Fouling tendency and ash deposition evaluation in large-scale pulverised fuel power plants

Jana Kalivodova, Michiel Carbo, Aaron D. Fuller, Jörg Maier, Eva Miller, Emmanouil Karampinis, Silvia Lattanzi and Patrick Savat

Kurzfassung

Untersuchung zur Verschmutzungsneigung und Ascheablagerung in kommerziellen Kraftwerksstaubfeuerungen

Bei der Strom- und Wärmeerzeugung können die Potenziale von Biomasse als erneuerbare Energiequelle und damit zur Verringerung von Treibhausgasemissionen genutzt werden. Durch den Einsatz von Biomasse ändern sich jedoch die Verbrennungsbedingungen und das Ascheverhalten, d.h. die Mitverbrennung kann zu verstärkter Verschmutzung und Ablagerungen auf den Wärmetauscherflächen führen.

Im Rahmen des EU-DEBCO-Projects (Demonstration of large-scale biomass co-firing and supply chain integration) wurde eine Studie durchgeführt, um die Kesselleistung in drei kommerziellen Demonstrationsanlagen zu untersuchen und die Ascheablagerung, Verschmutzung und das Ausbrandverhalten bei der Verbrennung unterschiedlicher Biomassefraktionen zu beobachten. Kurzfristige Tests wurden mithilfe der mobilen Analysesonde von ECN durchgeführt. Die Ergebnisse haben gezeigt, dass dieses Verfahren wertvolle Informationen im Hinblick auf Verschmutzung und Ascheablagerung liefern kann.

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Introduction

Fossil fuels are our main sources of energy, unfortunately fossil fuels are also the primary culprit behind climate change. To limit the average rise in global temperature, the emissions from coal-fired power generation will need to be reduced by around 90 % until 2050 [1]. One possibility of CO_2 emission reduction is the implementation of high-efficiency, low-emission technology. Another attractive option is the use of biomass. Biomass for heat and power holds a large potential as a source of renewable energy and greenhouse gas emission reductions. Replacing coal with biomass can also support and stimulate the domestic biomass industry and supply chain [2]. At present, biomass co-firing has been tested worldwide in demonstration projects in coal-fired power plants [3]. Full-scale application of biomass co-firing depends strongly on the boiler performance in terms of its availability and the impact it has on steam parameters.

At high co-firing levels, slagging and fouling are expected to favour technical bottlenecks [4, 5]. Biomass-derived ashes contain substantial amounts of potassium and chlorine that can result in fouling, formation of the ash deposits on heat transfer surfaces, and subsequent corrosion problems. Furthermore in most industrial situations, the inefficiency of heat transfer resulting from fouling has a direct link to excess fuel consumption.

The objective of this study was to focus on the monitoring of boiler performance according to the variations of operational parameters related to different fuel input quality (ratio of biomass/coal), boiler load, etc. The boiler performance was monitored in three demonstration plants in order to assess ash deposition, fouling, and burnout under co-firing operating condition at different biomass shares.

Experimental setup and methods

Four joint large-scale short-term measurement campaigns (JMC) were carried out within the DEBCO (Demonstration of large-scale biomass co-firing and supply chain integration) project. The study was focused on monitoring the boiler performance according to the variations of operational parameters related to different fuel input quality (ratio of biomass/coal), boiler load, etc. Three demonstration plants were monitored in the short term in order to assess the boiler performance and mainly the ash deposition, and fouling issues under the co-firing operating condition at different biomass shares.

The first campaign was carried out in the Rodenhuize power plant (Belgium) in October 2009 and the second measurement campaign took place in the Kardia power plant (Greece) in October 2010, followed by the campaign in the Fusina power plant (Italy).

Measurements of the ash deposition and fouling propensities of the ash in the boiler have been investigated employing ECN's mobile diagnostic probe. These measurement activities were focused on ash deposit formation on the superheater tubes of the boilers at a high share of co-firing different types of biomass. Usually, sampling locations for the mobile diagnostic probe were selected in the vicinity of the heat exchangers. The ash deposit formation, chemical composition of particulate matter, flue gas temperature, and online fouling data inside the boiler were monitored.

