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High Electrical Efficiency by Dividing The Combustion Products

Ole Hedegaard Madsen
ohm@volund.dk

Babcock & Wilcox Vølund
A subsidiary of The Babcock & Wilcox Company
Denmark

Martin Bøjer, Peter Arendt Jensen, Kim Dam-Johansen
CHEC Research Centre
Department of Chemical and Biochemical Engineering
Technical University of Denmark

Abstract

Energy recovery from waste is an efficient way to reduce emissions of greenhouse gas and other gaseous, liquid and solid pollutants and thereby to contribute to a sustainable development.

Waste fired power plants are an important part of the European waste management system, and the demands made to modern waste fired power plant are very focused on high electrical output.

Lately, Babcock & Wilcox Vølund (BWV) and the CHEC research centre at the Technical University of Demnark has developed a new technology and received a world patent. The basic idea is to improve the electrical efficiency by increasing the steam data. Especially, increasing the steam temperature without the risk of superheater corrosion. The new concept is fully integrated in the boiler and from the outside the waste fired power plant has the same lay-out as the classic waste fired power plant.

The goal is to achieve an increase between 50 °C to 100 °C in the superheated steam temperature and a total increase of electrical efficiency up to 30 % without any influence on the normal operation.

This paper presents the basic ideas that provide a basis for the patent. The core of the technology is a combination of a new furnace design and a new control system. At the moment, test results from an operating plant support the principal idea. Furthermore, the concept will be studied in the numerical laboratory where CFD simulation will be used to evaluate the technology and to determine the potential process improvements.

The final improvement of electricity production has to be determined in the coming test period on a full scale installation, which is currently being planned.

Introduction

Design and production of waste fired power plants comprises many parameters, and a very complex analysis is required to optimise the final design. The past few years we have focused on improving the thermal efficiency of the plants and thereby the steam and energy production. Our experience through the years, combined with our goal of being a reliable partner, have resulted in steam parameters that secure the plant availability and reduce operation and maintenance cost, independent of waste composition. The typical standard steam data are 400 °C and 45 bar and generally recognized as the presently best available technology [1].

With increasing focus on power production and favourable tariffs in many markets there is a need for maximizing electricity delivery to the grid. Increasing the steam temperature and pressure, will result in an improved performance of the steam turbine and thereby a higher electrical output.

The main risks associated with increasing the steam parameters are corrosion and fouling in the boiler. The ladder risk can be controlled by modern boiler cleaning equipment [2], whereas corrosion is destructive for the boiler and plant operation and it is still a unpredictable process. Today, we face requirements for plant availability up to 8000 hours per year. The operational hours are one of the most important factors for the plant owner, because this factor is the basis for his yearly income and thereby whether or not it is profitable business. This fact results in very conservative development where the investors tend to choose well-proven technology in order to minimise the financial risk.

Babcock & Wilcox Vølund has built waste fired power plants all over the world for more than 75 years. This effort has given us a unique knowledge about waste as a fuel. Waste is one of the most challenging fuels to burn giving many different problems, of which corrosion is one. We have learned that one of the most important factors is the waste composition. Waste from one geographic region or one type of waste will result in different corrosion problems.

The lifetime of superheater tubes is one of the critical parameters. New materials such as Inconel® and design tools such as CFD modelling have resulted in more progressive steam data and thereby increasing electrical efficiency. These developments have resulted in increasing steam data to 425 °C and 65 bar depending on fuel property.

During the years, many plants have reported problems when using ceramic tiles as corrosion protection in the boiler. It is therefore considered a major advantage to use Inconel® 625 instead of refractory as protection. For a number of years, this technique has been used successfully in the upper part of the post combustion chamber of the boiler. The new element is to replace as much as possible of the refractory in the boiler with Inconel®.

A number of studies have reported that resistance to corrosive environment is limited by the material temperature. BWV has tested Inconel® cladding for superheater tubes, but at temperatures around 400 °C and higher there are no improvements compared to normal boiler tubes. In the radiant part of the boiler, where we today use Inconel®, the metal temperature is more or less controlled by the steam pressure and thereby the evaporation temperature. The standard 45 bars correspond to a material temperature of 260 °C and in that range the Inconel® cladding is very resistant against the corrosive environment. If the pressure is increased to 100 bars the corresponding material temperature is 310 °C. At the moment no long-term well-proven experience or data are available that show how the Inconel® operates under these conditions. Therefore, industrial well-proven designs will be based on steam pressures less than 100 bars when using Inconel® in the furnace.

The basic idea and patent

Waste incineration is one of the most complex combustion processes. The processes in a burning refuse bed includes: drying, ignition, pyrolysis, gasification, solid and gas combustion. Figure 1 is a simplified illustration of the different processes in a fuel bed on a grate.

The rate of the process is difficult to determine, as the controlling partial processes are heterogeneous solids gasification and combustion, and homogeneous gas phase combustion in and above the waste layer. In general, the processes between the combustion air and the solid waste are diffusion controlled and relatively slow. The gas phase combustion, however, is controlled by the temperature and concentrations. The reaction speed is relatively high. In practice this means that the conversion rate of the whole process is primarily controlled by the mass flow of the primary combustion air.

A large zone on the middle of the grates is under stoichiometric and resulting in formation of combustible gases, like CO and H_2. The burnout of these gases is controlled by the turbulence created by the secondary air added in the furnace ceiling and at the entrance of the post combustion chamber.

Pyrolysis gases will be released in the ignition zone due to a quick heating of the top waste layer before the combustion starts. These combustible gases flow into the furnace room where they will mix with excess primary air from other areas of the grate and secondary air. Thus pure gas phase combustion is achieved right above the waste layer where a relatively large part of the total energy is released from the waste. The burnout of these gases, soot and particles leaving the bed forms the flame above the grate.

