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The Effect of Wood Fuels on Power Plant Availability

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Preface

This project was part of the Finnish *Puuenergia* (Wood energy) -technology programme funded by TEKES (the National Technology Agency of Finland). The project started in December 2000 and it ended in March 2003. Experts of the Energy Production research field at VTT Processes in Finland carried out majority of the research. System Technology Laboratory of Oulu University was responsible for the power plant automation systems related problems and for the research on boiler control technology. Boiler manufactures Kvaerner Power and Foster Wheeler, which are members of Värmeforsk, have participated in both the research work and financing of the project. Other participating companies also financing the project are Etelä-Savon Energia Oy (Mikkeli Power Plant), M-Real Oyj (Simpele Power Plant) and Värmeforsk Ab.

Co-operation with Värmeforsk Ab was made in the form of information exchange on experiences in the utilisation of wood fuels in Swedish power plants. VTT has also started to do in collaboration with Värmeforsk a similar power plant questionnaire that was done in Finland.

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Objectives

The objective of this research was to determine critical properties of wood fuels in respect of power plant operation, to determine the optimal conditions for reducing detriments, and to study how storing and processing of wood fuels affect boiler operation. The project focused on CFB and BFB technologies.

Summary

There is a growing international interest in utilising renewable fuels, also in multifuel applications. Main reasons for this are the objective to reduce CO_2 emissions and meet emission limits for NO_x and SO_2. On one hand cofiring, defined as simultaneous combustion of different fuels in the same boiler, provides an alternative to achieve emission reductions. This is not only accomplished by replacing fossil fuel with biomass, but also as a result of the interaction of fuel reactants of different origin (e.g. biomass vs. coal). On the other hand, utilisation of solid biofuels and wastes sets new demands for process control and boiler design, as well as for combustion technologies, fuel blend control and fuel handling systems. In the case of wood-based fuels this is because of their high reactivity, high moisture content and combustion residues' high alkaline metal content.

Combustion and cofiring properties of fuels have been studied both in VTT Processes' test facilities and in industrial-scale power plant boilers. The formation of alkaline and chlorine compounds in biomass combustion and their effect on boiler fouling and corrosion have been monitored by temperature controlled deposit formation and material monitoring probes. Deposit formation monitoring at full-scale boilers provides unique information on the rate of deposit formation, the effect of sootblowing and consequent changes in heat transfer. Additionally, the data from deposit formation monitoring has been shown to correlate with boiler performance, which gives basis for studying the interrelation of: fuel blend characteristics – deposit formation – boiler performance.

If biomass fuels are blended with coal or peat, following implications may be expected: increased rate of deposit formation, shorter sootblowing interval, cleaning of heat transfer surfaces in revisions may be required, bed material agglomeration (in fluidised beds), increased risk of corrosion, higher in-house power consumption, higher flue gas temperature. These factors affect operating and maintenance costs, but their effect can be reduced or even avoided with appropriate fuel blend control. By the aid of the aforementioned means, optimum share of biomass fuel in different fuel blends can be defined.

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1 Background

Finland is the world leader in utilisation of bioenergy. About 20 % of the primary energy is derived from wood-based fuels, a higher proportion than in any other industrialised country. Meeting the challenges of the mitigation of climate change has lead to the commitment to double the use of the renewable energy sources by 2025, as compared to the situation in 1995. The main focus is on bioenergy.

In Finland, the main provider and user of wood-based energy is the forest industry, which acquires wood fuels at a competitive price in connection with raw material procurement or as a by-product of wood processing. About 35 million cubic metres of solid wood (271 PJ) is used annually for energy production in Finland, covering the aforementioned 20 % of the total consumption of primary energy. Most of wood-based energy is recovered from liquid (black liquor) and solid industrial wood residues (bark, sawdust etc.). So far a modest – but fast growing - share comes from forest fuels. During the recent five years more than 100 district heating plants and 500 MW_e of new additional capacity for electricity production from wood-based fuels have been commissioned in Finland (total capacity more than 2 000 MW_e).

In larger CHP plants, FBC technology has become a dominant technology. Simultaneously, fuel-handling technologies have been developed. Also a lot of effort has been focused on utilising wood residues from the forest industry. In recent years, use of forest residues has been increasing. Integrating the fuel and raw material supply chains has decreased the costs of forest fuels.

Energy production based on biomass is rather often hampered by limitations in the supply and/or quality of the biomass. That is why cofiring with two or more fuels is widely used in large-scale electricity production, where the biomass can seldom meet the total fuel demand in a cost-efficient way. Successful cofiring of biomass requires attention to be paid on the fuel properties and mixing techniques. Various types of biomass are frequently burnt together with peat or coal. Fuel flexibility ensures the economical operation of the plant even when there are seasonal limitations in the fuel supply.

Increased concern about greenhouse gas emissions and the Kyoto protocol obligations are the driving forces in promoting and developing power generation technologies by using non-fossil fuels. Utilisation of biomass fuels and wastes may, however, cause unexpected problems during power production. This is also dependent upon the plant design. The quality of ash in biomass fuels differs remarkably in chemical manner from ashes of coals and peat. Alkaline metals, that are usually responsible for fouling of heat transfer surfaces, are abundant in biomass and will be easily released during combustion in gas phase. In addition, several observations have shown that alkali metals and chlorine in biomass cause hot corrosion especially at low sulphur conditions. Characterisation of fuel behaviour during combustion, fuel blend control and deposit formation monitoring is therefore needed to avoid decrease in power plant availability.

2 Blending of fuels equals blending of fuel properties

Biomass fuel properties, which vary in wide ranges, and the constituents of the fuel set demanding requirements for the optimisation of in-furnace conditions, and for the materials and structure of furnace membrane walls and superheaters. These properties include ash content, the chemical composition of the ash and ash behaviour characteristics. The quality classifications on wood fuels incorporate only properties related to the physical properties and energy content of the fuel. These classifications have primarily been prepared for the needs of fuel trade, and they do not account for the properties affecting fuel's behaviour during combustion. Chemical composition of ash, such as alkali metal, phosphorous, chlorine, silicon and calcium contents, as well as the chemical composition of the compounds, affect ash melting behaviour. This will contribute to the fouling and durability of the heat transfer surfaces in the boiler.

2.1 Ash properties affecting deposit formation

Deposits accumulate on heat transfer surfaces mainly by five different means:

- Inertial impaction, where the bulk of fly ash cannot follow the stream lines of the gas flow and hit the heat transfer surfaces. The particle size is usually greater that 10μm.
- Thermophoresis due to temperature difference in the gas. When the thickness of a deposit layer increases, the effect of thermophoresis is reduced as the temperature on the surface of the deposit layer approaches the gas temperature.
- Condensation of vaporised compounds occurs after vapours reach heat transfer surfaces which are at sufficiently low temperature. This mechanism is pronounced in biofuel combustion.
- Diffusion is an important deposition mechanism especially for vapours and particles smaller than 1μm.
- Chemical reactions within the deposit layer and between gaseous and solid compounds.

In biomass fuels alkaline metals are in the form of salts or are bound in organic matter, but for example in coal inorganics are bound in silicates which are more stable. Deposit formation inhibits heat transfer and reduces boiler efficiency, additionally, chlorine rich deposits induce hot corrosion of heat transfer surfaces.

2.2 Means to avoid chlorine-bearing deposit formation

Throughout the combustion process, the behaviour of a biomass fuel is affected by an existence of other fuels. It has been shown that even a small concentration of chlorine in logging residue chips will result in the harmful formation of alkaline chloride compounds on boiler heat transfer surfaces. This could be prevented by co-firing sulphur and aluminium silicate -containing fuel: when peat or coal is blended with biomass fuel such deposition formation can be prevented. In the latter case, vaporised alkaline metals of biomass ash are bound in sulphur and aluminium silicate compounds, the amount of alkaline chlorides in deposits is reduced or these are not formed at all, and chlorine is released as HCl to flue gases. The risk of bed agglomeration usually grows as the amount of alkaline metals (sodium and potassium) increases. When logging residue chips are combusted, the particle size of the bed material has been detected to grow. When peat is added, this phenomenon disappears.

Ash characteristics have important role also in boiler design, because deposit formation, erosion, corrosion and defluidisation of the bed sand should be minimised. Ash-forming matter in biomass fuels can be present in several forms: as soluble ions, associated to organic matter or as minerals. The form in which the ash-forming matter is present affects the behaviour of fuel ash. There are significant differences in how ash-forming elements are distributed in different fuels. In older fuels, ash-forming elements are present as minerals. In relatively young fuels, up to half of the ash-forming elements can be organically associated or present as easily soluble salts or as minerals.

According to present knowledge, control of the rate of deposit formation in biomass combustion is associated with the reactions between compound that contain chlorine, sulphur, aluminium silicate and alkaline substances. High-risk chlorine compounds are of the type NaCl or KCl. These alkaline chlorides can, however, react with sulphur and aluminium silicate compounds releasing HCl.

$$2KCl + SO_2 + \tfrac{1}{2}\,O_2 + H_2O \rightarrow K_2SO_4 + 2HCl$$

$$Al_2O_3 \cdot 2SiO_2 + 2KCl + H_2O \rightarrow K_2O \cdot Al_2O_3 \cdot 2SiO_2 + 2HCl$$

One parameter that has been often referred to is the sulphur-to-chlorine atomic ratio (S/Cl) in fuel or fuel blend. It has been suggested that if the S/Cl ratio in fuel is less than two, there is a high risk for superheater corrosion. When the ratio is at least four, the blend could be regarded as non-corrosive. The mechanism suggests therefore, that sulphur in the system is able to bind alkalis in sulphates (K_2SO_4, Na_2SO_4) through reactions in gas phase. However, limestone feeding, especially in fluidised bed combustion, changes the sulphur-to-chlorine balance of the gas phase. Calcium oxide, CaO, from limestone feeding or wood fuel co-firing (wood fuel ash is high in calcium), binds sulphur to calcium sulphate, $CaSO_4$. For this reason there is less sulphur available for sulphating potassium and sodium than fuel blend's sulphur-to-chlorine ratio indicates. In cases where there is plenty of calcium available in the system, i.e. with limestone feeding and biomass co-firing, fuel's sulphur-to-chlorine ratio should not directly be used.