Mobile industrial deposition probe

The mobile diagnostic probe was primarily developed to investigate the fouling behaviour of fly ash in the high temperature region of an industrial pulverised fuel-fired boiler. Next to deposit sampling, its influence on heat transfer from flue gas to boiler tubes can be investigated in real time.

To withstand the regime of the high-temperature region of a boiler, the probe consists of a water-cooled lance, manufactured from high-grade stainless steel, in which several instruments are positioned. These instruments are air-cooled, thus enabling independent selection of the lance temperature level at which the measurements will be performed. A photograph of the work end of the probe is given in Figure 1. The biggest advantage of the mentioned deposition probe is the compact size and simplicity. The following measuring instruments are located in the probe:

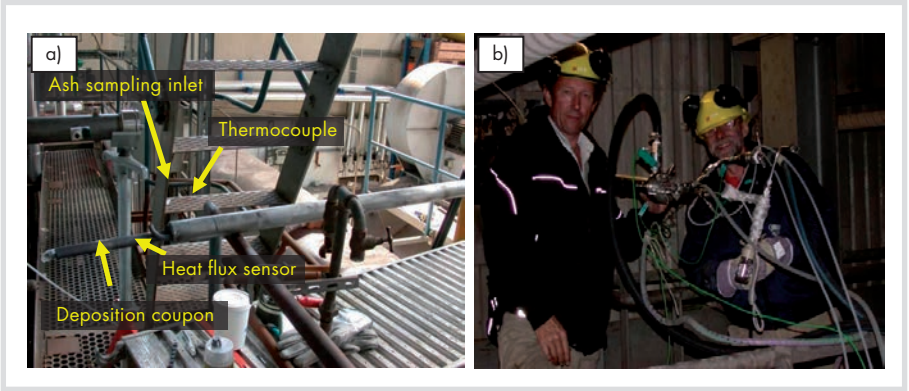

Fig. 1. Mobile diagnostic probe – a) the work-end of the probe; b) sampling locations in the boilers of the DEBCO Rodenhuize demonstration plant.

– deposition coupon, consisting of a temperature controlled tube-shaped piece on which fly ash deposits,
– heat flux/surface temperature sensors, and
– thermocouple.

The deposition coupon is detachable; and after embedding/preparation further investigations can be made be means of SEM/EDX analysis. The tube material can be chosen freely, thus simulating various stages of the boiler. Materials used so far include SS310/316 and several Inconel high alloys.

The fourfold of heat flux/surface temperature sensors is placed just before the deposition substrate. The heat flux/surface temperature sensors can measure on-line, in all four axial directions, the heat transfer to the simulated boiler tube. These sensors are also used to control very precisely the local tube wall temperature, which can be varied between 300 and 750 °C. The flue gas temperature can be measured independently by a retractable thermocouple placed close to the deposition coupon. The furnace/boiler fly ash samples can be collected from the flue gas flow by means of a quenched, isokinetic dust sampling system. To prevent condensation in the sampling tube the temperature of the flue gas sample is kept above the condensation temperature at all times.

As mentioned earlier, the main goal was to investigate the influence of the fuel composition on ash deposit formation onto a simulated superheater tube with variable surface temperature. For this project, the two materials for deposition coupons have been selected; stainless steel grade 310 – code B and high nickel alloy 617 – code D.

Fouling propensity

In order to relate the heat-flux data in a more independent manner with the fuel properties or the particular combustion conditions, the so-called fouling factor Rf can be calculated from the raw on-line data, which quantify the ash deposit heat transfer resistance:

$$R_f = \frac{1}{R_1} - \frac{1}{R_0} = \frac{T_g - T_c^1}{HF_1} - \frac{T_g - T_c^0}{HF_0} \quad (1)$$

where:

R_f = fouling factor, $(K \cdot m^2)/W$,

R_1 = ash deposits heat transfer resistance after time $t = t_1$, $W/(K \cdot m^2)$,

R_0 = initial heat transfer resistance (of the tube or ash deposits) after $t = t_0 = 0$, $W/(K \cdot m^2)$,

T_g = flue gas temperature, K,

T_c = coolant medium temperature inside the probe, K,

HF_1 = heat flux to the sensor after time $t = t_1$, W/m^2,

HF_0 = initial heat flux to the sensor $t = t_0 = 0$, W/m^2.