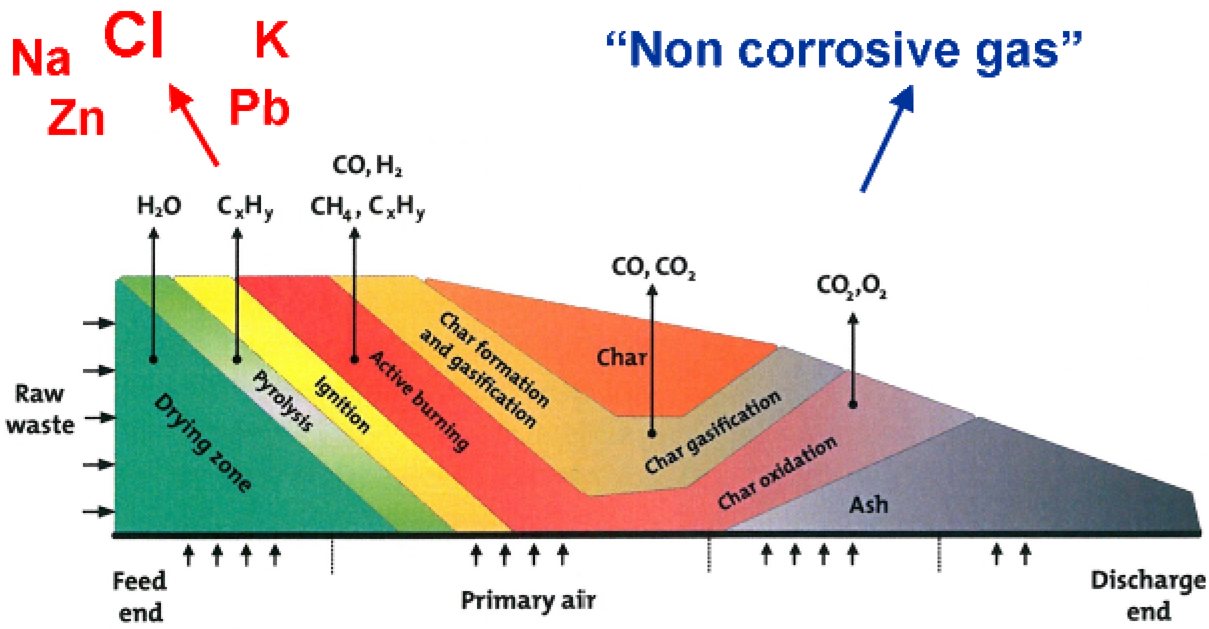

Figure 1. Schematic view of the fuel bed combustion process and the potential release of the volatile elements Cl, Na, K, Pb, Zn, and S to the flue gas in the first part of the furnace.

Measurements indicate that around 30%-40% of the total energy release in the system is released as combustible gases above the bed. The combustible gases consist mainly of light components such as: H_2, CO, CH_4 and some tar. Beyond the combustible gases, the gases released from the bed contain products from the combustion taking place in the bed: H_2O and CO_2. Furthermore, the heterogeneous combustion in the bed to some degree permits bypassing of primary air through the bed to the furnace.

The chemical composition of the waste includes a number of trace species Cl, Na, K, Pb, Zn, and S that will be released to the gas phase during the combustion process. The split between bottom ash and flue gas for the species does not differ much for different types of household wastes. About 90 % of the chlorine and about half of Pb and Zn are released to the gas phase. More than 75 % of S is released. Approximately, 10 % of Na and 33 % of K is typically released [4].

The release of the volatile elements Cl, Na, K, Pb, Zn, and S to the flue gas and the aerosol formation from those volatile elements is of special interest. The volatile elements are present in ash deposit layers at high concentrations where they may form a complex textured layer of different sulphate and chloride salts (Na, K, Ca, Fe and Zn) able to induce high corrosion rates. Deposits with a high Cl content, in particular, induce a high corrosion rate on boiler tubes.

It is well known that volatilisation of chlorine increases rapidly with temperature and nearly full volatilisation is achieved at 900 °C. This temperature is typically lower than the maximum temperature in the active burning zone. Moreover, Cl has been seen to promote volatilisation of alkali and heavy metals and to lower the melting temperature of ashes [4].

The release of chlorides from the fuel into the flue gas depends on the properties of the chlorine / chloride bearing components and of the firing conditions. The overall distribution is illustrated in Figure 1, where the first part of the grate and fuel bed contain the ignition, pyrolysis/devolatilisation, burning zones. The major parts of the corrosive species are released on the first part of the combustion grate and thereby in the front of the furnace.

The rear parts of the grate are characterized by a burnout of a relatively clean char, thereby releasing relatively clean combustion products which are much less corrosive.

This phenomenon can be applied to split up the flue gases from the grate into two or more fractions, one of which exhibits high heat flux and a low chlorine concentration. That fraction could then be used in a high temperature superheater to increase the steam temperature and thereby the electricity efficiency of waste fired power plants, see Figure 2. The concept is named SteamBoost™ [5].

