

New Furnace Concept Improving the Electrical Efficiency in Waste Fired Power Plants

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Abstract

Wastes to energy plants play an important role in European waste management system. Moreover, energy recovery from waste can reduce emissions of greenhouse gases and has a great potential for assisting in meeting the Kyoto obligations.

Lately, Babcock & Wilcox Vølund have developed a new technology and received a world patent. The basic idea is to improve the electrical efficiency by increasing the steam data. The steam temperature, especially, can be increased 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 layout as the classic waste to energy plant. Thus having the same superior operation performance as new European plants have today.

The goal is to achieve an increase in steam temperature of between 50°C to 100°C and to increase total electrical efficiency of more than 30% without influencing normal operation. The project is carried out together with the CHEC Research Group at the Danish Technical University and is partly funded by the Danish Ministry of Energy. This paper will present the basic idea and patent. The core of the technology is a combination of a new furnace design and a new control system. Test results from an operating plant demonstrate that the principal idea works. A comprehensive CFD study has been carried out and supports the principal idea. The paper gives simulation examples and how they are used in furnace design optimisation.

The final improvement of the electricity production can first be determined in the coming test period on a full scale installation which now is currently in the process of being planned.

Introduction

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 plant availability and reduce operation and maintenance cost, independent of fuel composition. The typical standard steam data are 400°C and 45 bar and generally presently recognized as the best available technology [1].

With increasing focus on power production and favourable tariffs in many markets, there is a need for maximising 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 latter can be controlled by modern boiler cleaning equipment [2], whereas corrosion is destructive for the boiler and plant operation and 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 the plant owner's 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 have 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 learnt that one of the most important factors is 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[®]'s and design tools such as CFD modelling have resulted in more progressive steam data and thereby an increase in electrical efficiency. These developments have resulted in a steam data increase to 425°C and 65 bar depending on fuel property [2].

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 Inconel[®]'s 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 by 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 to 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 fuel bed include: 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 processes are gasification and combustion of heterogeneous solids and phase combustion of homogeneous gas 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 sub-stoichiometric and results in formation of gasification products, like CO and H₂. 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 mix with 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 radiant flames above the grate.

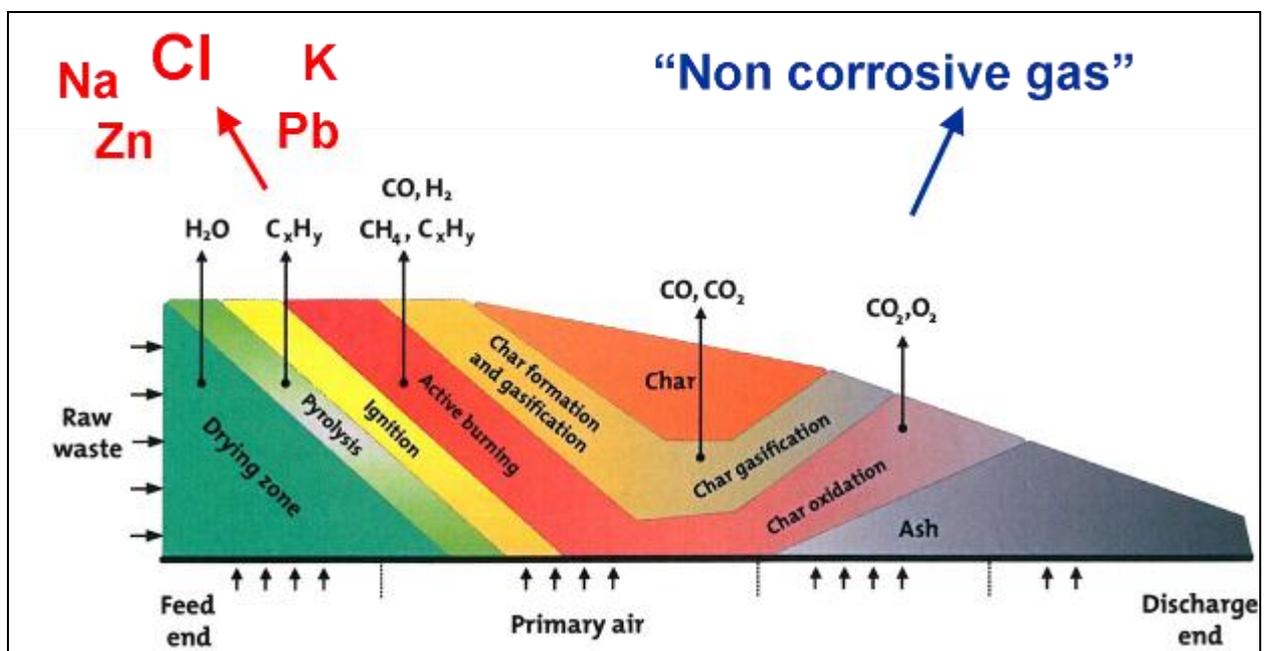


Figure 1 Schematic view of the fuel bed combustion process and the potential release of the volatile elements Cl, Na, K, Pb, Zn and S to the flue gas in the first part of the furnace. Measurements indicate that around 30%-40% of the total energy release in the system is released as combustible gases above the bed. The combustible gases consist mainly of light components such as: H_2 , CO , CH_4 and some tar. In addition to 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 the by-passing 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 [3].

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 the increase in 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 [3].

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 in the first part of the combustion grate and thereby in the front of the furnace. The rear parts of the grate are characterised 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 electrical efficiency of waste fired power plants, see Figure 2. The concept is named SteamBoost™ [4].

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 enter the post combustion chamber, they are then 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.