Next to the physical deposit samples, data on its influence on the heat transfer have been processed and a fouling factor for each experiment has been calculated [6].

The point at which the temperature of the deposition substrate stabilised was taken as the beginning of the heat flux measurement. The heat flux decreases after a certain period. When sufficient ash has been deposited, positive Rf values are found.

Sampling locations in the boiler

Test were usually carried out at one location of the boiler, only in the Fusina power plant the measurements were performed at two locations. The probe accesses the boiler horizontally. The probe was inserted into the boiler perpendicularly to the flow and to the penetration depth of 1500 mm. More details are given further below.

Chemical analyses of the deposited ash samples

After visual observation, photographic record and thickness measurement were performed. The deposited ash on each deposition coupon was fixed with epoxy resin. Subsequently the samples were cross-sectioned and subjected to metallographic preparation. Samples were prepared in a water-free environment to prevent any dissolution, recrystallisation, or removal of water soluble salts. A JEOL FEG-SEM with a coupled EDX system was used to study composition and structure of the deposited ash on the coupon. Each cross section of the coupons was thoroughly inspected all around the circumference. The fly ash has been usually impacted on two sides (the wind – W and the lee side – L) of the substrate. Next to the morphology, also the elemental composition (EDX) of each side of the deposit was analysed.

Results and discussion

Chemical characteristics of DEBCO project fuels

Particularly the quantity and quality of biomass ash depends on largely different factors. The kind of biomass fuel, its physical characteristics (e.g. particle dimensions, bulk and energy densities, gross and net calorific value, moisture content), and chemical composition (e.g. presence of macro and micro elements) influence the whole process of biomass utilisation. Several types of pulverised fuels were combusted in demonstration plants during the short-term joint measurement campaigns:

– wood and hard coal – Rodenhuize power plant,
– cynara and lignite – Kardia power plant, and
– hard coal and RDF – Fusina power plant.

Prior to the tests in the boilers, the existing ash indices, used for the evaluation of slagging and fouling tendencies of coals, were applied on chemical composition of project fuels. Clearly the indication based on the slag viscosity index is not in line with the observation that was obtained during the measurements on site. Although several attempts in the development of the ash indices for biomass ashes have been undertaken, current indices are not sufficient and further development is needed.

Mechanisms of deposit formation

Ash particle inertial impaction is the dominant process in high-temperature slag formation and for larger ash particles. The rate of deposition by impaction is a function of the particle flux and of the deposition efficiency, which, in turn, is dependent on the degree of fusion of the particles and/or the deposit surface. The condensation of volatile inorganic species, in vapour or fume form in the flue gases, on cooled surfaces is the principal driving mechanism for convective pass fouling, and this is of particular importance for biomass materials due to the relatively high levels of volatile species in these fuels [7].

The ash content of tested biomass fuels varies in a broad range from around 1.3 wt% (d.b.) for Rodenhuize woody biomass up to 20.0 wt% (d.b.) for RDF (refuse derived fuel). There are generally two sources for inorganic ash forming matter in biomass