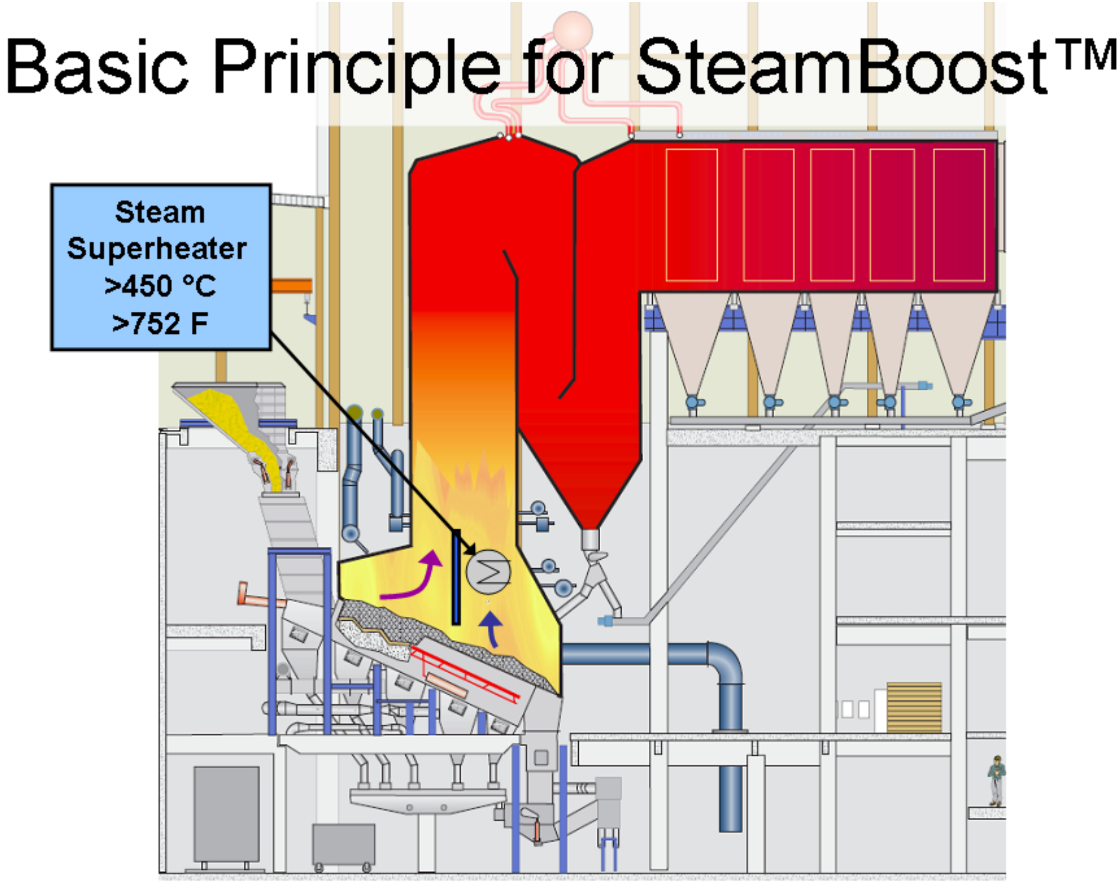

Figure 2. Generic waste fired power plant with two-stage furnace and SteamBoost™ superheater.

In order to ensure the separation of the two flue gas fractions in the furnace, a water cooled membrane wall is installed above the middle of the combustion grate. When the two streams of flue gases are entering the post combustion chamber, they will be mixed by the VoluMix™ secondary air system for final burnout.

The CHEC Research Centre, Department of Chemical and Biochemical Engineering at the Technical University of Denmark has carried out full scale experiments in order to verify the Cl release profile in a typical waste fired power plant.

The objective of the study was to measure a concentration profile of the elements Cl, Na, K, Zn, Pb, and S as function of location on the grate in a waste to energy boiler. A heat flux and chlorine release profile along the grate will provide information on the position where the heat is released with the lowest concentrations of corrosion promoting species in the flue gas. This will test the basic idea of separating the flue gas from the grate into two or more fractions while having one fraction of the flue gas with a relatively high heat flux and a low chlorine concentration.

Measurement of the concentration and the location of the release of Cl, Na, K, Pb, Zn, and S from the grate, combined with information on the magnitude and location of the heat flux from the grate, may be used to reveal the region of the flue gas that has a high heat flux, but low concentrations of corrosive elements. This portion of the flue gas may be directed to a separate superheater section, where it can raise the steam temperature. The elevated superheater steam temperature could then increase the electrical efficiency of the waste fired power plant.

Measurements were conducted at Vestforbrænding Unit 5 - a heat and power generating waste fired power plant in Copenhagen, Denmark. The plant was commissioned in 1998 and may processes up to 30 tonnes per hour. The waste is burned on a hydraulically operated forward-acting grate which is 9.75 m wide and 13.1 m long, and consists of 18 zones. Each zone is supplied with individually controlled primary air.
The location of the measuring positions (1-6) relative to the grate is shown in Figure 3. The measurements were performed by inserting a suction probe into the designated ports L2, L3, L4 and L5. All the detailed information about the test and instrumentation is found in reference [4, 6].