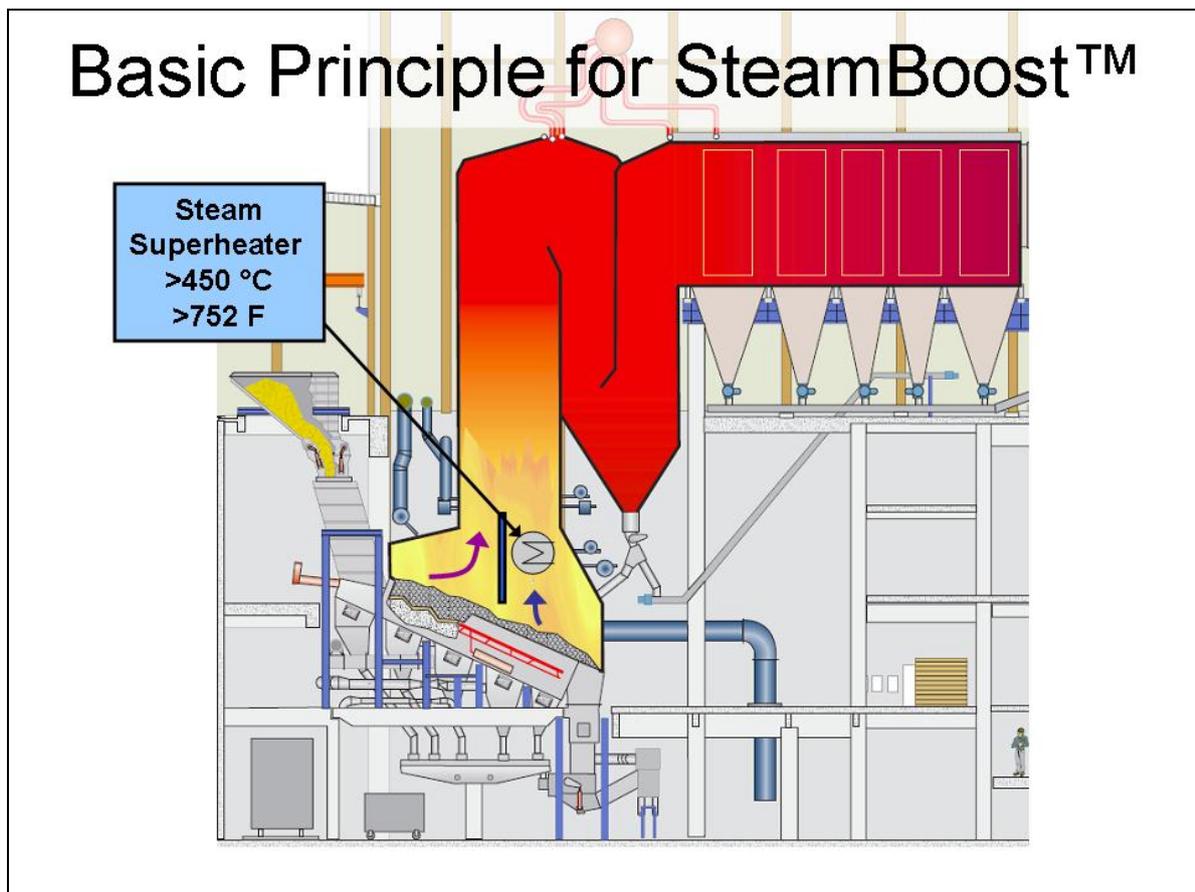


Figure 2 Generic waste fired power plant with two-stage furnace and SteamBoost™ superheater.

The objective of the study was to measure a concentration profile of the elements Cl, Na, K, Zn, Pb and S as a function of the 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.

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 can process 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, consisting of 18 zones in all. Each zone is supplied with individually controlled primary air and grate speed. 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 the instrumentation is found in reference [3, 5].

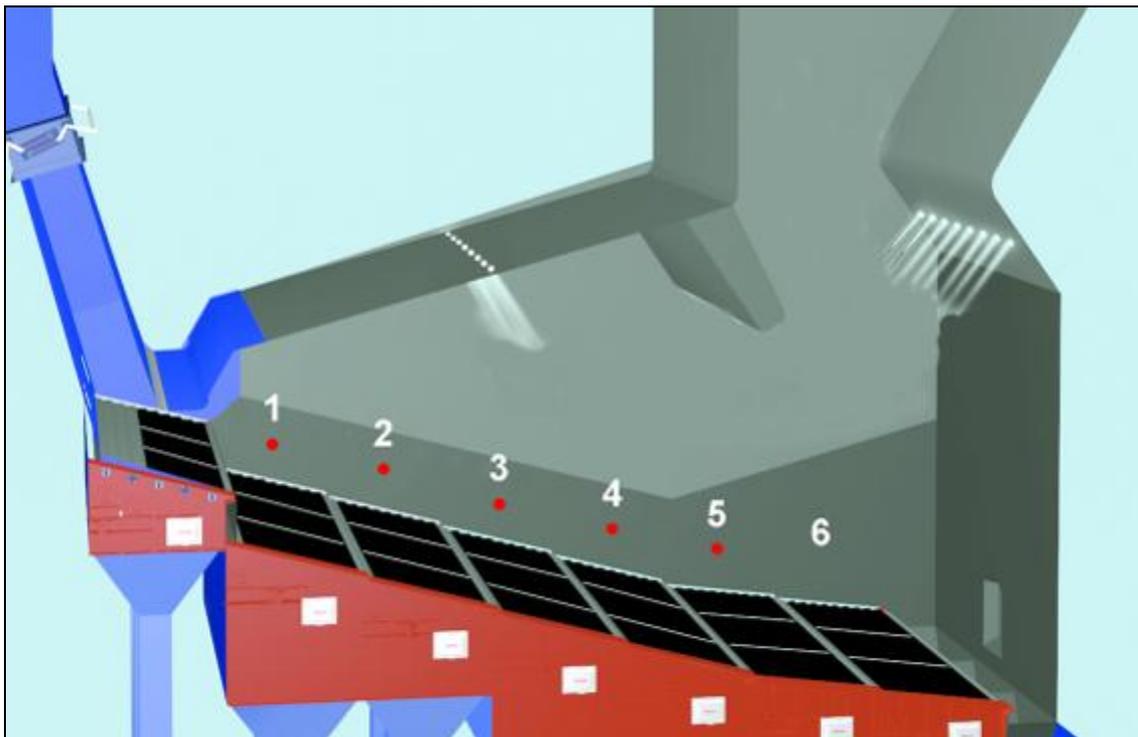


Figure 3 The furnace, grate and position of measuring ports at Unit 5 Vestforbrænding.