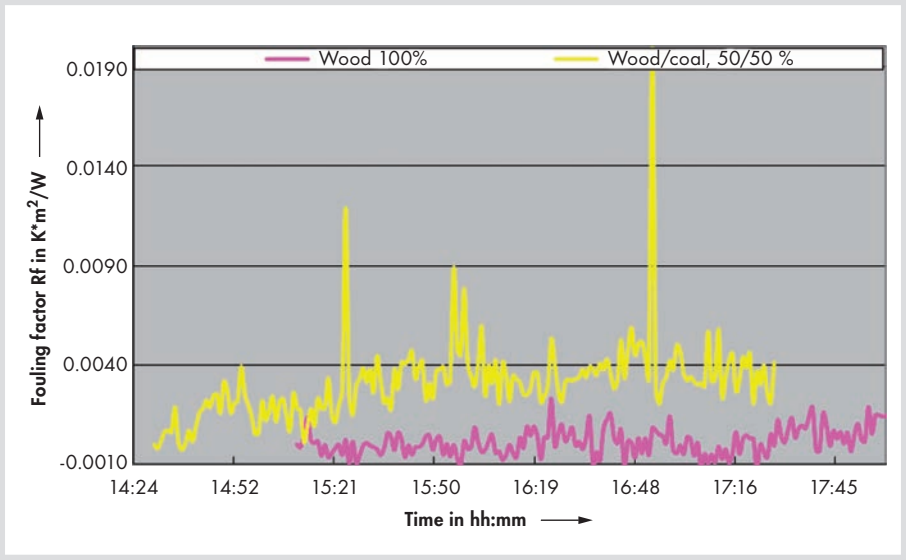

Fig. 2. Online heat flux measurement translated in fouling factor; comparison 100 % wood and 50/50 wood/coal scenario.

fuels. On the one hand, ash forming elements originate from the plant itself, as they are part of the structure of the fibres (e.g. Si, Ca) or they are macro or micro plant nutrients (e.g. K, P, S, Zn). On the other hand, inorganic matter in biomass fuels can also come from contamination with soil, sand or stones. The ash content of the fuel is essential for the choice of appropriate combustion and gas-cleaning technologies.

Major (Al, Ca, Fe, K, Mg, Na, P, Si, Ti) and minor (As, Ba, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb, Tl, V, Zn) elements form, together with Cl and S, the ash components. These elements are of relevance for ash melting, deposit formation, fly ash, and aerosol emissions as well as corrosion (together with S and Cl) and utilisation/disposal of the ashes.

High alkali (potassium) and Si content typically gives low ash melting temperatures while Mg and Ca increase ash melting temperature. Si in combination with K and Na can lead to the formation of low-melting silicates in fly ash particles. Moreover, low melting mixtures of alkali and heavy metal chlorides can also cause corrosion by sulphation reactions [8]. The smaller the amounts of K and Na in the fuel, the better the performance of the ash melting behaviours.

Minor ash-forming elements occurring in various biomass fuels are Fe, Al, Mn, and heavy metals. After the combustion of biomass fuels the majority of the heavy metals are bound in the ash. The heavy metal concentrations in biomass ashes are of considerable importance for sustainable ash utilisation. The ecologically-relevant elements are primarily Cd and, to a smaller extent, Zn. Ashes from straw, cereals, grass, and olive residues contain significantly lower amounts of heavy metals than wood and bark ashes. This can be explained by the long rotation period of wood, which enhances accumulation, higher deposition rates in forest, and lower pH of the forest soils that increase the solubility of most heavy metals.

During the combustion process, sulphur contained in solid biofuel forms mainly gaseous SO_2 (to a certain extent also SO_3) and alkali as well as earth-alkali sulphates. Due to the subsequent cooling of flue gas in the boiler section of the combustion plant, SO_x forms sulphates and condenses on the heat exchanger surfaces or forms fine fly ash particles, or reacts directly with fly ash particles deposited on heat exchanger surfaces (sulphation). The efficiency of sulphur fixation in the ash depends on the concentration of alkali and earth-alkali metals (especially Ca) in the fuel (fuels like wood and lignite can contain high Ca amounts and therefore can cause a high S fixation).

100 % wood and 50 % wood/ 50 % coal, prior to boiler retrofit – Rodenhuize, Belgium 2009

The ash deposition and fouling tendency under different biomass co-firing conditions has been studied at the Rodenhuize power plant. During the JMC in 2009 two firing scenarios were applied: the high share co-firing of wood with coal (50/50 wt.%) and 100 % wood combustion. In addition, natural gas has been also co-combusted. During the course of the measurement campaign a set of several deposition samples were collected together with the samples of raw ash and fly ash.