Easily leached elements are the main constituents of fine fly ash, i.e. the fraction of ash that is formed from easily volatilised ash-forming matter, and consequently reasonable approximations of fly ash compounds. ´Chemical fractionation´ can be applied in determining how ash-forming elements are bound in the fuel. This is done by determining the constituents' solubility in different solvents. In chemical fractionation increasingly aggressive solvents, i.e. water (H_2O), ammonium acetate (NH_4Ac) and hydrochloric acid (HCl) leach fuel samples into a series of four fractions (including the unleached residue) for analysis. Typical ash-forming components that are leached out by water include alkali sulphates, carbonates and chlorides. Elements leached out by NH_4Ac are believed to be organically associated, such as Mg, Ca as well as K and Na. HCl leaches carbonates and sulphates of alkaline earth and other metals. Silicates and other minerals remain in the insoluble residue.

3 Power plant availability and operation cost analysis

3.1 Experiences of wood fuel's effects on power plant availability

VTT Processes studied the availability of wood-fired boilers in twelve Finnish power plants: four CFB and eight BFB plants with thermal output 100-300 MW. Special attention in the questionnaire was paid on the following issues:

- the connection between the reported failures and the fuels used
- fouling of heat transfer surfaces and the material effects
- behaviour of bed material; need for bed sand replacement, blockages interfering fluidisation, slag formation
- need for soot blowing
- the effects on smooth fuel feed, the homogeneity of fuels and on how fuel distributes in the furnace
- temperature fluctuations in the furnace caused by heterogeneous fuel quality and fuel feeding

This questionnaire supports previous studies where it was found that wood fuels cause problems in plant operation. Almost all plants have faced problems with stock discharging gears, conveyers and feeding gears. The problems originate from unsuitable equipment and their tendency to get stuck due to the unexpected nature of wood fuels. Majority of the plants can feed fuel smoothly into furnace, however, only in few cases fuel spreads evenly in the furnace.

In most of the power plants bed related problems have occurred during the use of wood fuels. Problems involve bed temperature fluctuation due to the moisture changes of the fuel and a higher risk for bed sinter. To solve the problems plants have increased the bed sand replacement frequency and mixed moist and dry fuels. In over a one half of the plants the need for bed material replacement has increased.

Majority of the respondents has discovered that wood fuels have affected the rate of furnace deposition. The rate of deposition has increased when the share of wood fuels has increased. At most of the plants detailed studies concerning super heater deposition have been carried out. VTT Processes has conducted research at several of these power plants on deposit formation and fouling with a cooled deposit formation monitoring probe. Already in a monitoring period of 30 days there have been found indications that heat transfer and boiler efficiency is influenced by deposit formation.

It was not generally found that wood fuels would increase the need for soot blowing. Average soot blowing interval was 1.2 times per day. Adequate and functional soot blowing supports the use of wood fuel and it should be carefully recognised when plant is planning to increase the use of wood fuels. Half of the respondents noted that wood fuels have changed the nature of ash. In addition, it is very difficult to find further use for the ash from peat and wood co-combustion (for example in cement industry).

All of the respondents stated that flue gas emissions have decreased significantly during the use of wood fuels. Especially SO_2 emissions have diminished and as a consequence the need for lime usage. The use of wood fuels has not resulted in notable changes in the amount of work during revisions.

Majority of the plant operators stated that after starting the use of wood fuels the maximum power generation capacity is more difficult to achieve. This is caused by high moisture content of wood fuels. One reason for this is that flue gas blowers may be underrated. Also the capacity of conveyers and feeding gears is limited.

The following figures show the respondent's experiences of wood fuel usage. The figures show the format of questions asked in the questionary.

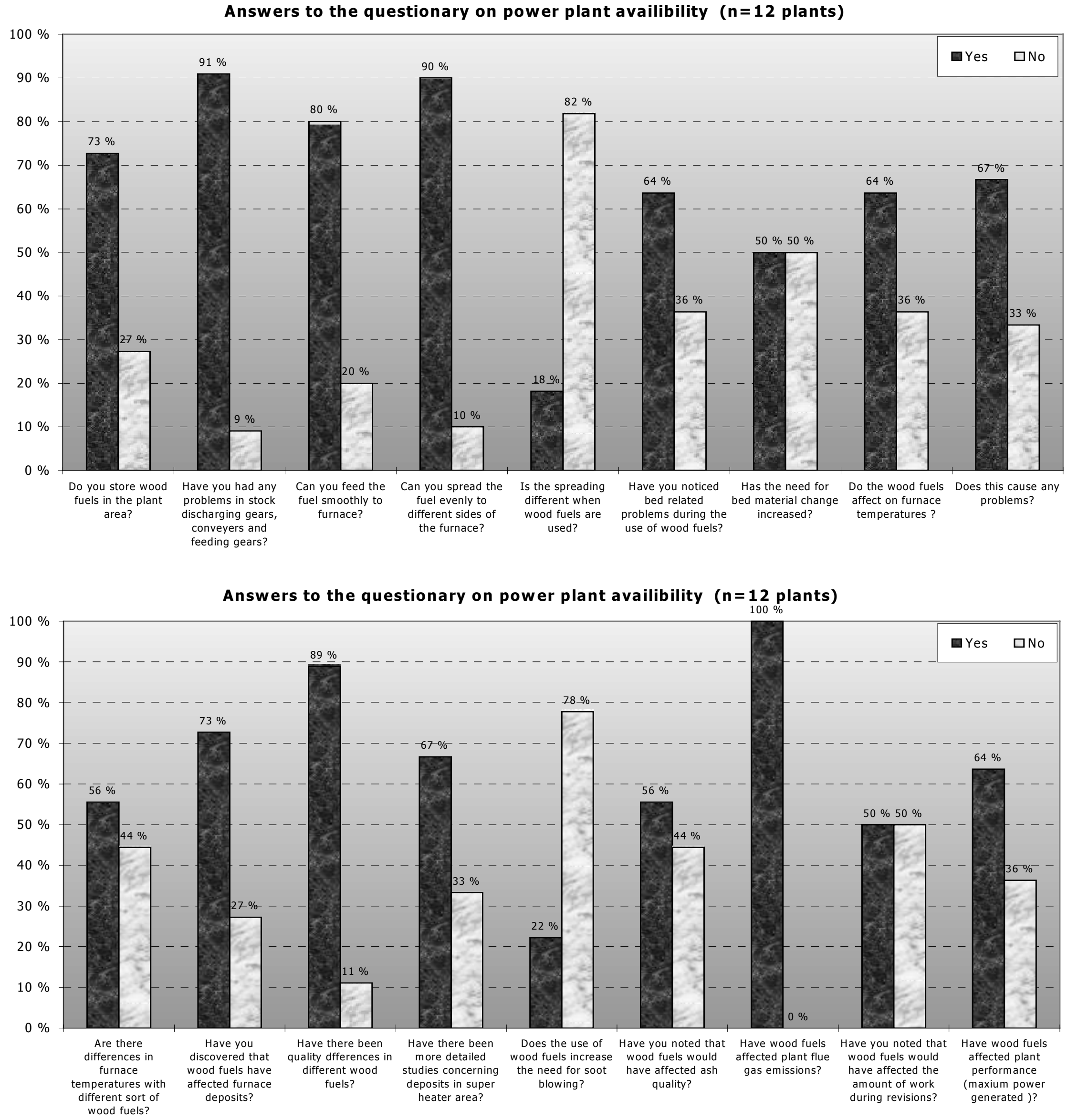


Figure 1. Answers to the questionary on power plant availability.

3.2 Operation cost analysis of wood fired power plants

The effects of the operating and maintenance costs of wood combustion were compared with those of peat combustion. In a study where operating experiences from a period of two years were collected from power plants in a questionnaire. In year 1 of the study only peat was combusted and in the year 2 wood fuels were blended with peat. For both of the periods unit costs (€/MWh_{fuel}) were calculated.

The difference between those costs gives some indication about the influence of wood combustion on power plant running costs and it is possible to establish cost comparisons between the two cases. The effects of different factors were analysed separately in every plant, and the costs caused by these factors in combustion of pure peat and co-combustion of peat/wood blends were determined. Following factors were analysed:

- need for soot blowing
- need for changing bed sand
- changes in ash composition
- changes in plant's power consumption
- fuel storage

The increment of the costs caused by the above-mentioned factors was estimated to be 0.1 €/MWh_{fuel} when the share of wood of the total fuel power is 70 %. At a plant where the share of wood is 30 % the corresponding value is negligible. The increase of the flue gas temperature, caused by the combustion of wood fuels, decreases boiler efficiency and increases operating costs, depending on the price of the fuel, by 0.1 €/MWh_{fuel}. When the requirement for additional investments at the plant, where the share of wood is 70 %, are taken into account, the additional costs vary from 0.05 to 0.1€/MWh_{fuel}. Obviously, this number depends on the applied interest rate and payback time (here 5-15 % and 10-15 years, respectively).