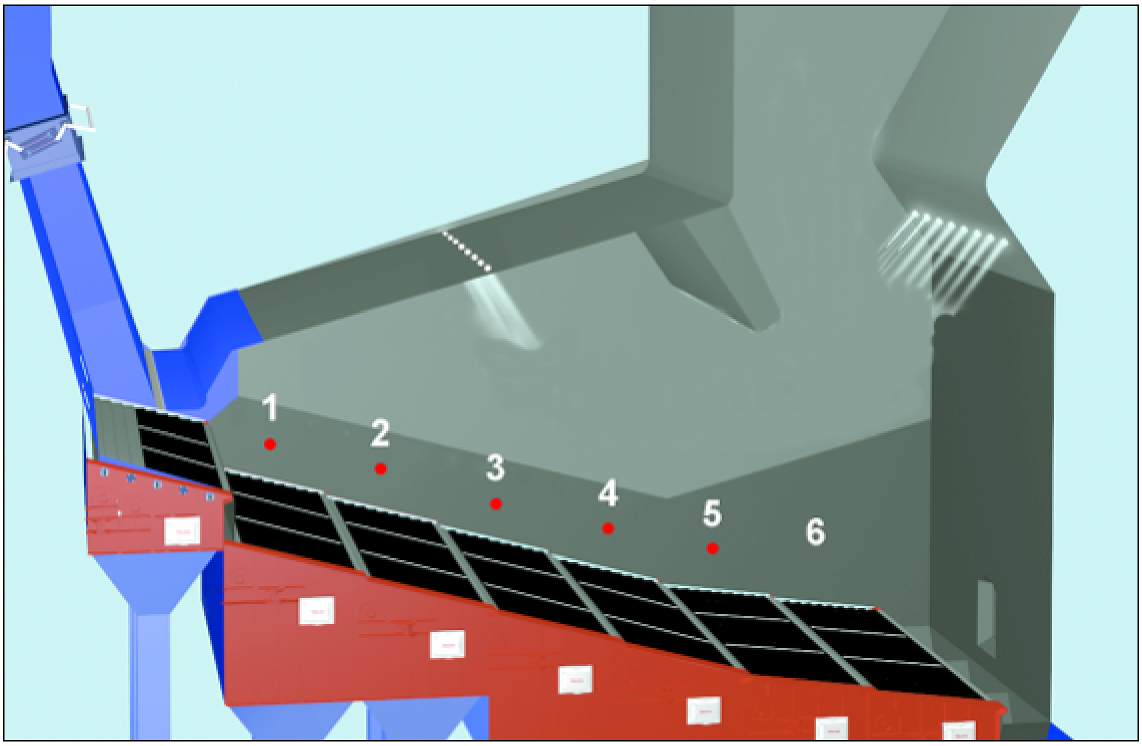

Figure 3. The furnace, grate and position of measuring ports at Unit 5 Vestforbrænding.

Results and discussion

Figure 4 shows the gas temperatures measured at ports 1-5 and in the top of the first draught – the position is named EBK1. The highest average temperature is measured in port 3 followed by a decrease in temperature at ports 4 and 5. This corresponds well to the location of the end of the flame front between ports 3 and 4.

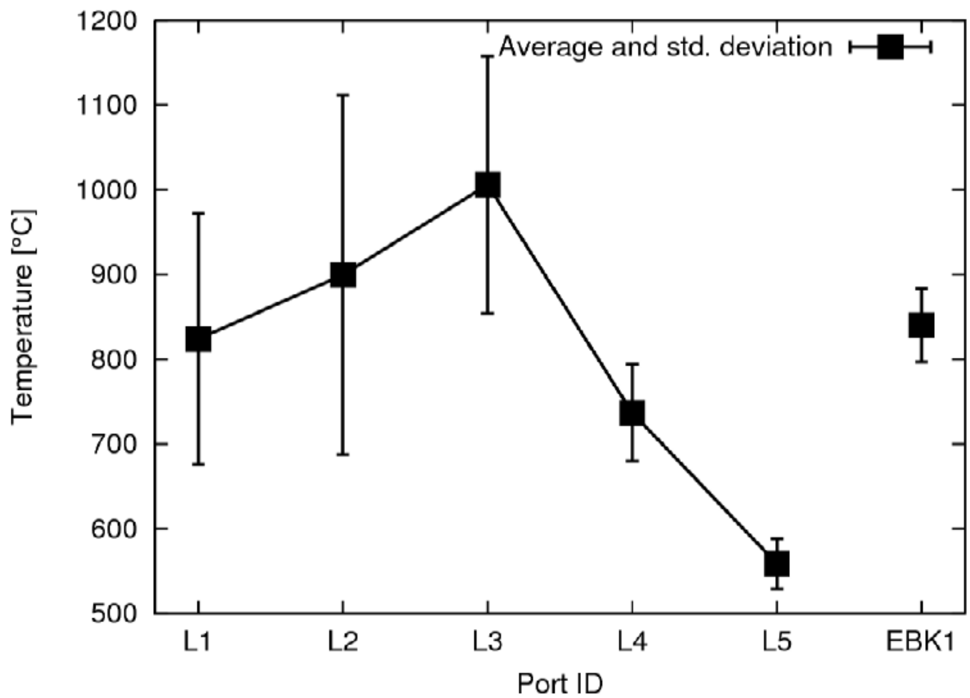

Figure 4. Temperature measurements along ports L1-L5 and in first draught (EBK1).

Figure 5 shows the measured gaseous concentration on a dry basis of CO, CO_2, and O_2 along the grate at ports 2-6. CO and CO_2 is present in high concentrations at ports 2 and 3 and then decreases to low levels at the remaining ports, whereas O_2 is very low at port 2 and present at approximately 3 % at port 3 and increases to approximately atmospheric levels at ports 4-6. These results support the placement of the end of the burnout zone between ports 3 and 4.