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 at the end of the flame front between ports 3 and 4.

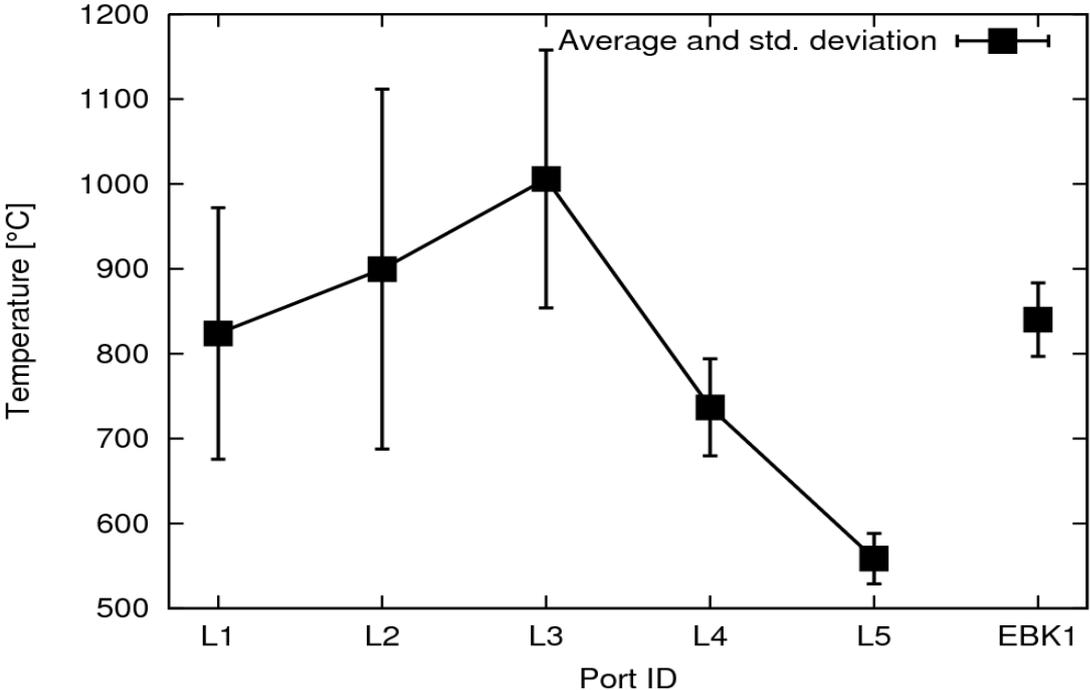


Figure 4 Temperature measurements along ports L1-L5 and in first draught (EBK1).

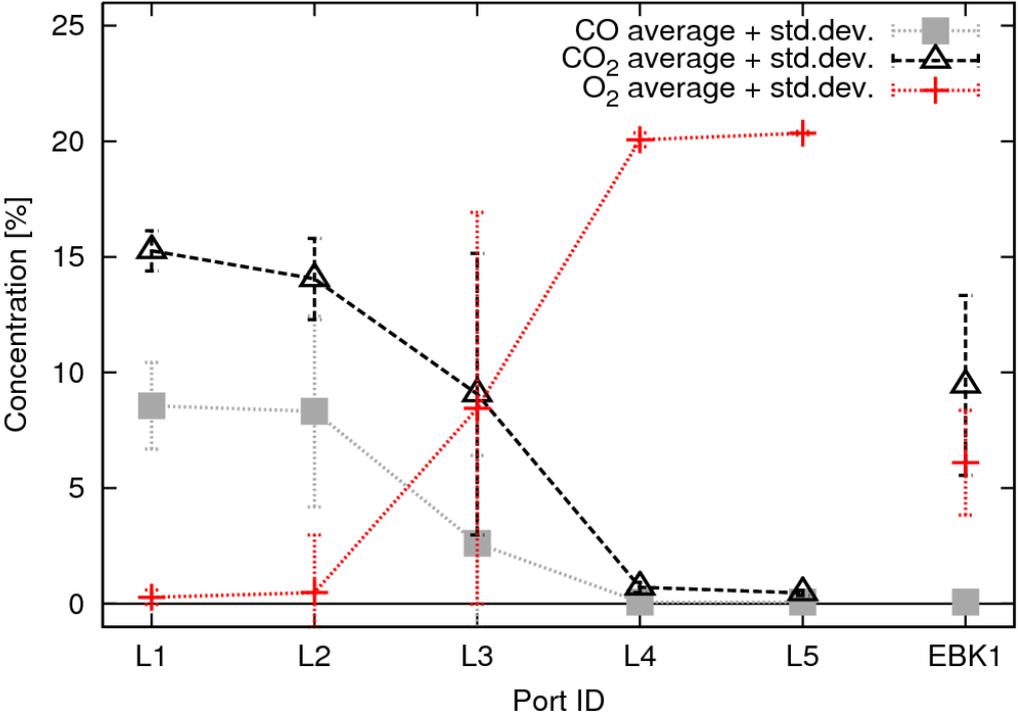


Figure 5 Concentration of CO, CO₂ and O₂ at ports L2-L6 along the grate.

Figure 5 shows the measured gaseous concentration on a dry basis of CO, CO₂ and O₂ along the grate at ports 2-6. CO and CO₂ are present in high concentrations at ports 2 and 3 and then decreases at the remaining ports to a lower level. O₂, on the other hand, 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 at the end of the burnout zone between ports 3 and 4.