When all the factors affecting the costs are taken into account, the increment of the costs equals to 0.26 €/MWh_{fuel}, This corresponds to 70 % wood share in the fuel blend. The results indicate, however, that even with as low wood share as 25 – 30 % the effect of increased unit cost starts to have influence on the annual utilisation of the boiler. When small amounts of wood are used, the share being about 10 %, the plants had no problems and the costs did not increase.

4 Methods for optimisation of multifuel-based bioenergy production

Understanding of deposit formation and ash behaviour is a key issue in optimising boiler operation and in securing good level of plant performance and high availability. Boiler fouling has effect on several factors at power plants. The increase in operating and maintenance costs caused by boiler fouling can increase the total energy production costs significantly. The formation of harmful deposits can be reduced or even avoided with appropriate fuel blend control. Combustion behaviour of fuels can be efficiently studied with pilot-scale reactors. Additionally, to support full-scale power plant operators in daily decision-making and in plant optimisation advanced methods for deposit formation monitoring and process calculations are being developed. These methods will help power plant operators to achieve better power plant performance with improved fuel flexibility.

In developing methods for multifuel operation optimisation, combustion and co-firing properties of fuels have been studied both at VTT Processes' test facilities and at industrial-scale power plant boilers. The formation of alkaline chloride compounds in biomass combustion and their effect on deposit formation and corrosion have been monitored by deposit formation and material monitoring probes.

The objective is to characterise deposit build-up and its effect on heat transfer in biomass (especially wood) combustion. With the knowledge gained it is possible to develop methodologies and mathematical models to better understand the changes in heat transfer caused by biomass co-combustion. With mathematical models and simulations, the interrelation between fuel composition and deposit formation tendency can be studied and the causalities between heat transfer, in-furnace conditions and fuel & fuel-ash characteristics correlated. The results from these calculations can be applied in estimating and optimising the factors that have effect on plant availability.

Studies have also been conducted on fuel production, transport, receiving and handling systems. Co-firing of biomass and peat requires uniform fuel blend quality and even fuel feed to boiler. This sets demands to fuel supply logistics and to plant's fuel handling systems. The necessities and possibilities of modern fuel supply chain have to be taken into account when targeting to maximum plant availability.

4.1 Pilot-scale combustion tests

Pilot-scale test facilities at VTT Processes include Circulating Fluidised Bed test rig and Bubbling Fluidised Bed test rig. The CFB reactor (See Figure 2) has 50 kW fuel capacity and it consists of an air/water-cooled ceramic chamber with fluidised bed within. The inner diameter of the reactor is 16.7 cm. The temperature levels in the reactor can be maintained with electrical heaters, cooling system and by feeding combustion air in appropriate proportions. The amount of primary- and secondary air fed from three levels is adjusted and measured by thermal mass-flow meters. Due to the 8-metre rising height, a sufficient residence time is also achieved at high flue gas velocities. Particulate matter is separated from the flue gases in the primary and secondary cyclones and in a fabric filter. With the reactor it is possible to study combustion behaviour of different fuels, deposit formation, formation of pollutants and ash properties under CFB conditions. Sampling ports at different locations enable the determination of combustion profile as a function of residence time. Also material samples can be taken for material characterisation and particle size analysis. With the aid of dense temperature measurement network temperature profiles with reactor height can be defined.

The Bubbling Fluidised Bed test rig (Figure 2) has 13-15 kW fuel capacity. The height of the FB reactor is 4.1 metres and it has inner diameter of 16 cm. The reactor can be heated up to the desired temperature levels by using electrical heaters and it can be cooled down by applying cool air to lower parts of the reactor. Combustion air can be preheated and fed into the reactor in appropriate proportions as fluidisation-, secondary- and tertiary air, in order to optimise conditions during experiments. Combustion conditions can be adjusted to correspond those prevailing in full-scale BFB boilers. Particulate matter is separated from the flue gases in a cyclone and in a fabric filter. The test rig is applied in research work relating to the formation of pollutants, ash property characterisation and combustion behaviour characterisations of problematic fuels. Deposit formation can be studied by inserting air-cooled probes into the reactors' furnace and flue gas paths. It is also excellent environment for characterising fine fly ash emissions in multifuel and waste combustion. The main research interests are in the fields of ash behaviour characterisation and pollutant formation prediction.

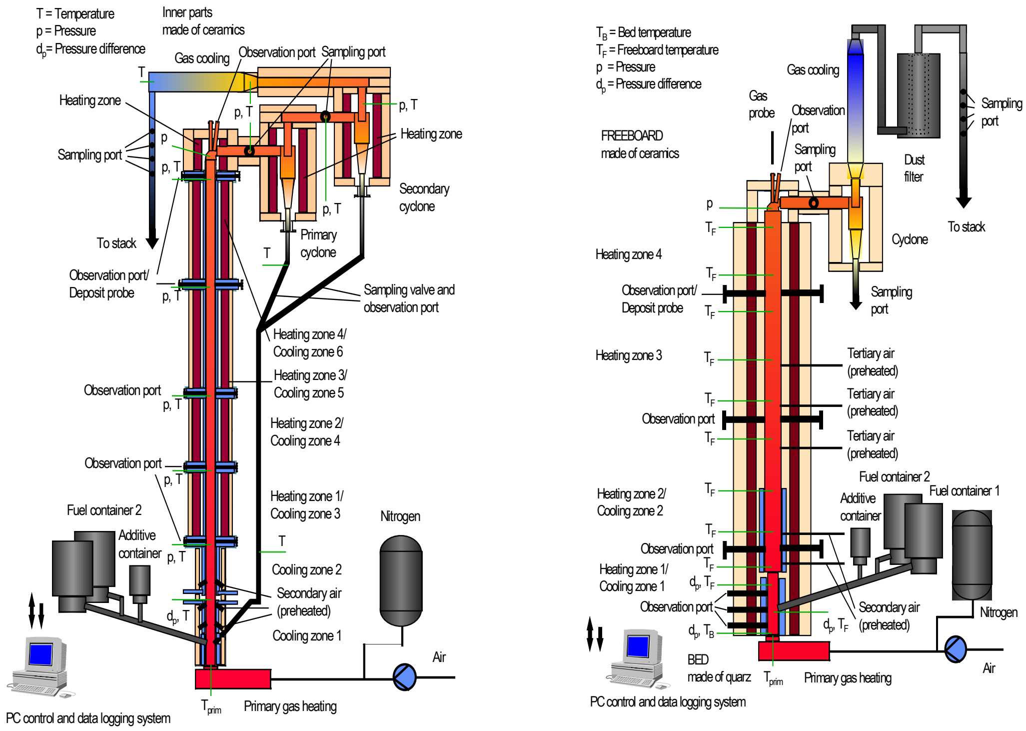


Figure 2. General scheme of the CFB (left) and BFB (right) test rigs.

The pilot plants are used for characterisation of fuel combustion behaviour at fluidised bed combustion conditions. In this project the main focus was on establishing the effect of change in the fuel mix, in this case the share of aspen bark with peat and spruce bark and the effect of fuel blends quality on flue gas emissions and on deposition formation in conditions prevailing in large-scale industrial boiler. According fuel analysis of used fuels: aspen bark, spruce bark and peat, Table 1, properties of spruce and aspen bark seem to be quite similar.

Table 1. Proximate and ultimate analyses of aspen bark, spruce bark and peat.

	Aspen bark	*Spruce bark*	*Peat*
Moisture content before pretreatment (%)	56,4	62,3	-
Moisture content after processing (%)	6,2	10,4	23,6
Ash content at 500 °C (%)	3,91	4,06	4,77
Ash content at 815 °C (%)	2,73	3,11	4,76
Calorimetric heating value (kJ/kg)	21422	20309	22078
Effective heating value in dry matter (kJ/kg)	20069	19055	20859
Effective heating value of wet fuel (kJ/kg)	18668	16812	15350
C-content (%)	52,5	51,1	54,7
H-content (%)	6,20	5,75	5,59
N-content (%)	0,68	0,48	1,73
O-content (%)	37,82	39,5	33,0
S-content (%)	0,06	0,03	0,16
Cl-content (%)	0,02	0,02	0,05
Moisture of fuel blends during the tests varied from 35 to 37 %			

Fuel ash analyses reveal that there are significant differences in aspen and spruce bark elemental composition. Aspen bark contains nearly two times more sodium, manganese, potassium and notably less calcium, aluminium and silicon than spruce bark. Spruce bark's ash composition is typical when compared to values found in literature. Peat ash is rich in aluminium, sulphur, iron and silicon in comparison to spruce and aspen bark, see Table 2. In terms of deposit formation propensity high Cl, Na, K contents and coincident low Al, Si and S contents can be considered as a potential risk.