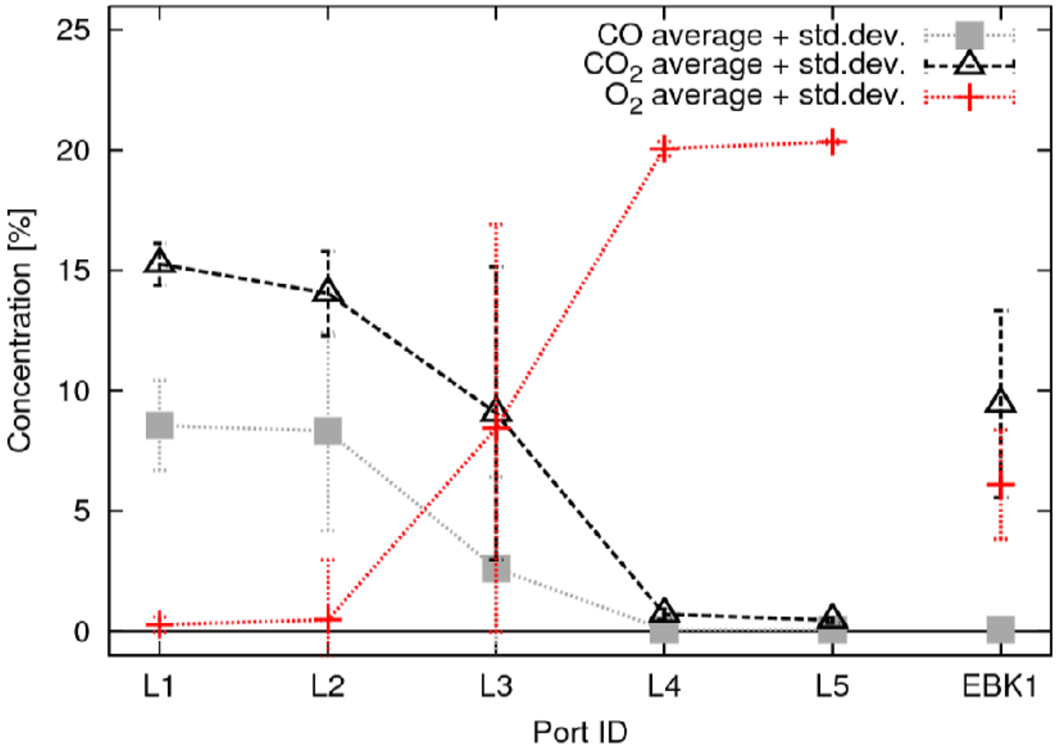

Figure 5. Concentration of CO, CO_2, and O_2 at ports L2-L6 along the grate.

Figures 6 and 7 show the release concentration of chlorine and sulphur at ports 1-5 and in the top of the first draught (EBK1). The concentrations of Cl and S peak at port 2 and then decrease at the remaining ports. Especially S was seen to be significantly lower at port 3 than at ports 1 and 2. The values measured at the top of the first draught rep-resent average con-centrations of the flue gas as the flue gas is presumed to be well-mixed at this stage.

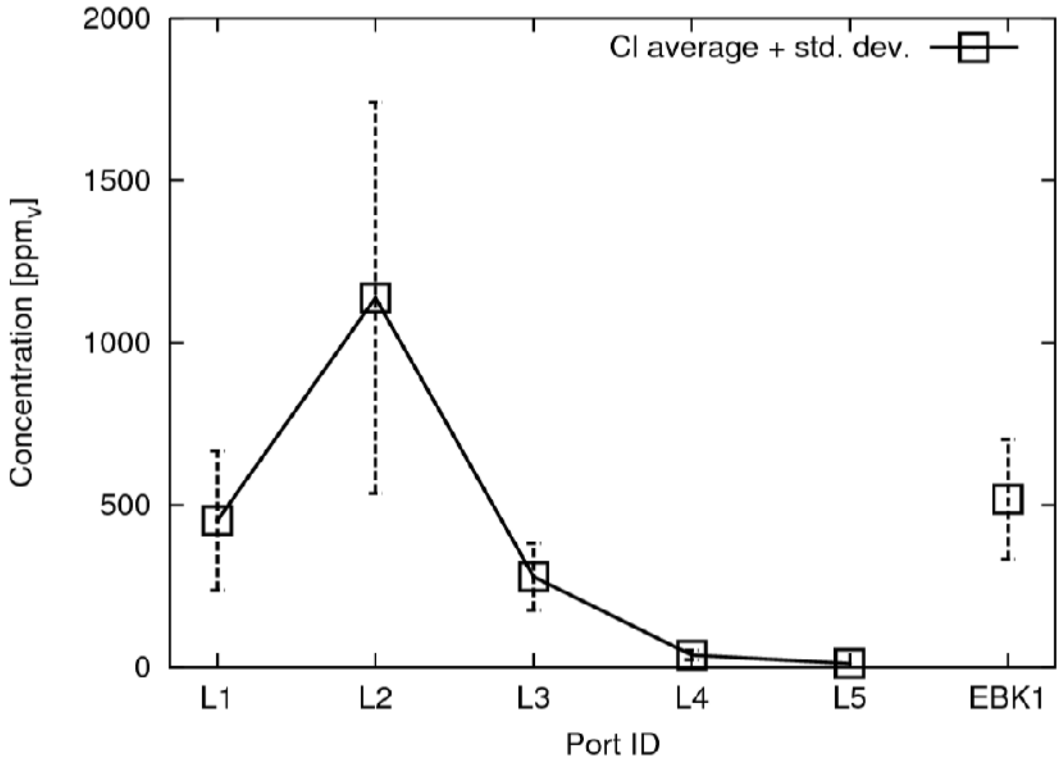

Figure 6. Chlorine concentration at ports 1-5 and in the top of the first draught (EBK1).

A position between port 3½ and 4 will give favour-able conditions for a final superheater. The Cl and S levels are very low and the temperatures of the flue gas are in the range of 800 °C.