The fouling propensity of studied samples from RH campaign is dependent on fuel composition (ash content) as well as the surface temperature of the simulated SH tube. The worst fouling propensities were observed for a sample exposed during (wood and coal) co-firing, at surface temperature of 500 °C, followed by a sample also from co-firing conditions (wood and coal) at a surface temperature of 570 °C and a sample from wood combustion at a sample surface temperature of 500 °C. The least problematic deposit conditions with respect to fouling propensities of the ash were during wood combustion and a deposit surface temperature of 570 °C (Figure 2).

Clearly, at least two main deposition mechanisms can be distinguish on the deposition coupon. The impaction is the prevailing deposition on the wind side of the deposit while mainly condensation on the lea side of the deposit was observed.

Even though that no significant build-up of the deposit has been observed, the fouling-related compounds (KCl, K_2SO_4) were identified. Those components could contribute to increase the sticking probability of the deposit by the formation of the low melting compounds. The bulk of the ash consists of the elements Si, Ca, Mg, and Al during the co-firing scenario. A higher concentration of potassium, sulphur, and chlorine can be observed in deposited ash when 100 % wood was fired. Although phosphorus is a non-volatile element and under combustion conditions it is for a greater part collected in the bottom ash, phosphorus was also detected in all studied fly ash deposits. It has been observed that this element is clearly present in the sub-micron particles, primarily associated with calcium.

Figure 3 shows mapping images of the B18 (50/50, wood/coal) substrate, obtained by energy dispersive X-ray spectrometry (EDX). The distribution of the elements indicates presence of alumina silicates accompanied by potassium, sodium, and magnesium. Close to the metal interface sulphur is incorporated in the surface of existing larger agglomerates. These agglomerates contain besides calcium also magnesium. It is also clear that potassium, although also present in the earlier mentioned "free" fine particulate, is for a large part also present in the alumina silicate matrix. In this sample, the concentration of chlorine remained below the detection limit.

10 % cynara/ 90 % lignite – Kardia, Greece 2011

During the measurement campaign in the Kardia boiler the ash deposit formation and fouling propensities of the deposits were studied under two combustion scenarios: 100 % lignite and a co-firing scenario with approximately 10 % of the biomass cynara (thermal share). During the visual inspection of the deposition samples, no significant differences between various firing scenarios have been observed.