Table 2. Elemental composition of ashed fuels from BFB experiments.
Ashing in 500 °C prior to XRF-analysis

wt-% in ash	*Aspen bark*	*Spruce bark*	*Peat*
K	12.29	5.37	1.48
Na	0.51	0.30	1.37
Mg	3.09	1.89	1.11
Ca	26.94	31.23	7.38
Al	0.64	1.22	8.15
Mn	0.36	1.59	0.12
Fe	0.37	0.63	9.90
S	0.87	0.46	1.17
Cl	0.07	0.07	0.14
Si	2.01	4.01	21.60
P	1.38	1.09	0.93

It was found that it is advantageous to combust aspen bark with peat as a homogeneous mix. In the experiment where the fuel mix consisted of equal proportions of aspen and spruce bark, bed sand agglomeration was observed. Agglomeration was not observed when peat was added to amount for 50 % of the fuel's energy content. The materials between the sand particles, suggested to cause the agglomeration, were potassium, calcium and silicon compounds. Bed-material analyses showed that Ca-, K-, Mn-, P- and Mg-concentrations increased linearly during the tests. In Figure 3 is shown how potassium concentration increases in the bed sand during the test period.

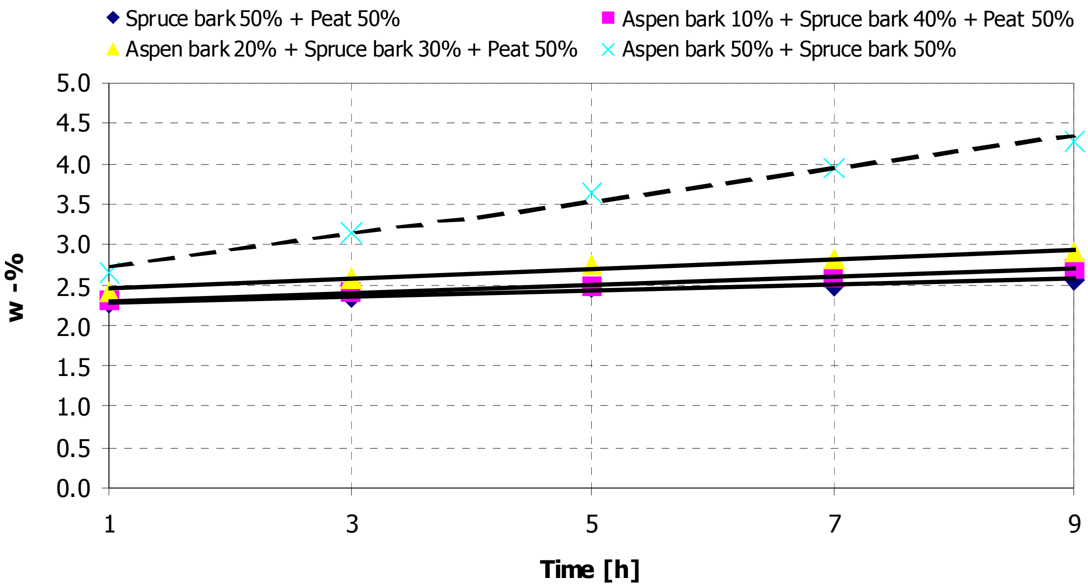


Figure 3. Potassium content of the bed-sand material during the test period. The results with bark fuel only are market with dash line.

Deposit samples collected from the experiments with different fuel blends were analysed with SEM-EDX. In the analysis differences were found only in sulphur concentrations. In co-firing peat with bark deposit layers were mainly formed of calcium and potassium together with sulphur. When peat was not used deposits contained oxides and silicates. Phosphorus was found in small concentrations and in selected locations also chlorine. According to the elemental analysis of fly ash samples the increase of aspen bark share from 0 to 50 % resulted in clearly higher concentrations of S, Ca, Mg, Na and K in filter ash, as well as higher Ca and Mg concentrations in cyclone ash.

10-20% aspen bark share did not change notably NO, NO_2, N_2O, SO_2, hydrocarbon nor HCl-concentrations. The blend with 20% aspen bark + 30% spruce bark + 50% peat produced 136 ppm of NO, <0.5 ppm NO_2 and 2 ppm N_2O. SO_2 concentration was 22 ppm and HCl $\leq$ 5 ppm.

Table 3. Flue gas (dry) composition when combusting different fuel blends and furnace temperatures

	O_2 %	CO ppm	NO ppm	SO_2 ppm	T_{bed}	T_{riser}
Spruce bark 50% + Peat 50%	4,0	118	146	31	835	918
Aspen bark 10 % + Spruce bark 40% + Peat50%	4,0	59	136	23	852	928
Aspen bark 20 % + Spruce bark 30% + Peat50%	4,2	75	136	22	857	922
Aspen bark 50 % + Spruce bark 50%	4,3	137	69	1	848	925

4.2 Full-scale combustion tests

Deposit formation monitoring at full-scale boilers provides unique information on the rate of deposit formation, the effect of sootblowing and consequent changes in heat transfer. Additionally, the data from deposit formation monitoring has been shown to correlate with boiler performance, which gives basis for studying the interrelation of fuel blend characteristics – deposit formation – boiler performance. This enables the development of on-line methods for maximising boiler efficiency and quantifying the implications of applied fuel blend on boiler performance.

A specific deposit-monitoring probe has been developed at VTT Processes based on design, which is applied in corrosion measurements. There are three temperature measurements in this air/water cooled heat transfer probe (see figures 4 and 5).

Figure 4. A specific deposit-monitoring probe can be applied in analysing both short- and long-term deposition build-up.

The probe has completely closed annular structure, which enables the use of both water and air as a cooling medium. The probe does not introduce any disturbing blasts into the furnace; instead cooling water and air are circulated back from the head of the probe. During the tests the 3 metre casing remains cool, in the order of 200 °C, whereas the temperature of the thinner 48 mm diameter head (with the bright test material rings in Figure 4) is adjusted to the level of superheater tube temperatures. Due to the mechanical structure of the probe and wide range of temperature levels on the probe's surface it is impossible to reliably measure heat transfer only on one specified area of the probe, which in this case would obviously be the sampling surface in high temperature at the head of the probe, only by monitoring the temperature increase of cooling water and air. The design will be improved further by mounting specific heat flux sensors to this area on each side of the probe.

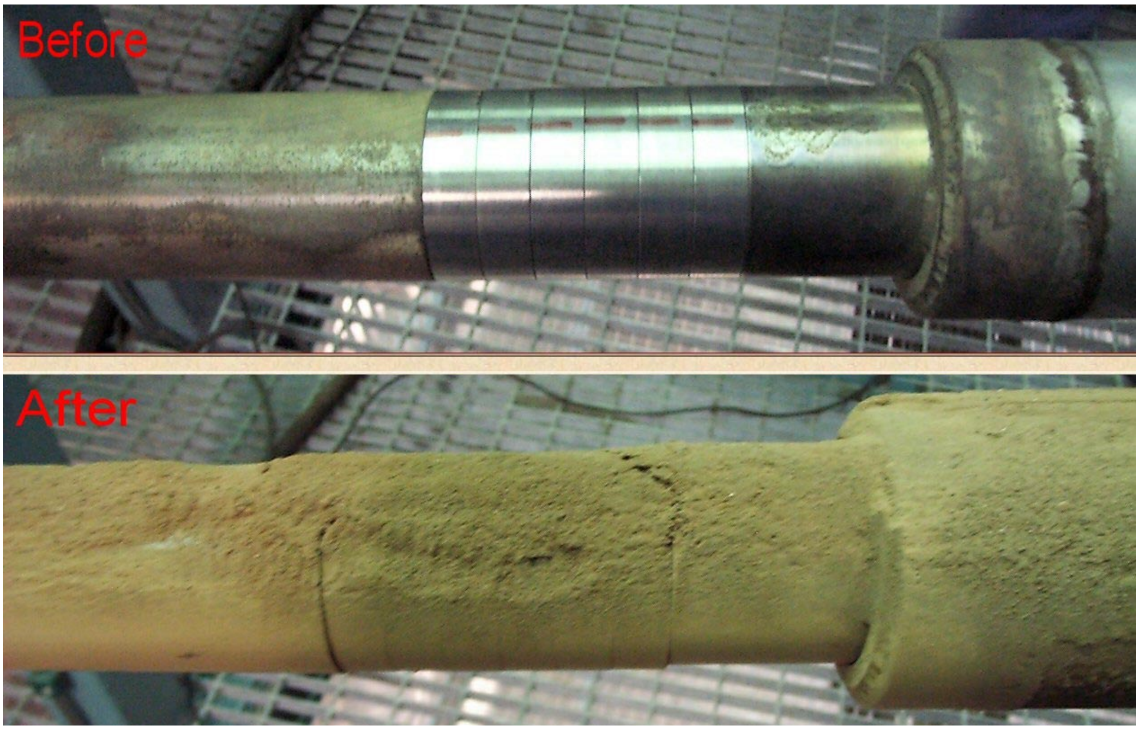


Figure 5. Deposit formation monitoring probe before and after a four week measurement campaign in a BFB-boiler. Fuels were wood, peat and REF.

During four-week measurement campaign in a CFB boiler (84 MW_{th}, 33 kg/s, 535 ºC, 114 bar) used fuels were about 40 % peat and 60 % wood fuels. Peat was milled peat and wood was mainly bark and saw dust. The share of logging residue wood chip was also significant, seen in Table 4. Fly ash analysis results are presented in Appendix 1.

Table 4. Fuels used at CFB boiler in the 4 week combustion test. Fuel moisture varied between 40-52 %.