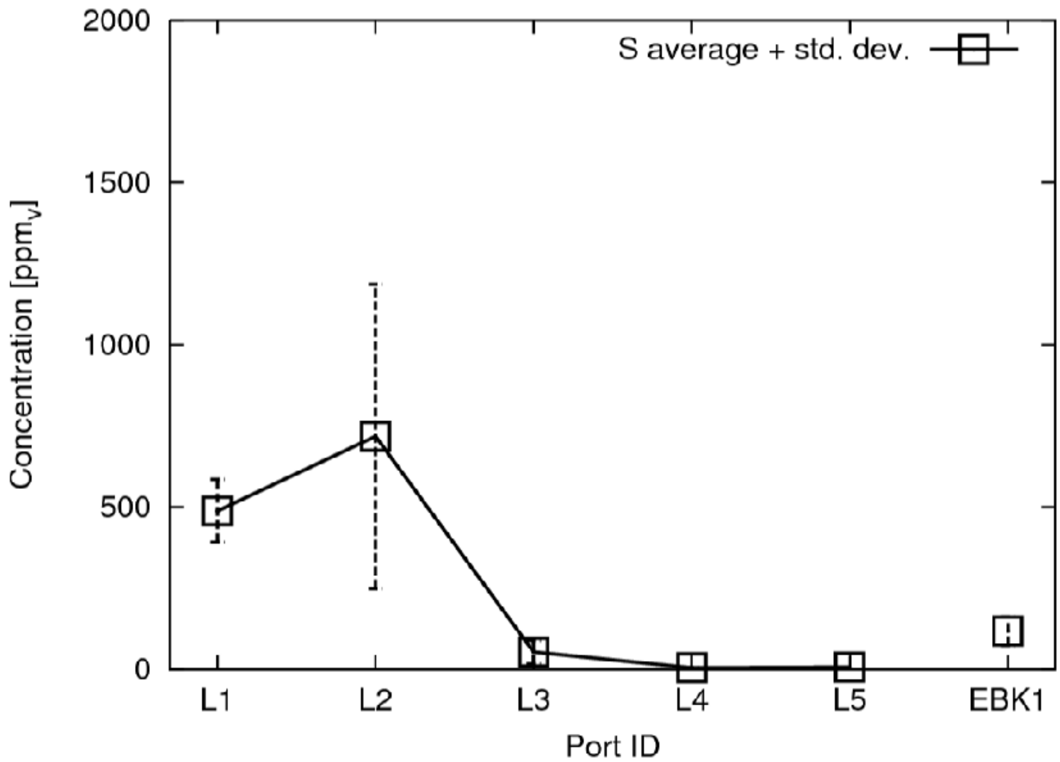

Figure 7. Sulphur concentration at ports 1-5 and in the top of the first draught (EBK1).

Advanced Combustion Control Systems - Image algorithm

As previously mentioned, there is a strong connection between the burning rate and the amount of primary air, both the total amount and the distribution along the grate. As regards control and operation, the major difficulties appear to be:

- Adjustment of operating conditions to compensate for changes in the waste quality and quantity
- Fixed position of main combustion and burnout zone
- Lack of measurement techniques available for rapid evaluation of the combustion processes in the fuel bed

The last problem has been the aim of several research projects and development activities during the latest 10 years [3]. Babcock & Wilcox Vølund has developed a measurement and monitoring system based on a CCD camera, capable of providing a thermal mapping of the light intensity across the fuel bed.

Recording of high radiation in one area results in high light intensity originating from high concentrations of burning particles and soot, which are characterizing a flame. It is well-known that the transition zone from active burning to the burnout zone on a combustion grate is very pronounced. The main objective of this technique is the interpretation of the data and determining the position of the active flame front. The image is evaluated to give an indirect indication of the intensity of the combustion on the grate.

The camera is a normal RGB camera. To identify the flame, a threshold on the light intensity is used, so the pixels over the threshold are identified as a flame. This image is then filled with disturbances, and to remove these disturbances a morphological transformation of the threshold image is executed and the flame position is subsequently identified by statistical means - see Figures 8 and 9. It is the statistically filtered flame position that is used for control purposes.

In Figure 8, the pink line is the calculated threshold line defined as the flame front. The new image processing software will perform statistical data processing for a number of locations across the grate, resulting in a relatively average position – the blue horizontal line. In Figure 9, the estimated flame front position is shown as a function of time. The Y axis is a relative position measured from the start of the combustion grate.

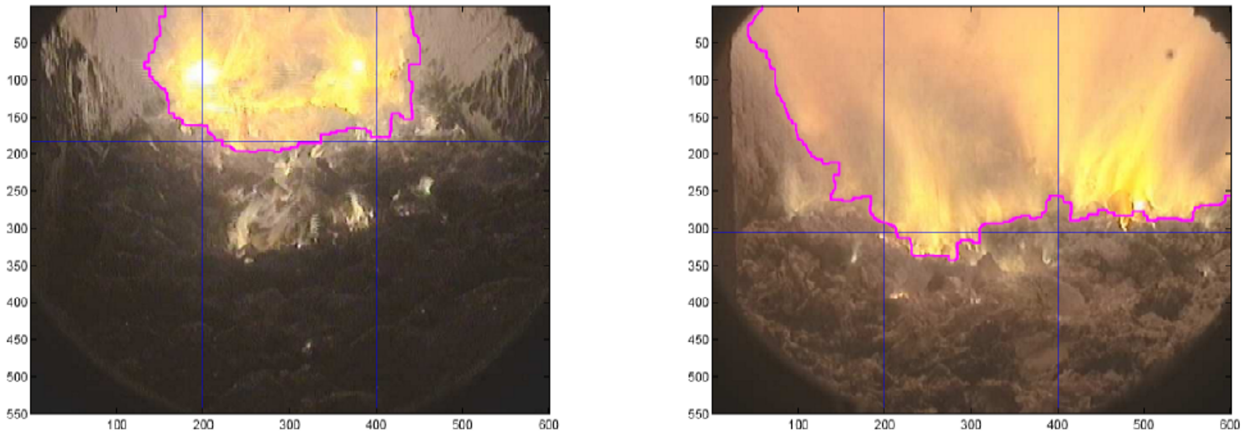

Figure 8. Image from a CCD camera showing the flame front position.

This information can then be used to fix the position of the flame front at a certain position along the grate by controlling grate speed and primary air distribution. At the moment, Babcock & Wilcox Vølund is developing and testing new control loops based on this technique.