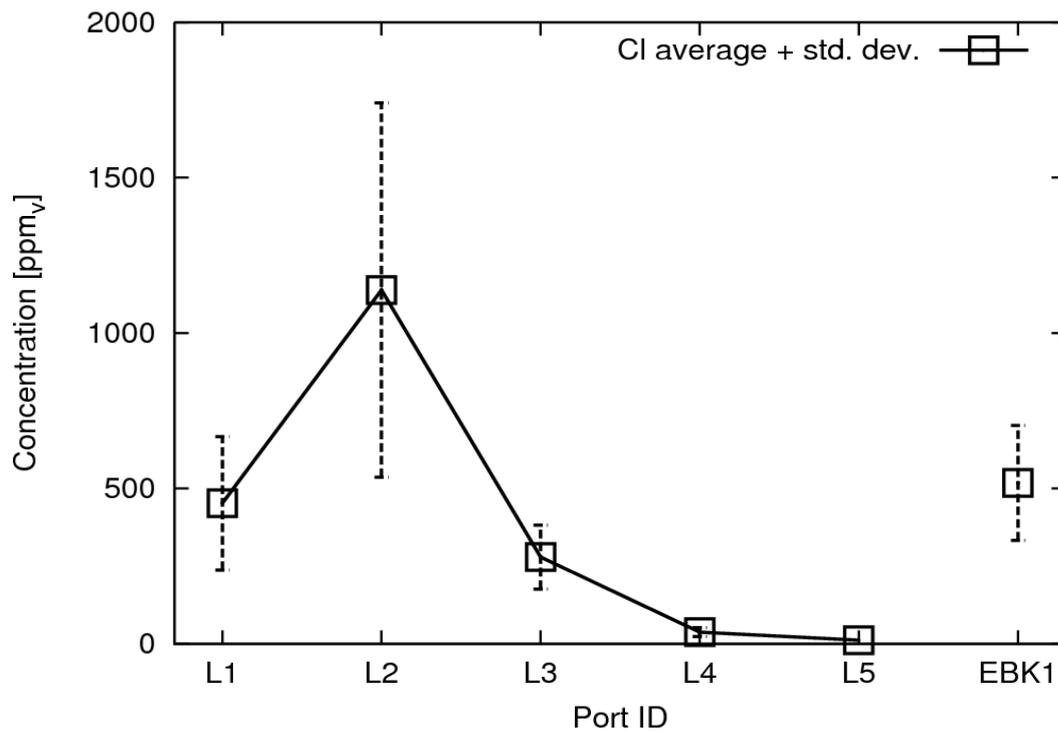


Figure 6 Chlorine concentrations at ports 1-5 and in the top of the first draught (EBK1).

Figures 6 and 7 show the concentration of respectively chlorine and sulphur in the flue gases. 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 represent average concentrations of the flue gas as the flue gas is presumed to be well-mixed at this stage.

A position between port 3½ and 4 will give favourable 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.

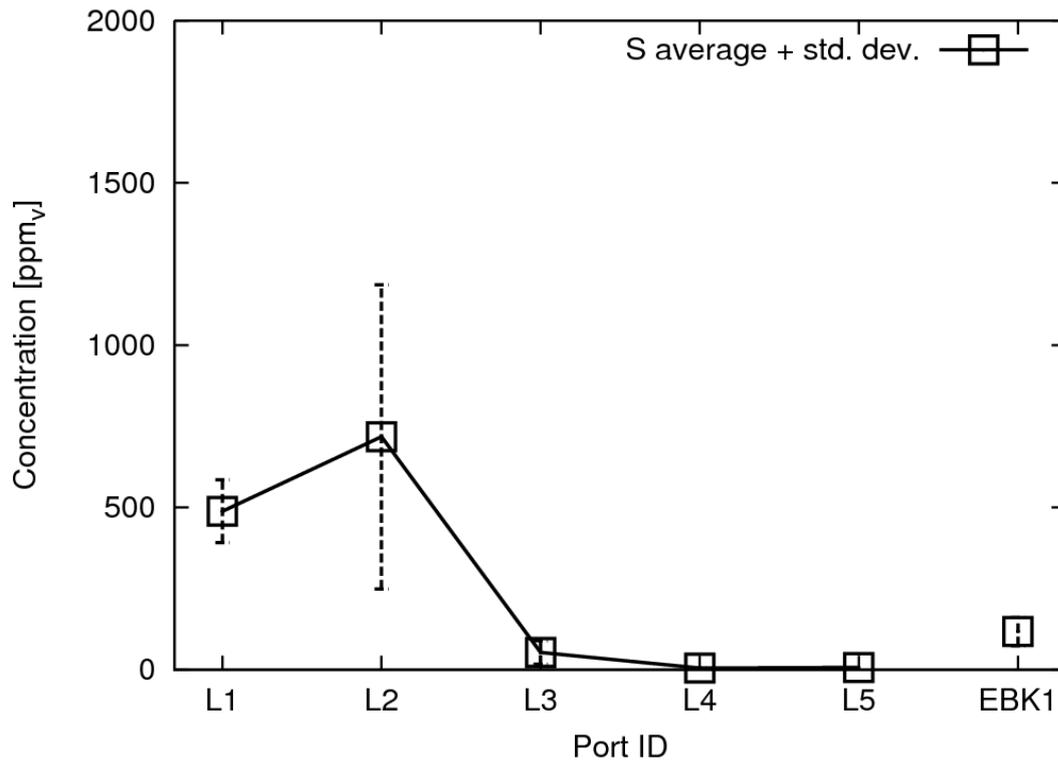


Figure 7 Sulphur concentration at ports 1-5 and in the top of the first draught (EBK1).

Advanced Combustion Control Systems - Image algorithm

As previously mentioned, there is a strong connection between the burning rate and the amount of primary air, of 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 [6]. 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 is characterised by 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.

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 the graph to the right, 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.