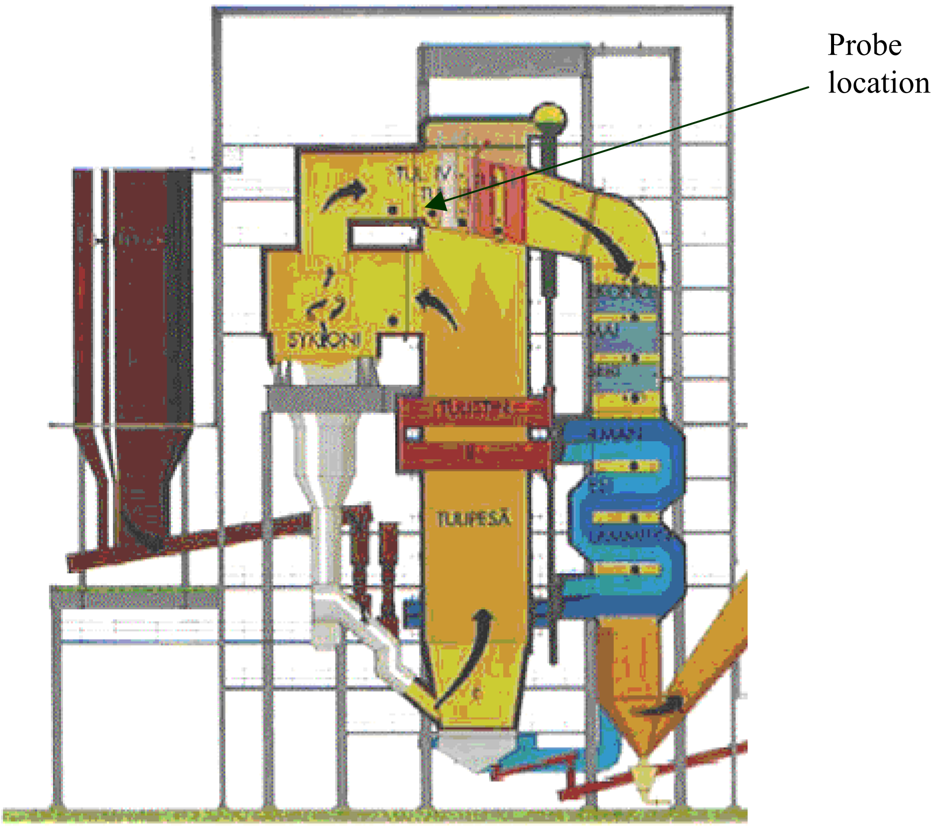
Fuel species	Share by weight	Share by volume	Energy [MWh] (Effective heating value in dry matter)	Energy [MWh] (Effective heating value of wet fuel)
BILLET WOOD CHIP	0.1 %	0.1 %	0.1 %	0.1 %
WOOD CHIP	3.5 %	4.4 %	3.4 %	5.5 %
WOOD CHIP/DEMOLTION WOOD	1.7 %	2.4 %	1.6 %	2.4 %
LOGING RESIDUE	6.3 %	6.6 %	6.3 %	7.3 %
MILLED PEAT	39.6 %	35.0 %	41.6 %	40.9 %
WHOLE TREE WOOD CHIP	3.1 %	3.8 %	3.0 %	3.5 %
CUTTER CHIPS	0.9 %	3.0 %	0.8 %	1.5 %
REF	0.4 %	0.6 %	0.4 %	0.5 %
SAW DUST/BARK MIXTURE	18.7 %	16.9 %	18.1 %	15.6 %
SAW MILL BARK	3.3 %	2.9 %	3.1 %	2.7 %
SAW DUST	22.3 %	24.2 %	21.5 %	19.7 %
OIL	0.1 %	0.0 %	0.2 %	0.4 %
Total	**100.0 %**	**100.0 %**	**100.0 %**	**100.0 %**

In Table 5. are presented main temperatures in the CFB boiler and in Figure 7. probe's temperature profiles during four-week measurement campaign.

Table 5. Main process temperatures in CFB boiler during monitoring period.

Week N:o	37	38	39	40	Averages
Bed temperature average, ^{O}C	863	860	856	850	857
Gas temperature before cyclon 1, ^{O}C	933	933	846	843	889
Gas temperature after cyclon 1, ^{O}C	913	914	925	936	922
Gas temperature before cyclon 2, ^{O}C	932	932	874	869	902
Gas temperature after cyclon 2, ^{O}C	923	924	916	933	924

The probe located in the flue gas stream right after the cyclone and before the tertiary superheater. The flue gas temperature was around 780 ºC measured at the top of probe.



Probe location

Figure 6. Deposit formation monitoring probe n CFB-boiler

The windward temperature of the probe is maintained constant by regulating cooling but the increase of side- and leeward temperatures is apparent on this four-week period due to long-term deposit build-up. The short-term deposit formation results in a decrease of side- and leeward temperatures on soot blowing intervals, however, the temperatures recover quickly after every soot blowing. It was noticed that deposits from the windward surface could not be removed efficiently.

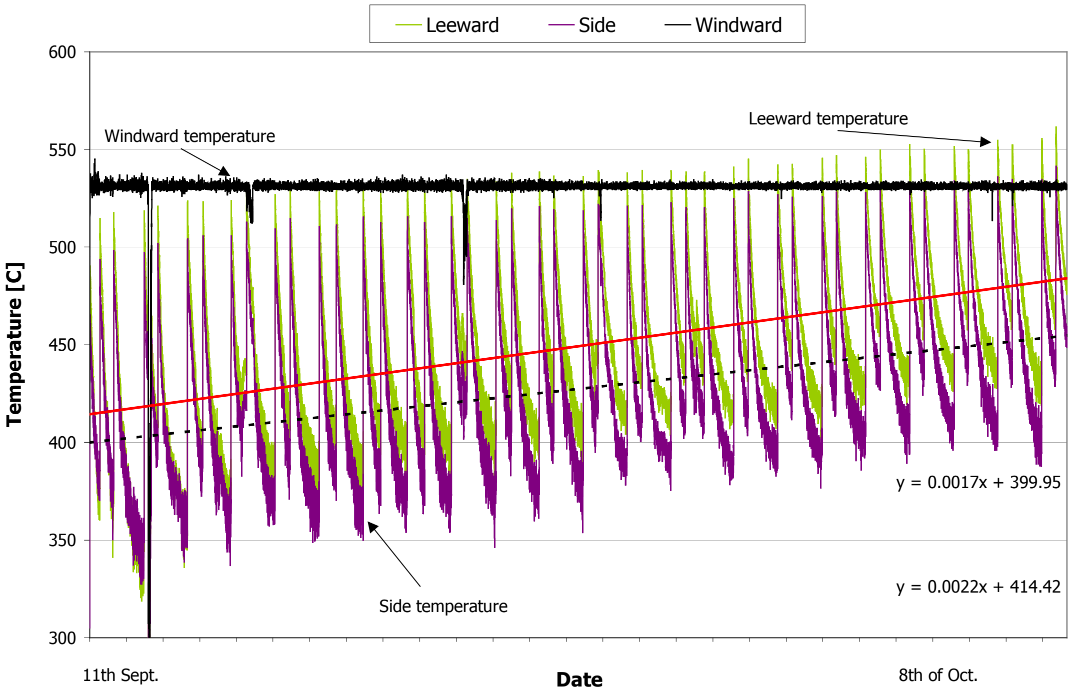
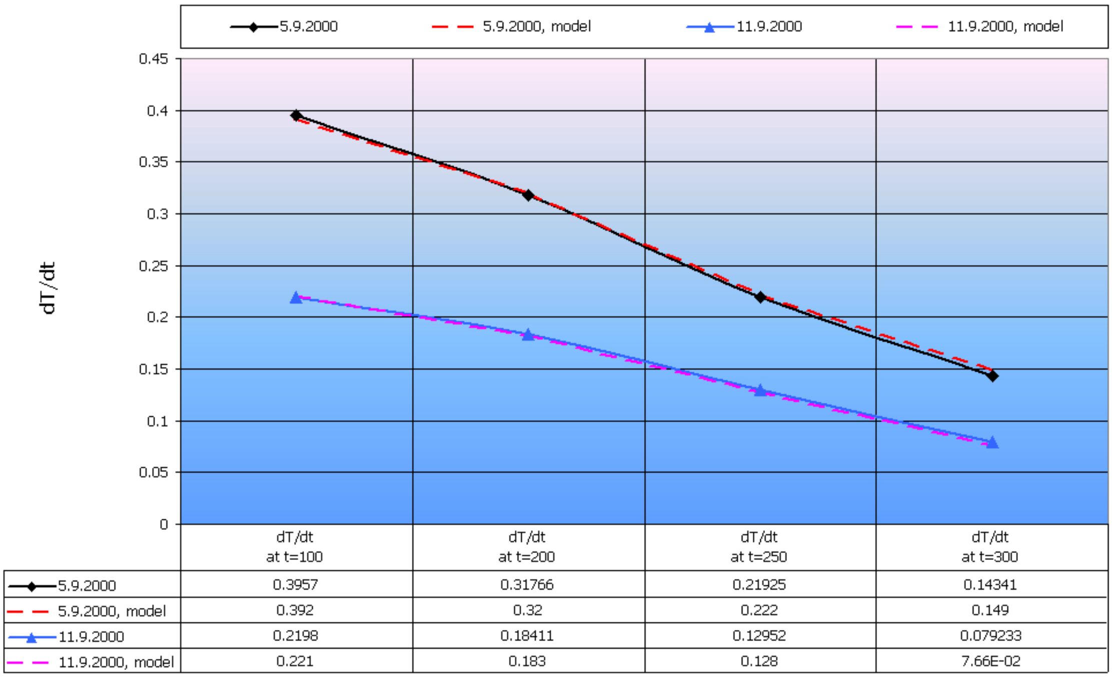


Figure 7. Temperature fluctuation on the three sides of the probe.