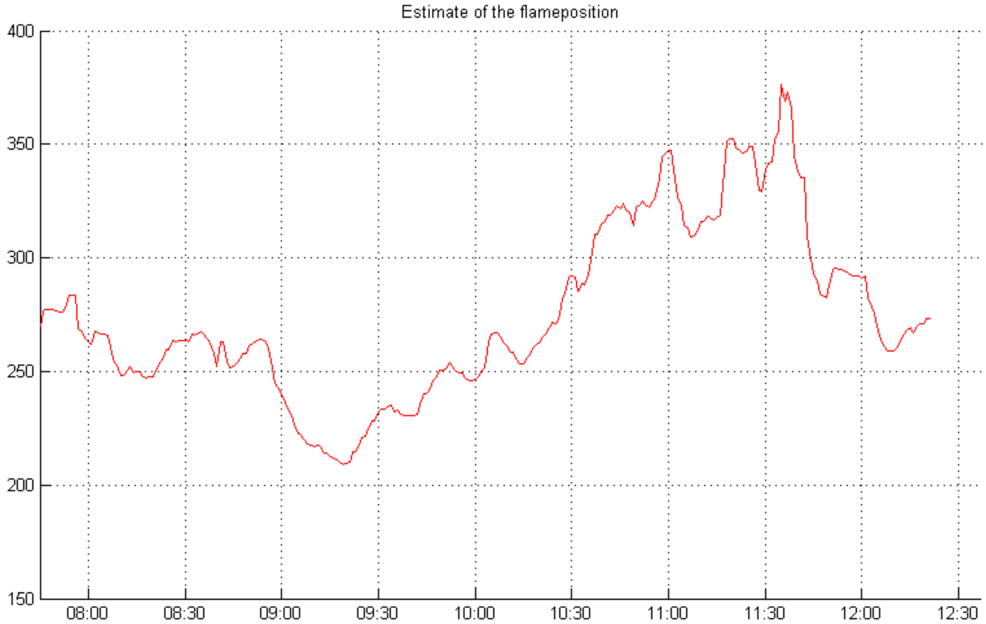

Figure 9. The estimated flame front position as a function of time.

In the future, the flame front control will be an important part of the combustion control systems. Moreover, this control system will be a vital part of the separation of the two flue gas fractions in the furnace. The main purpose is to control the flame front position and compare it to the position of the separation membrane wall, across the furnace. Based on the measurement of the release of corrosive elements along the grate, it will be possible to estimate the ideal position of the flame front. This position is characterized by a minimum of corrosive species in the flue gas and a maximum of energy in the remaining char.

Electrical efficiency

There are many process parameters that have an impact on the steam turbine performance and thereby the electrical efficiency. Some of the most important are the steam temperature and pressure. In Figure 10 some results of a study of a generic 20 tonnes per hour waste fired power plant are shown. The base case is a Scandinavian plant with a condenser cooled by a district heating system. In the figure it can be seen that a typical electrical efficiency of 24 % is achieved at the classical steam data 400 °C and 50 bar.

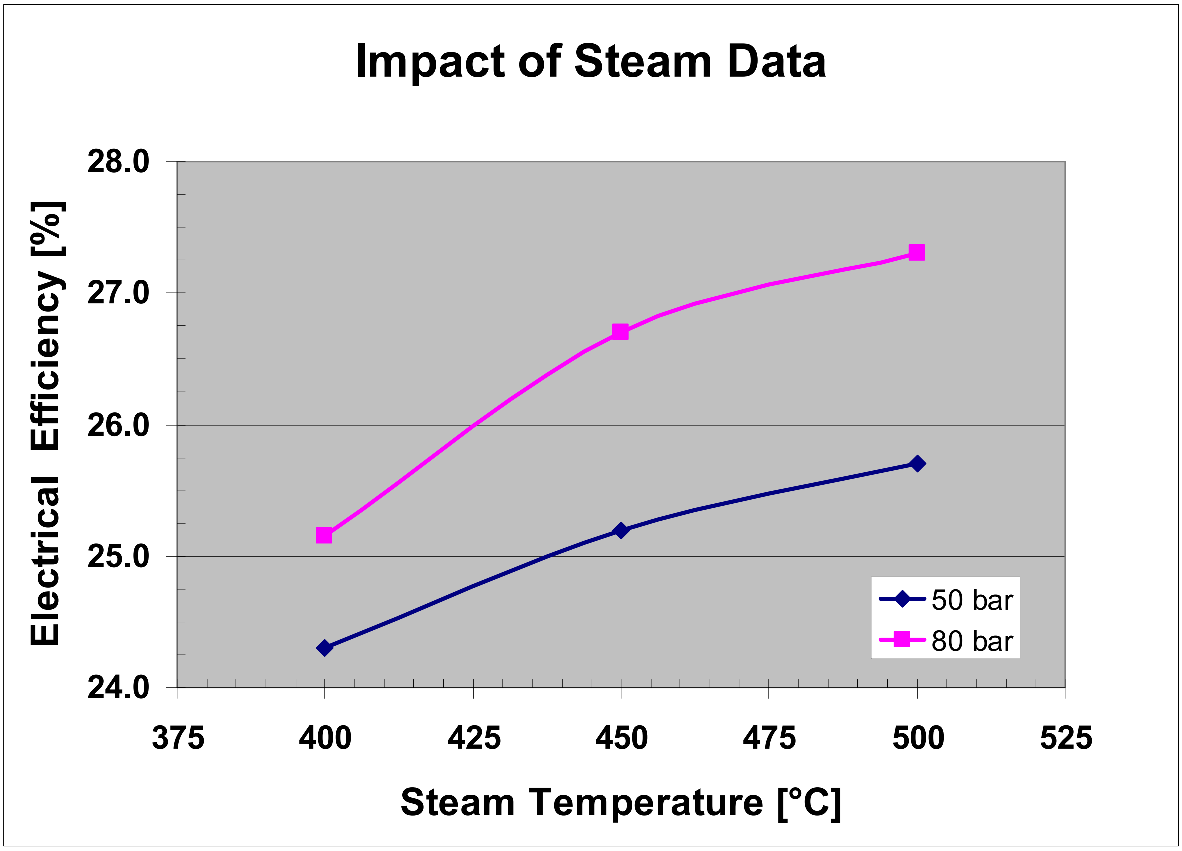

Figure 10. Electrical efficiency as a function of steam temperature and pressure.