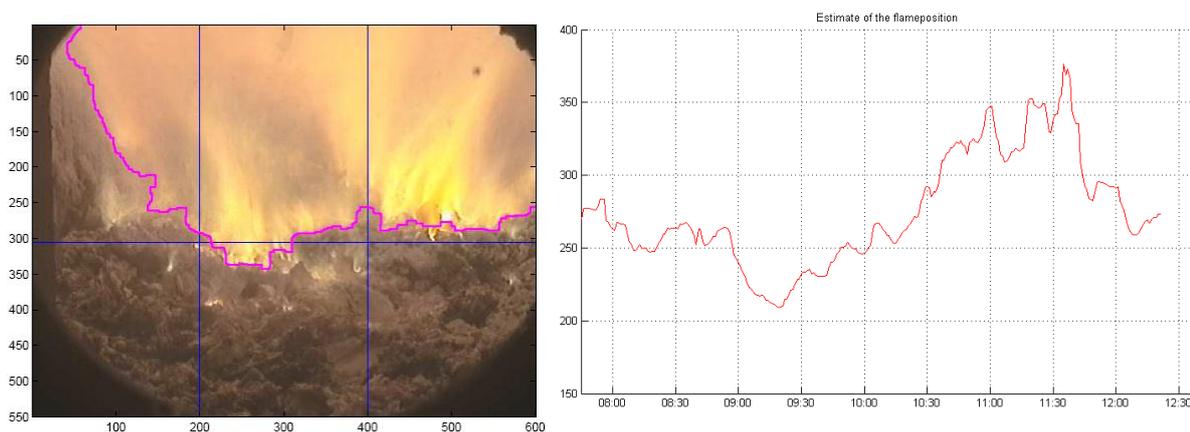


Figure 8 Left: Image from a CCD camera showing the flame front position. Right: The estimated flame front position as a function of time.

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.

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 species along the grate, it will be possible to estimate the ide-

al position of the flame front. This position is characterised 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. Figure 9 shows some results from a study of a generic 20 tonnes per hour waste fired power plant. 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.

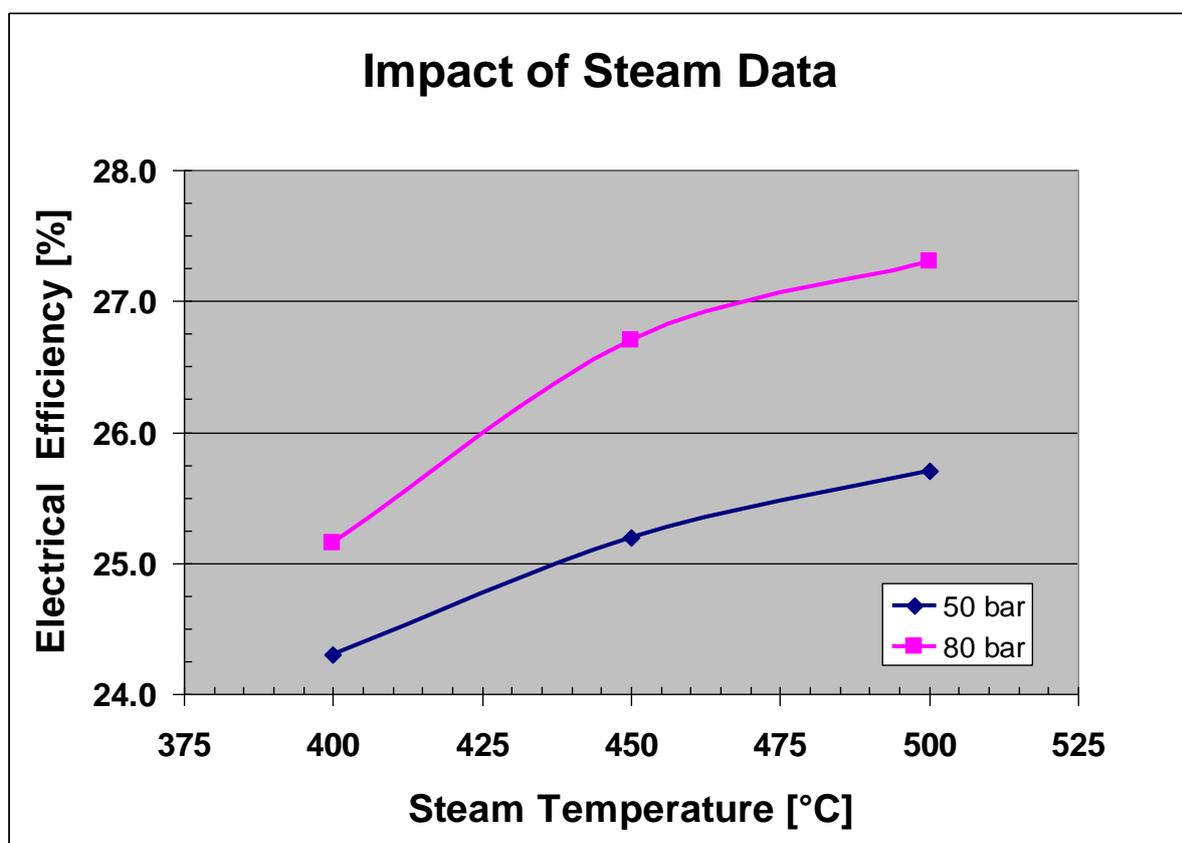


Figure 9 Electrical efficiency as a function of steam temperature and pressure.

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 increases the steam data to for example 500°C and 80 bar and results in an increase in electrical efficiency of 3 percentage points.

A classical method to improve the efficiency is to reheat a part of the steam after the high pressure turbine. This technique increases the electrical efficiency by approximately 3 to 4 percentage points. 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 tube temperatures of more than 350°C. At this temperature level there is a high risk of 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 10. In this case it is possible to gain more than 3 percentage points by reducing the water temperature by 35°C.