In a test period of several weeks, it was noticed that the rate of change in the leeward temperature over the soot blowing intervals changed towards the end of the test period. The rate of change in temperatures was examined together with elementary analyses of fuel and fly ash and boiler operational parameters. Correlation was detected between the rate of change in the temperatures and presence of some elementary substances. An equation for describing this correlation was developed. The equation which gives the rate of change in the temperature at a particular point of time, t_{th}, reads

$$\frac{dT}{dt}(t = t_{th}) = \sum_{i=1}^{n} q_i w_i + B0$$

where q_i is a constant for element i and w_i is the share of the element i in the substance (i.e. by mass). In figure 8 are presented the estimated rates of temperature changes calculated with the equation and also the original, measured, values of two separate soot blowing intervals. As we can see, the model predicts quite well the temperature behaviour, even though the validity range for the model is so far rather limited.



	dT/dt at t=100	dT/dt at t=200	dT/dt at t=250	dT/dt at t=300
5.9.2000	0.3957	0.31766	0.21925	0.14341
5.9.2000, model	0.392	0.32	0.222	0.149
11.9.2000	0.2198	0.18411	0.12952	0.079233
11.9.2000, model	0.221	0.183	0.128	7.66E-02

Figure 8. The estimated rates of temperature changes calculated with the equation and the original, measured, values of two separate soot blowing intervals.

The parameters applied in the calculation model are presented in Table 6.

Table 6. The parameters applied in the calculation model

	Na	Mg	Al	Si	K	Ca	B0
w_{min}	*1.2*	*0.9*	*5.9*	*20.1*	*3.0*	*8.4*	-
w_{max}	*1.8*	*1.5*	*7.9*	*25.8*	*4.1*	*14.3*	-
$q_{i\ (t=100)}$	0.197	0.104	0.057	-0.006	0.014	0.025	-1.304
$q_{i\ (t=250)}$	0.166	0.058	0.039	-0.002	0.013	0.013	-0.902

The deposition/corrosion probe can also be used for examining how combustion conditions affect the durability of superheater materials. There were also corrosion tests carried out at the 84 MW_{th} CFB boiler during the 4 week period. The tested materials on the probe were a ferritic compound X20 CrMoV 12 1 and two austenitic compounds AC 66 and Sanicro 28. AC 66 showed the best endurance throughout the probing period. In Sanicro28 some traces of corrosion were detected, mainly on the windward surface. X20 CrMoV 12 1 materials corroded in greater extent.

The short-term deposition build-up can also be analysed by using the heat transfer probe. In figure 10 is presented the relative rate of deposit formation over a soot blowing interval in superheater area with different shares of wood fuels combusted in a BFB –boiler (113 MW_{th}, 40 kg/s, 525 ºC, 112 bar). Fuel analyses are shown in Table 7. Fuel ash analyses and more detailed fuel moisture values can be found from Appendix 2 and probe temperature measurements from Appendix 3.

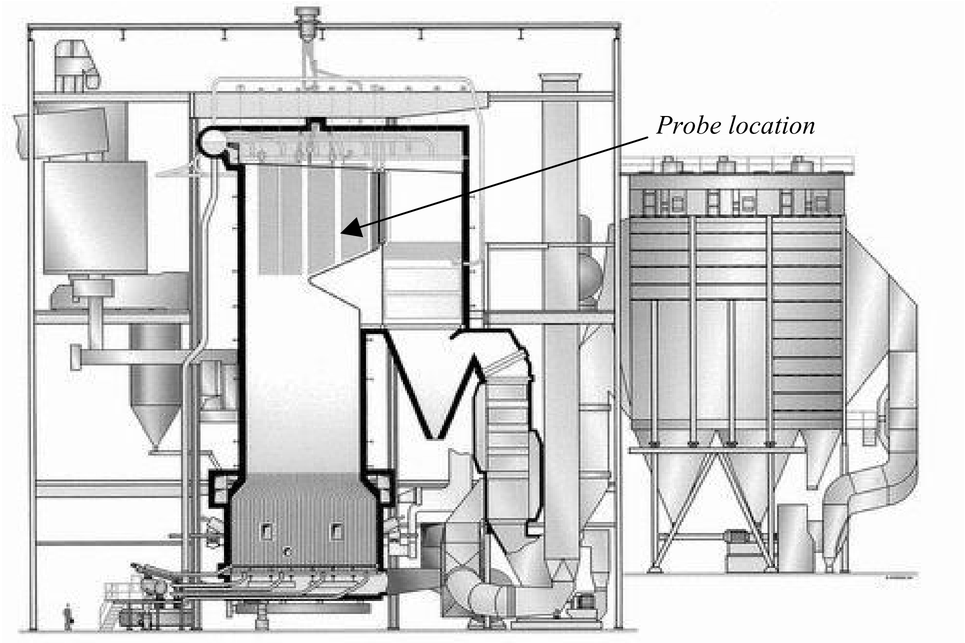


Figure 9. Schematic of the BFB boiler and location of heat transfer/deposit formation monitoring probe.

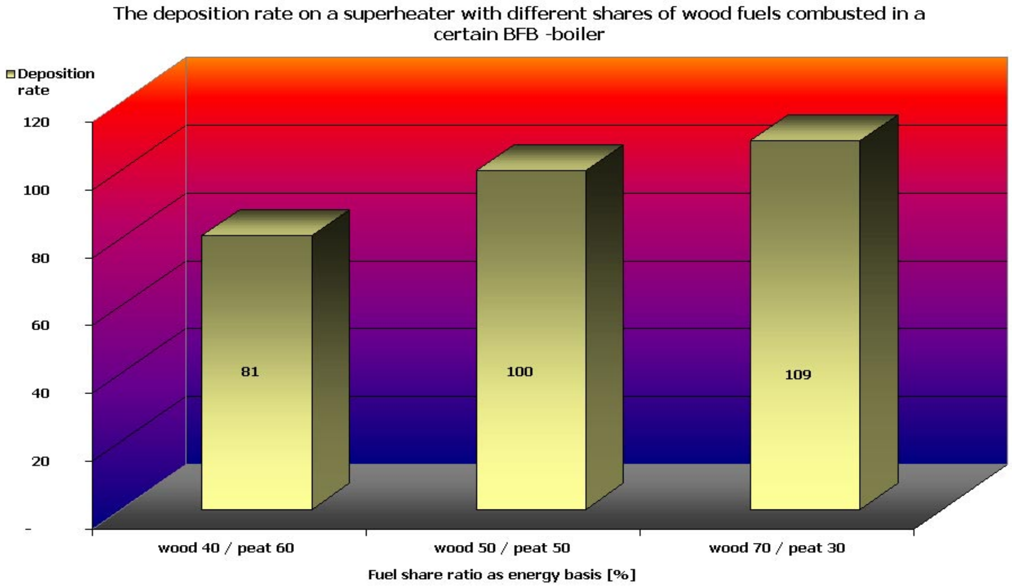


Figure 10. The relative rate of deposition with different shares of wood fuels in a BFB -boiler superheater area over a soot-blowing interval. Deposition built-up increases with the share of biomass in the fuel blend.

The model discussed can be developed further by widening the database of measured information, making use of previously measured data and by taking into account process conditions in the form of heat transfer correlations. Such evolution could give basis for developing a tool for evaluating optimal fuel blends and soot blowing intervals. In addition, it could be possible to quantitatively estimate how much different fuel types inhibit heat transfer in the furnace and consequently boiler operation.

Table 7. Fuel analyses from tests 1 to 3.

	Test 1	**Test 2**	**Test 3**
Share of wood (%)	50	70	40
Share of peat (%)	50	30	60
Fuel Moisture (%)	61.65	54.04	60.48
Ash content 550 °C (%)	5.61	3.69	5.18
Ash content 815 °C (%)	5.94	4.00	5.51
Higher heating value (kJ/kg)	20 629	21 179	20 730
Lover heating value, dry solids (kJ/kg)	19 377	19 912	19 500
Lover heating value, as received (kJ/kg)	5 927	7 833	6 230
C wt-%	50.92	52.25	51.83
H wt-%	5.74	5.80	5.64
N wt-%	0.72	0.63	0.82
S wt-%	0.16	0.12	0.17
Cl wt-%	0.03	0.02	0.02
O wt-%	36.84	37.50	36.34
S/Cl atomic ratio	7.2	6.8	8.2

Table 8. Bed and flue gas temperatures in the tests 1 to 3.

	Test 1	**Test 2**	**Test 3**
Bed temperature (°C)	856	857	845
Flue gas temperature near probe (°C)	660	678	670

With the aid of measurements, analysis and modelling methods the impact of fuel blend and fuel-ash on deposit formation and heat transfer has been established. To support the estimation of the impact of different fuels on deposit formation, a simple superheater simulation model has been developed, where the efficiency of the superheater is calculated by using the plant's operational data.

5 CONCLUSIONS

Fuel and process optimisation is needed when substituting ordinary fuels with solid biomass fuels. As fuel blending changes the behaviour of fuels in combustion, optimisation of the proportion of fuels in the fuel blend is required. Several approaches are available for the optimisation work. Pilot-scale reactors have been applied in studying the interaction of sulphur – chlorine – aluminium silicate species in order to find optimal shares of fuels in terms of safe and efficient combustion. At large-scale plants deposit formation monitoring methods have been developed for optimising boiler performance from heat transfer point of view.