The basic idea of the SteamBoost™ concept is to use all the advantages of a modern waste fired power plant combined with an integrated final superheater, as shown in Figure 2. The final superheating will increase the steam data to for example 500 °C and 80 bar and result in an increase in electrical efficiency of 3 percentage points.

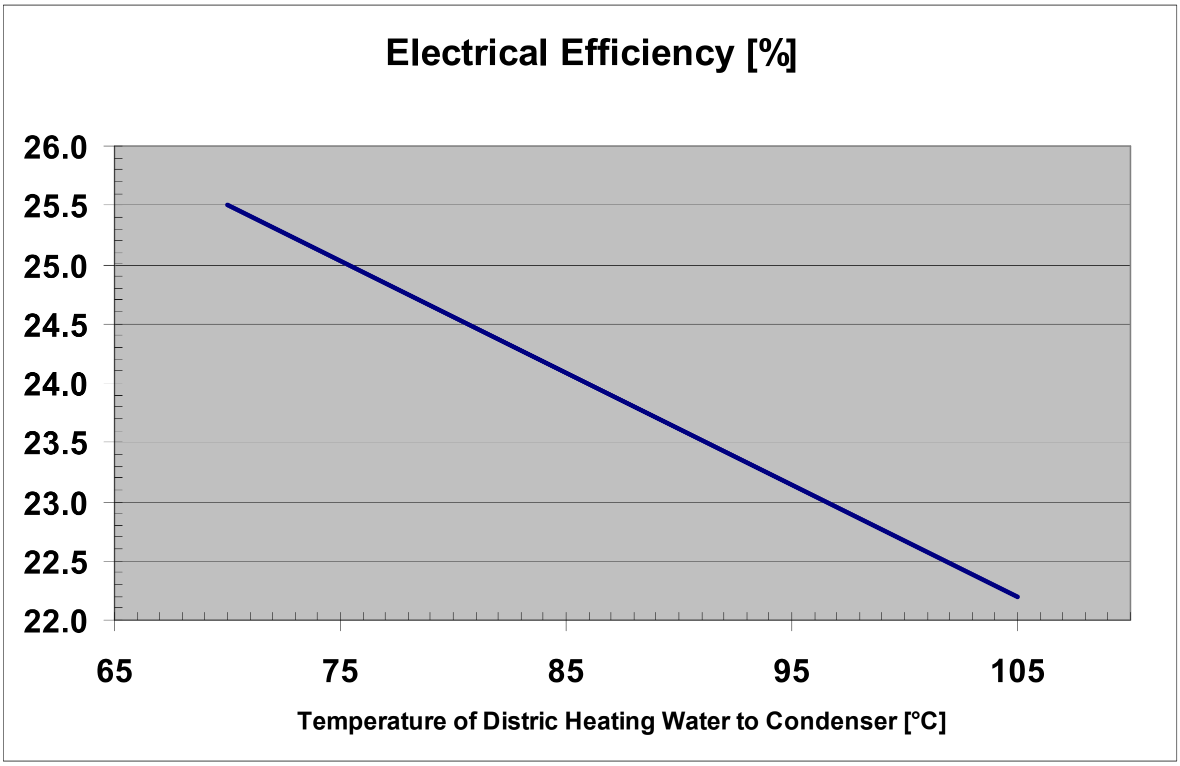

Figure 11. The influence of electrical efficiency and the temperature of the cooling medium in the condenser.

A classical method to improve the efficiency is to reheat a part of the steam after the high pressure turbine. This technique can increase the electrical efficiency by approximately 3 to 4 % point. In order to gain maximum effect from this setup, the steam pressure has to be increased to at least 120 bar, which results in a saturated vapour temperature of 330 °C and surface steam tubes temperatures of more than 350 °C. At this temperature level there is a high risk for corrosion if Inconel cladding is used for boiler protection.

It is well-known that the temperature of the cooling medium for the condenser has a significant impact on the overall efficiency of a Rankine thermodynamic process. The influence of electrical efficiency and the temperature of the cooling medium as the district heating water are illustrated in Figure 11. In this case it is possible to gain more than 3 percentage points by reducing the water temperature by 35 °C.

In many geographic regions the climate is so warm that the benefit of a district heating system is rather limited. The cooling of the condenser will be based on sea water or ambient air, both of which provide a much lower temperature level – often called condenser mode. These power setups will typically only result in significantly higher electrical efficiencies. An increase of 5 percentage points is typically possible when comparing a power only plant with a combined heat and power plant. The overall thermal efficiency will of course be much higher for CHP plants and there are several examples of plants in Scandinavia with thermal efficiencies higher than 95 % [2].

Conclusion

A new patent concept named SteamBoost™ is under development. The final objective is to achieve electrical efficiency between 27 % and 33 %, depending on the design of the cooling system for the condenser. The basic idea of the SteamBoost™ concept is to use all the advantages of a modern waste fired power plant combined with an integrated final superheater.

The idea is to separate the flue from the grate and into two or more fractions, having one fraction of the flue gas with a high heat flux and a low chlorine concentration. This isolated portion of the flue gas may be directed to a separate superheater section, where it can raise the steam temperature. The elevated superheater steam temperature could then increase the electrical efficiency of the waste fired power plant.

Acknowledgement

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