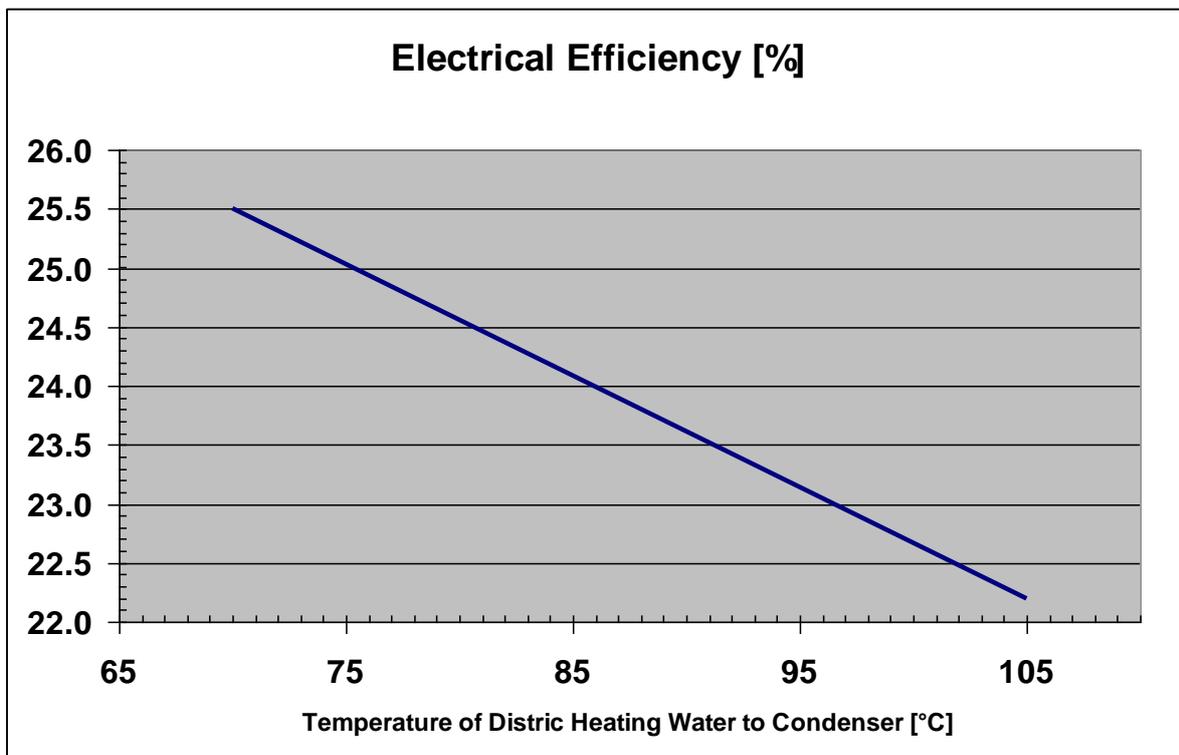


Figure 10 The influence of electrical efficiency and the temperature of the cooling medium in the condenser.

In many geographic regions the climate is so hot that the benefit of a district heating system is rather limited. The cooling of the condenser is then 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].

The Numerical Laboratory - CFD simulation

A CFD model is based on control volumes. The furnace and boiler which are to be modelled are divided into small volumes. These volumes adjoin each other or the wall, the outlet or the inlet. The momentum, the mass and the energy conservation equations are solved for each control volume. The quality of the solution depends, therefore, to a great extent on the number, shape and position of the control volumes. In addition to solving the momentum (Navier-Stokes), mass and energy conservation equations, the equations describing turbulence, chemical reactions, transport of particles and radiation are also solved.

CFD simulation is an effective method for evaluating different design alternatives that are otherwise too expensive, time consuming or impossible to test. The final improvement of electricity production will be determined in the coming test period on a full scale installation, which is currently planned to be carried out at the waste to energy plant FASAN line 4 with a nominal capacity of 8 t/h. In order to study the possibilities for implementing the system at FASAN, a CFD simulation was carried out.

FASAN is a union of 14 municipalities in South Zealand, which treats all waste from the municipalities. The waste treatment consists partly of the sorting and reuse of waste and partly of the combustion of waste with the subsequent supply of heat to the local district heating station and the generation of electricity for the supply grid. In total, FASAN is presently supplying 200,000 citizens in the area, and in 2006 the waste-to-energy plant treated 115,000 tons of waste, resulting in an annual production of 13 MW of electricity and 50 MW of district heating.

