three sections

- furnace, lower part of the boiler including all walls covered with refractory
- first pass, walls of the first pass not covered with refractory
- second pass, modelled part of the second pass.

The amount of transferred heat is only slightly higher for the 110% load case in the furnace. This can also be explained by the temperature profiles shown in Figure 9. In the first few metres there is no difference in the temperature; higher temperatures only start at post combustion. The effect of the higher temperature can be seen clearly in the first pass section. The temperature for the 110% load case decreases for the same amount as for the 100% load case, but the amount of flue gas is higher, so for the same temperature decrease more heat has to be transferred, which is also clear since higher flue gas temperatures imply more transferred heat (Figure 10). The same effects as those responsible for the higher amount of heat transfer in the first pass apply to the second pass.

Conclusions

A study was performed in one line of the new Amsterdam block equipped with the HRC energy concept consisting of a

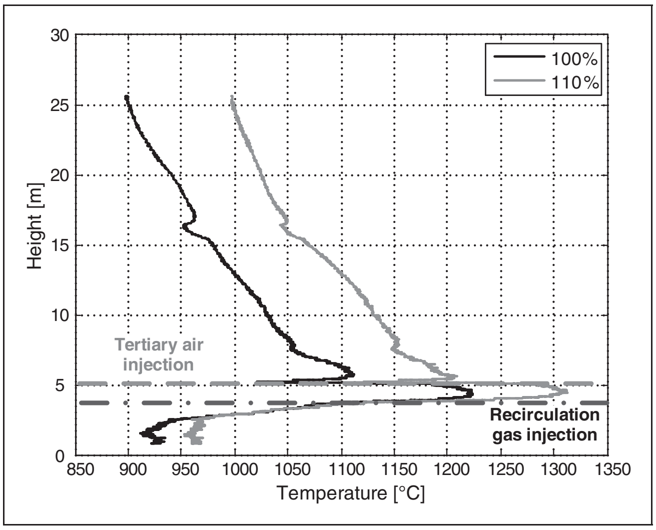

Figure 9. Averaged temperature distribution on 48 vertical lines distributed in the first pass for boiler load 100 and 110%, effect of flue gas recirculation and post combustion by tertiary air can be seen. A small temperature drop at 16 m is evident where the lines for temperature investigation cross close to an SNCR injection point.

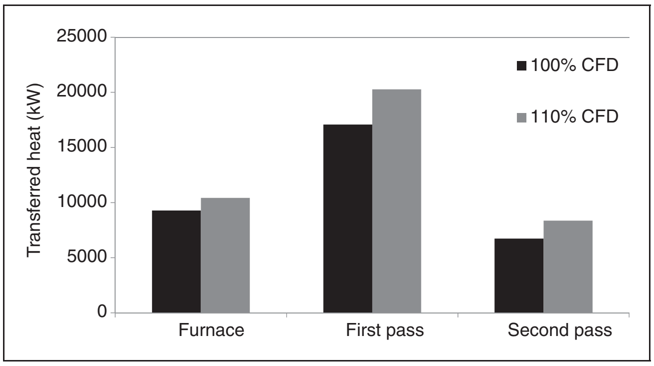

Figure 10. Comparison of heat transferred in the modelled boiler sections for 100 and 110% load.

130 bar boiler with an intermediate reheater. Owing to the improvement of the availability and operation in the past few years, it has been possible to achieve a subsidy-efficiency above 30% as a moving yearly average since December 2010. This degree of efficiency is unique for a WtE plant producing mainly electricity. The corrosion pattern of the super heater and the Inconel-protected membrane walls is very positive after more than 30 000 operating hours.

The combustion and furnace conditions were investigated by various measurements and CFD simulation. Suction pyrometer measurements have confirmed the validity of the acoustic pyrometry. The acoustic pyrometer was further used to validate the temperature level in the CFD calculation.

A CFD model was developed and adapted to the Amsterdam furnace conditions. Special emphasis was laid on the development of tools for taking into account the variability of combustion conditions.

Furthermore, the CFD model was used for predicting temperature profiles and heat transfer to compare cases with varying waste throughput. It was shown that in the lower furnace up to 4 m above the grate there is no significant temperature increase with load increase. A temperature increase of around 100°C is predicted for 10% load increase after injection of recirculation gas.

It is obvious that the objective of increasing the throughput as well as the live steam temperature is linked to higher flue gas temperatures and corrosion risk. In order to realize these 'next steps' it is crucial to have a clear understanding of the combustion and furnace conditions and to use validated CFD tools. The positive corrosion pattern observed at the actual combustion settings in the Amsterdam plant creates further opportunities for advanced improvements. This will make it possible to propel WtE technology further towards even higher energy efficiency and improved total cost of ownership.

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