Described ash behaviour monitoring system is currently in demonstration phase. The objective is that the obtained probing data as well as process data from the plant will be implemented into a simulation programme to form an advisory tool for power plant operators.

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Appendix 1: Fly ash analysis results from CFB tests 1(2)

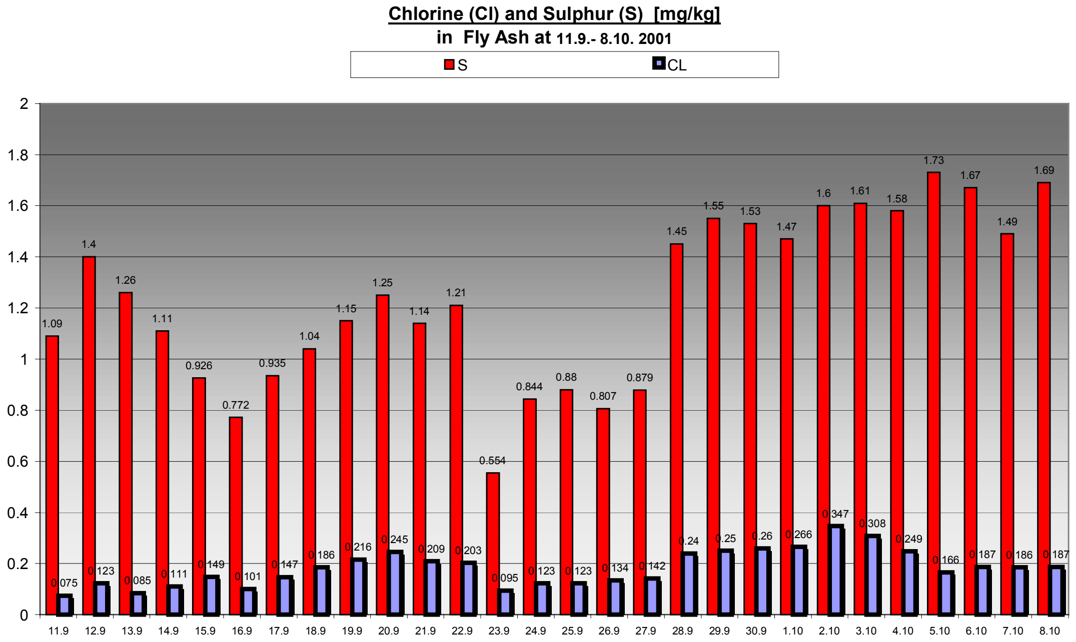

Figure A1. Chlorine and Sulphur in fly ash during four weeks monitoring period.

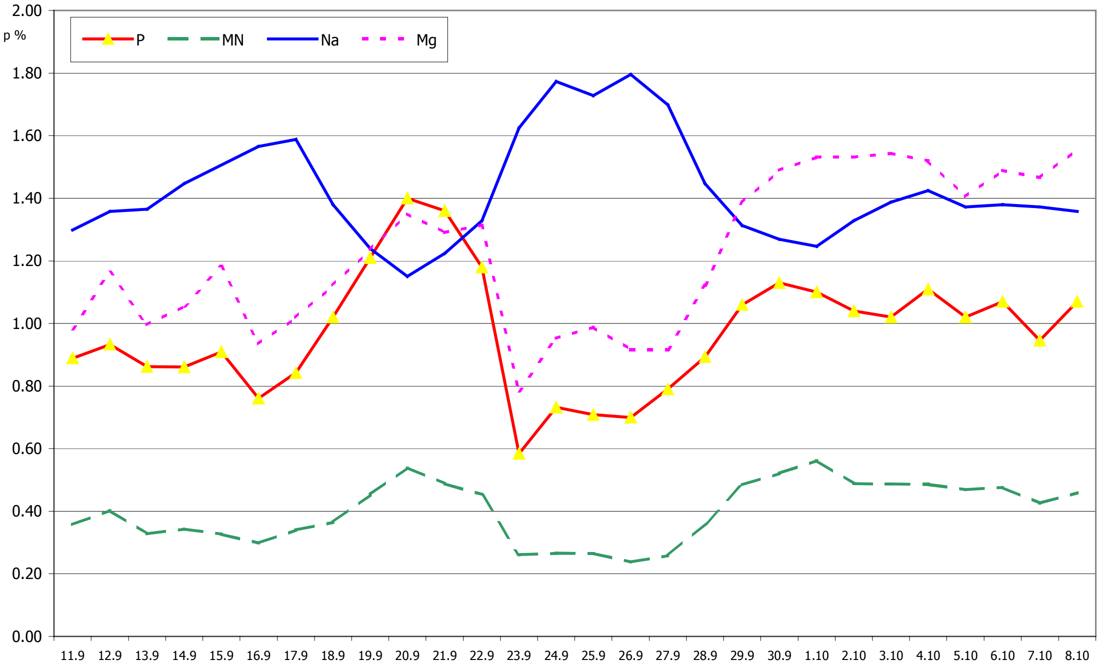

Figure A2. P, Mn, Na and Mg in fly ash.

Appendix 1: Fly ash analysis results from CFB tests 2(2)

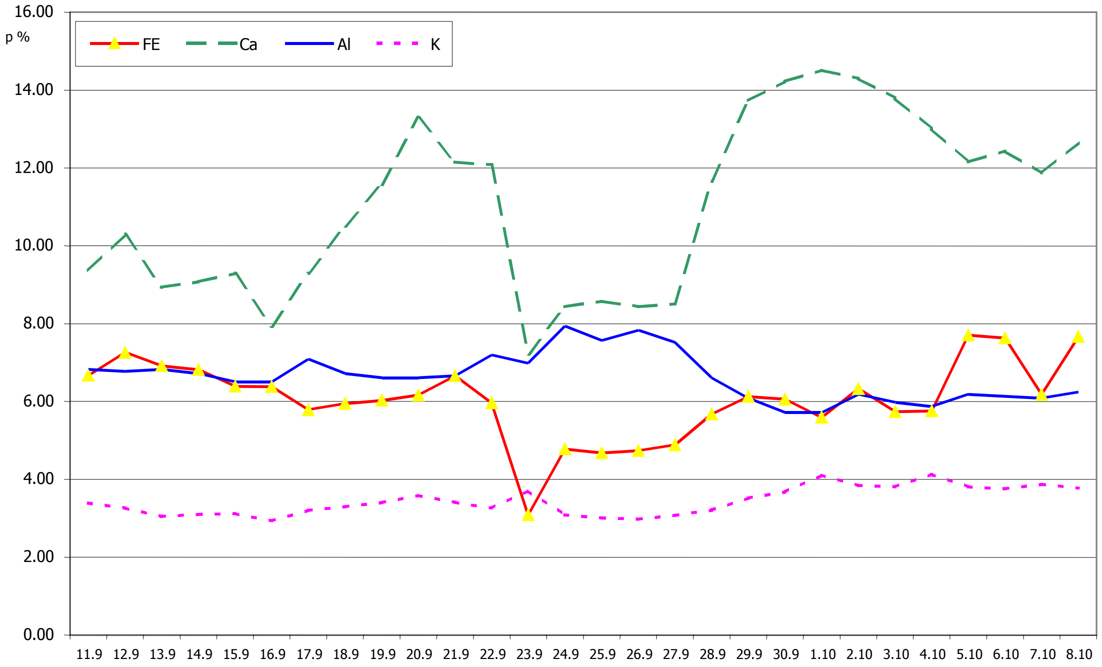

Figure A3. Fe, Ca, Al and K in fly ash.

Appendix 2: Fly ash analyses from BFB tests

Table A1. Fuel ash analyses in experiments 1 to 3. Ashing at 550°C

	Test 1	Test 2	Test 3
S	1.46	1.70	1.53
Cl	0.06	0.10	0.08
Na	1.29	1.72	1.07
Mg	4.25	4.05	4.38
Mn	0.40	0.55	0.34
P	0.90	0.95	0.88
Ca	13.08	17.30	15.30
Al	9.26	7.73	8.10
Fe	2.71	2.86	3.51
K	1.27	1.88	1.54
Si	19.21	15.80	17.16
Sum	**53.9**	**54.6**	**53.9**

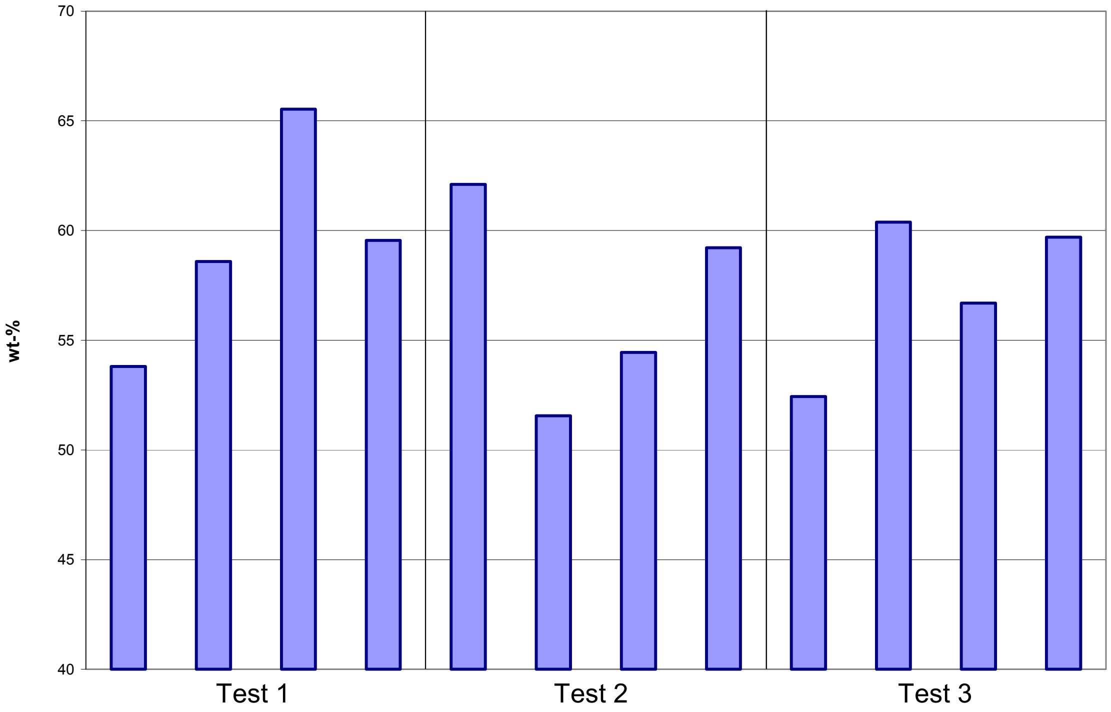

Figure A4. Fluctuation in fuel moisture in tests 1 to 3. Fuel sampling in every two hours during the 6 hour tests.