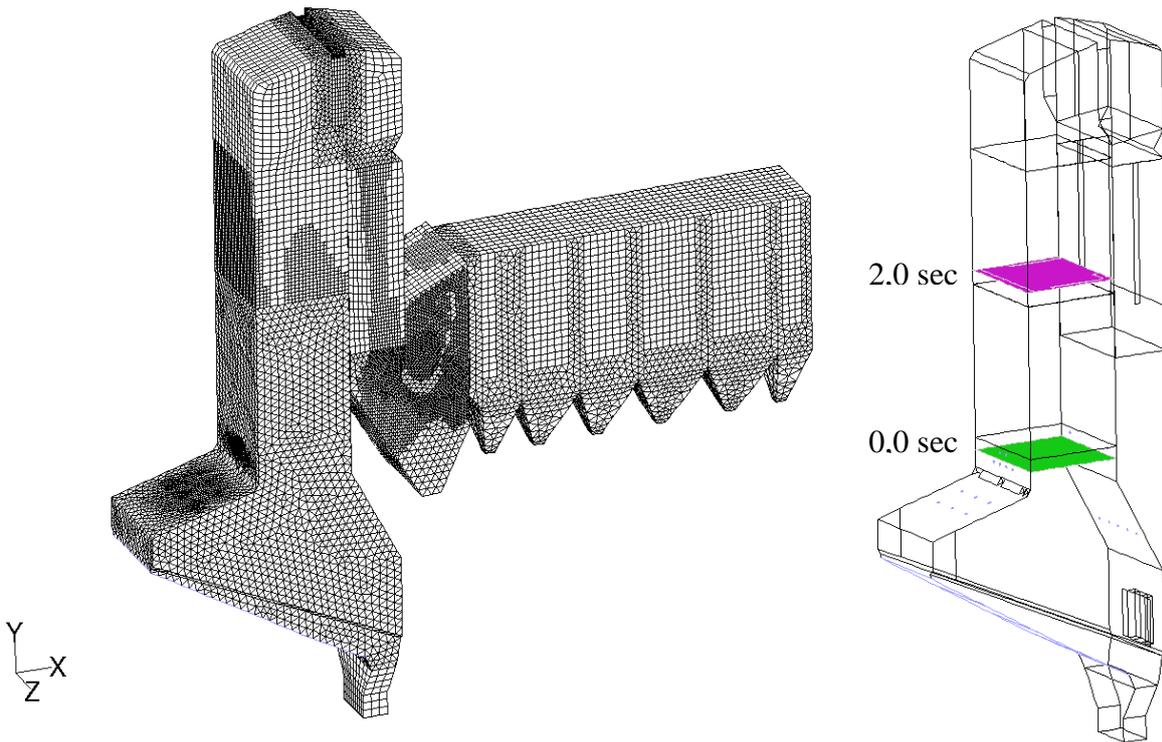


Figure 11 The FASAN computational grid.

In figure 11, the mesh for FASAN line 4 is shown, including the positions of jets for secondary air. The grid is refined in areas where there are large changes in the flow field e.g. at air nozzles and guide vanes. The grid consists of 200,000 cells.

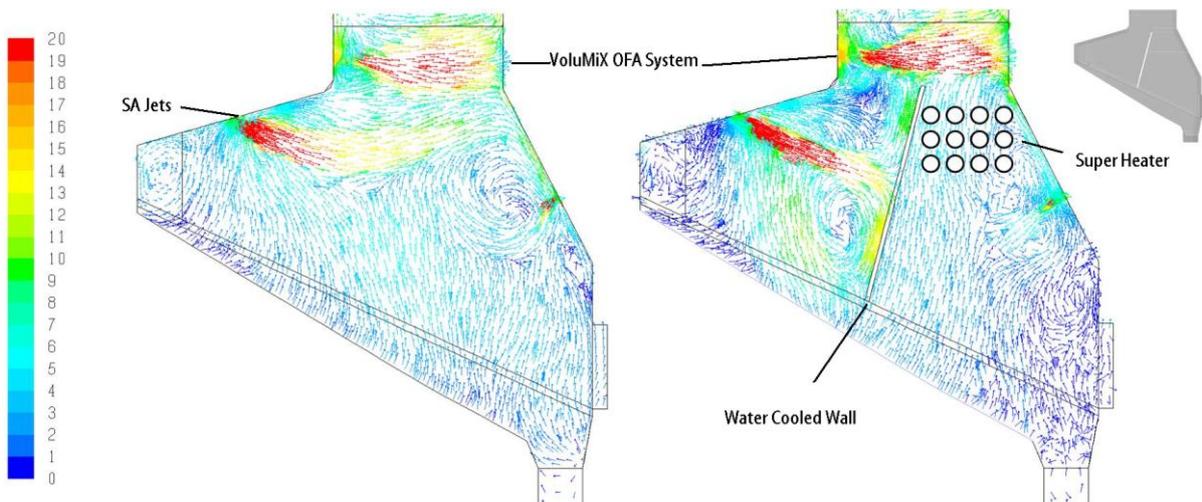


Figure 12 Velocity [m/s] vector plot, in a plane with jets, close to the centre of the furnace.

The flow field is represented by velocity vectors. Figure 12 shows the velocity vectors in the centre of the first row of the jets from the symmetry plane. The plot, on the left, is the original built furnace, and, on the right, the furnace is divided into 2 chambers by a wall. The geometry of the furnace and the placement of the jets have been made with the objective of creating several vortices. The vortices create highly turbulent conditions in the furnace, thus ensuring high combustion efficiency and thereby a good gas phase burnout.

The main goal for the design of the jets in the front ceiling is to form a vortex that is able to pick up hot combustion gases coming from the fuel bed and move it directly towards the ceiling. The purpose of this is to move energy from grate 2 to the zone above grate 1 for drying and ignition purposes.

Introducing a separation wall across the furnace will divide the flow into more or less two separate rooms. In the first room, the SA jets in the ceiling are still moving hot gases to the front of the furnace, thereby ensuring a stable ignition. The direction and speed must be adjusted in order to avoid particle impingement, resulting in slagging problems on the new wall. In the rear part of the furnace, a zone with low velocities exists above the burn out grate. This zone is created intentionally to facilitate good burn out in the fuel bed.

When the two streams of flue gases enter the post combustion chamber, they are mixed by the VoluMix™ secondary air system for final burnout. The reason for placing the jets in this section is the requirement of turbulent conditions that ensure complete burn out of the CO coming from the furnace.

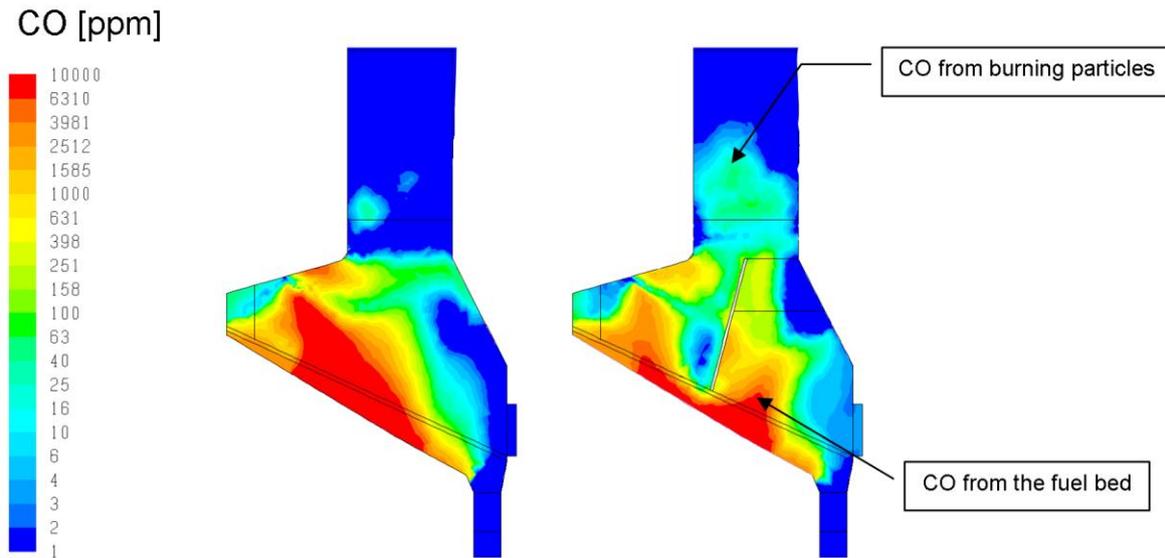


Figure 13 CO concentrations in the centre of the furnace - note that scales are logarithmic.

In figure 13 the CO concentrations are shown in the two cases - in the case to the right we simulated the influence of the separation wall. It is clear that the CO concentrations are higher in the first part of the post combustion chamber when the separation wall is installed. The flow field above grate 3 is more laminar and there are no major vortices. The result is a minimum amount of oxygen and a residence time for the burning particles. The burning particles emit CO, causing an increase in the level of carbon monoxide in this part of the boiler.

Despite the higher CO levels, the CFD calculations show that the VoluMix™ secondary air system works effectively and guarantees a complete burnout of the gas phase.

The computed temperature distribution in the furnace is shown in figure 14. The large vortex, seen on the velocity vector plots figure 12, is reflected in the temperature distribution. The vortex, which is created by SA jets in the front ceiling, controls the gas phase combustion zone and the hot combustion products from the top bed layer are pulled towards the furnace front. With the new separation wall this phenomenon is even more distinct.

Many different scenarios were calculated in order to investigate the most important process limitation. The actual temperature difference and the highest possible energy in the flue gases are very important factors for heat transfer in the tube bundles and thereby the final steam temperature.

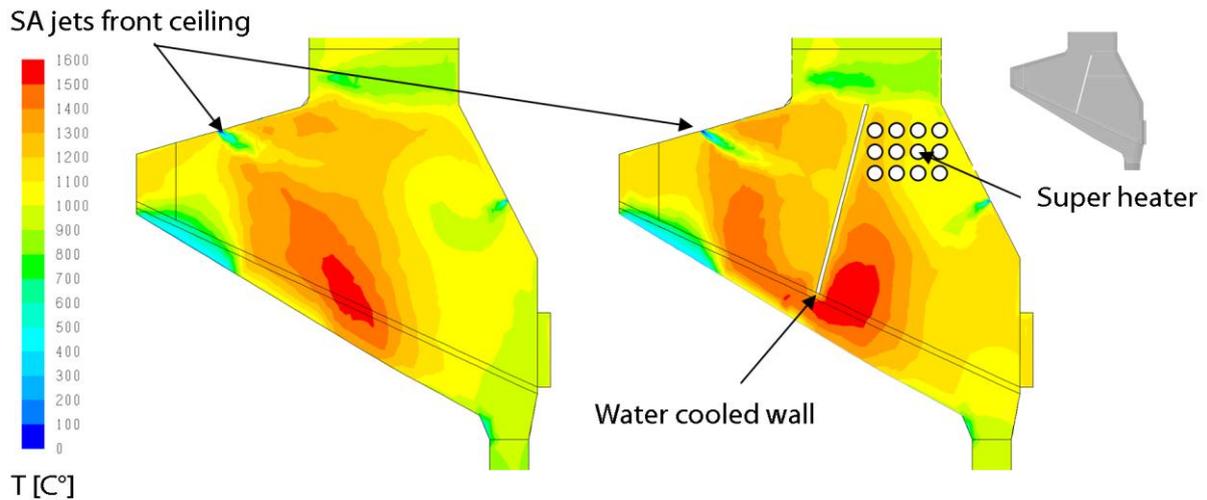


Figure 14 Gas temperature distributions in the centre of the furnace.

In the second room, the gas temperatures are quite high above grate 3 as a result of the burning char, which is the dominating component in the fuel bed at this position along the grate. The tube bundles will be located in an area with relatively high flue gas temperatures in the range of 800°C to 1100°C. The main flow of hot gases goes directly towards the Steam-Boost™ superheater, thereby ensuring maximum heat transfer to the steam. On the other hand, this could give slagging problems depending on the ash composition.

FASAN line 4 has a steam production of 30 t/h at 405°C and 54 bars. The objective is to increase the super heating temperature by +50°C, and in this case this corresponds to an energy input of 1 MW or 4% of the fuel energy input.

One very important constraint is the residence time in the post combustion chamber. According to the Waste Incineration Directive [1] this must be more than 2 seconds after the last secondary air injection. In figure 11, these 2 levels are illustrated by the green and red plateaus in the post combustion chamber. If heat extraction in the final superheater is too high the average temperature out of the furnace will be too low to achieve the 2 seconds of residence time.

The CFD simulation indicates that it will be possible to extract at least 1 to 1½ MW in the final superheater SteamBoost™ and still meet the demand for sufficient residence time. Moreover, the CFD study supports the basic idea of dividing the furnace into two chambers. Minor adjustment must be performed with the design of the secondary jets in the furnace in order to optimise the flow field.

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 divide the flue from the grate into two fractions, having one fraction of the flue gas with a high heat flux and another fraction with a low chlorine concentration. The test, carried out on an operating waste fired power plant, supports this concept.

The low corrosive part of the flue gas may be directed to a separate superheater section, where it raises the steam temperature. The elevated superheater steam temperature could then increase the electrical efficiency of the waste fired power plant. The CFD calculations indicate that it is possible to extract at least 4% of the fuel energy input in a final superheater.

Acknowledgement

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