Appendix 3: Probe temperature measurements in BFB boiler 1(2)

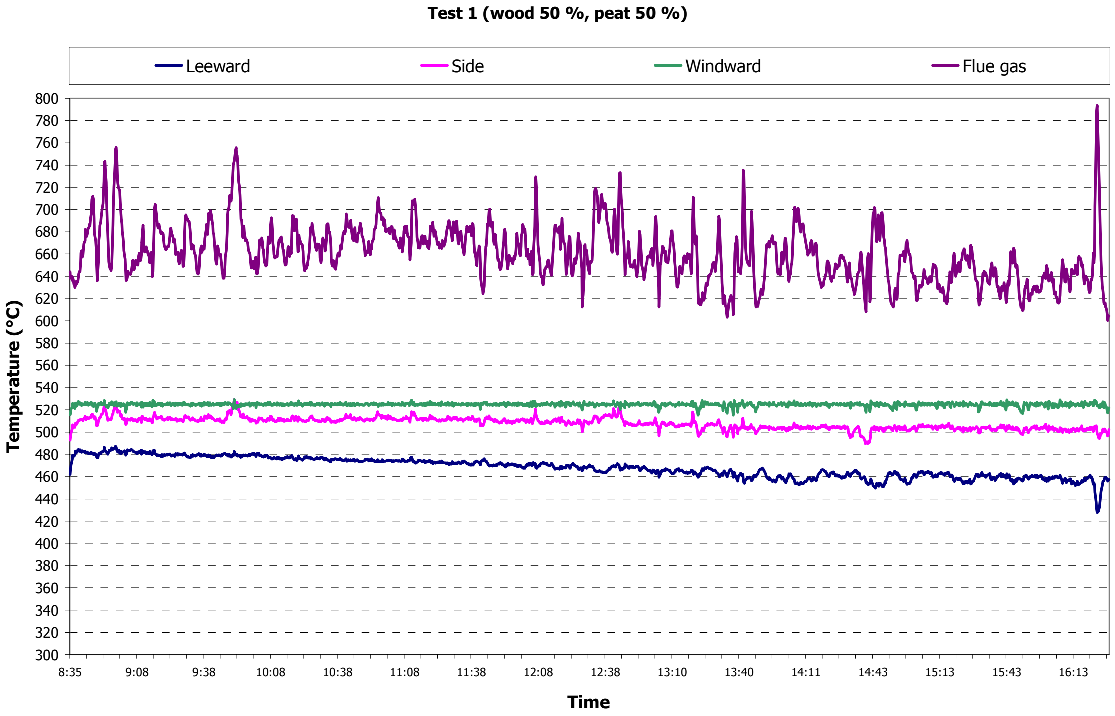

Figure A6. Probe's surface temperature behaviour in the BFB tests, test 1.

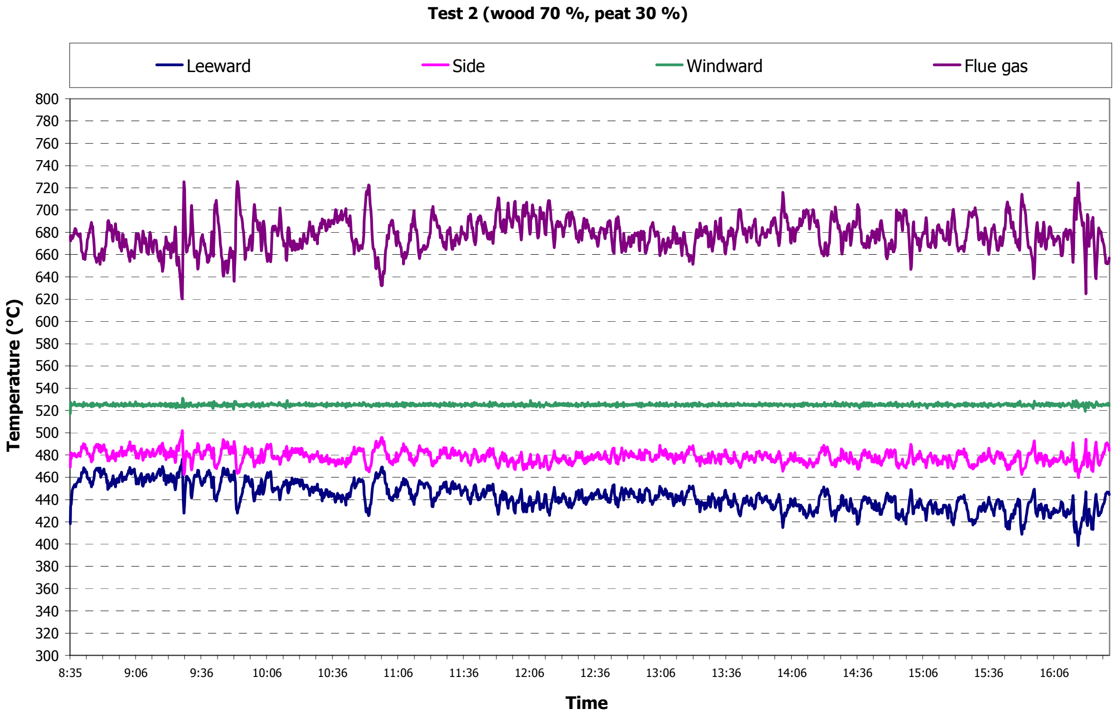

Figure A7. Probe's surface temperature behaviour in the BFB tests, test 2.

Appendix 3: Probe temperature measurements in BFB boiler 2(2)

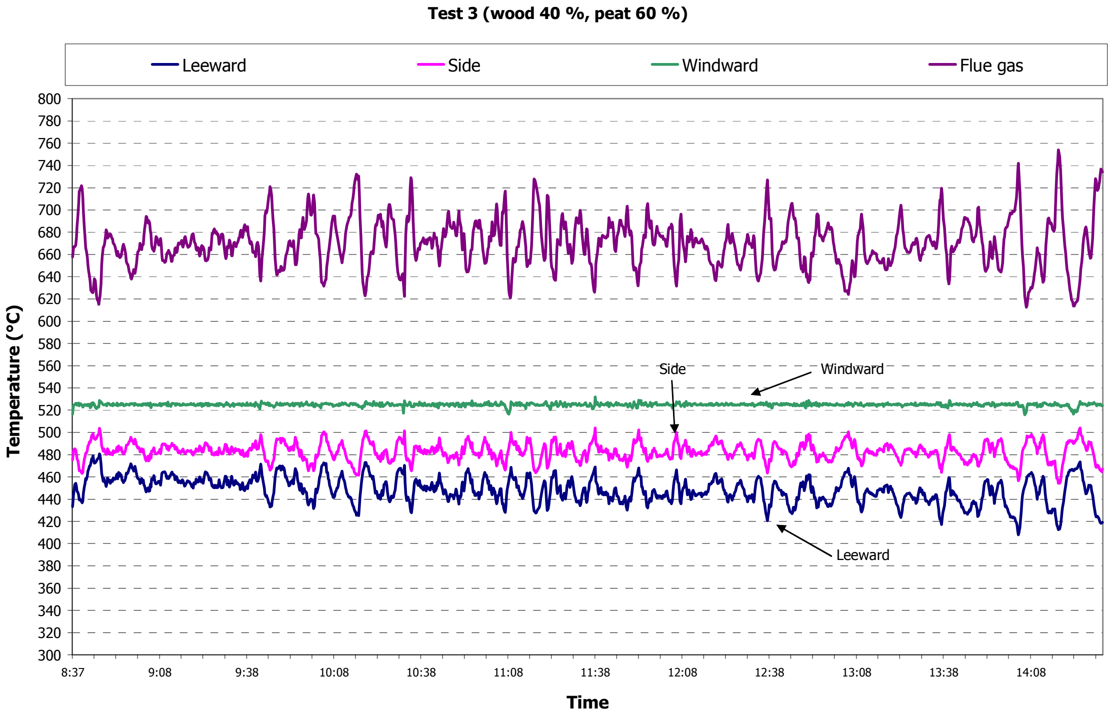

Figure A8. Probe's surface temperature behaviour in the BFB tests, test 3.

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