Particle sampling in the boiler was performed using a water-cooled mobile di-

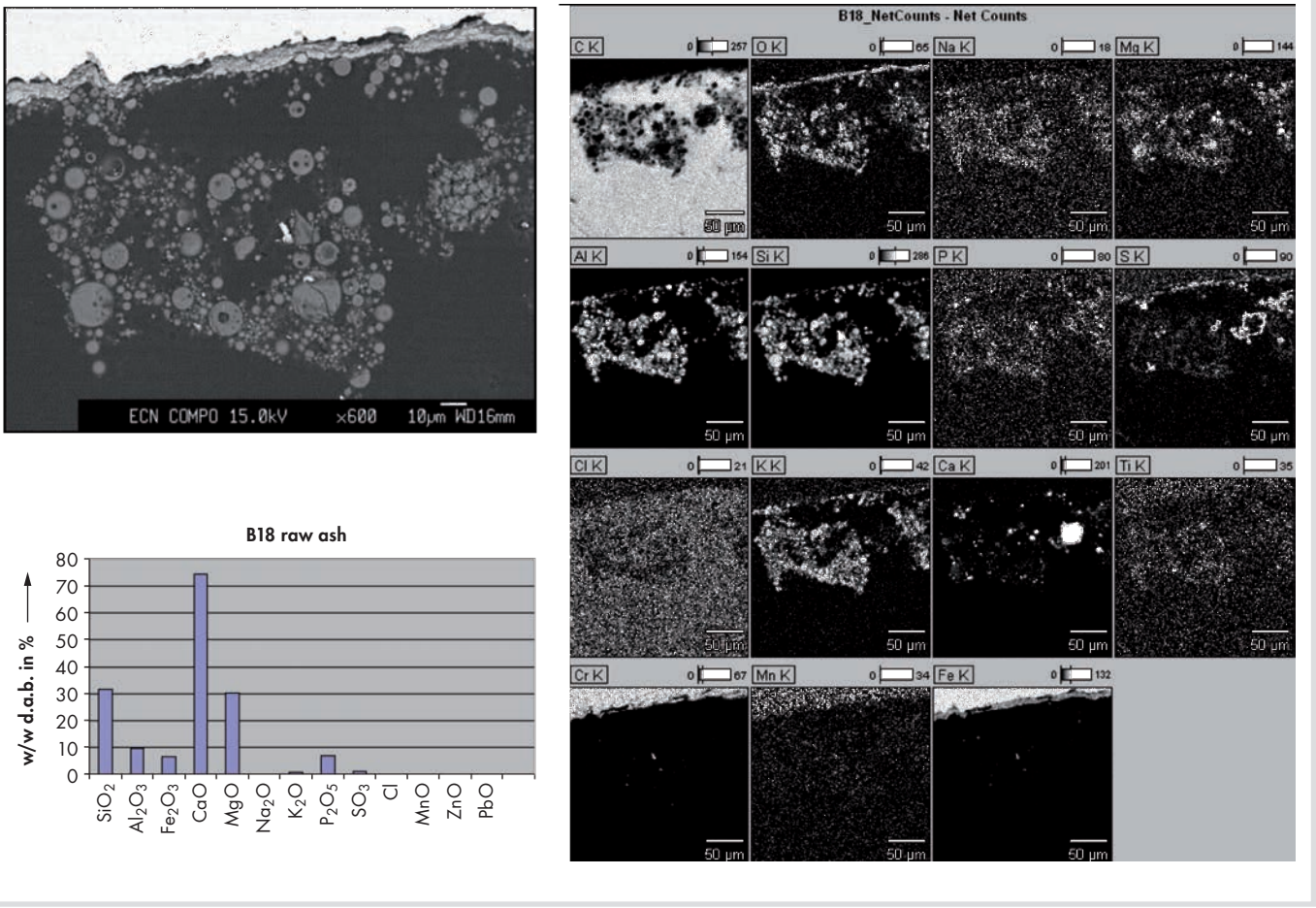

Fig. 3. SEM/EDX mapping of deposited ash on substrate B18; 50/50 wood/coal; the raw ash SEM/EDX analysis.

agnostic probe at the superheater level of 42 m. Deposit samples at the same level were also collected with a residence time of 4 to 6 hours. As regards particle sampling, co-firing appeared to lower the loss-on-ignition, thus indicating better combustion conditions.

For both lignite-fired operation and co-firing, the deposit probes indicated a high tendency for deposit formation and fouling, as a result of the high ash content of lignite. However, sintering was not observed and conventional cleaning methods, e.g., soot-blowing, are expected to be sufficient for the removal of deposits. The deposits were mostly on the leeward side and were formed by a fine powdery ash layer.

Overall it can be concluded that under 100 % lignite and 10/90 cynara lignite scenario, no significant changes in fouling characteristics have been observed. The comparison of the online heat flux measurement translated to fouling factor is given in Figure 4. Furthermore deposits, the reference case 100 % lignite as well as 10/90 cynara/lignite collected during combustion are shown in Figure 5. The surface temperature during the test was 500 °C. The deposit is composed of relatively coarse particles.

The results of the chemical composition of the deposited ashes collected during both combustion scenarios are given in Figure 6. Large particles in the deposits were found to be composed mostly by calcium oxide, silicates (including potassium silicates during co-firing), and $CaSO_4$, while the finer particles also included iron oxides and sulphates. Chlorine was not detected in the deposits in significant quantities; however, a high concentration of sulphur in the deposits, as a result of calcium auto-capture was found. It should be noted that during firing of lignite, black, unburnt

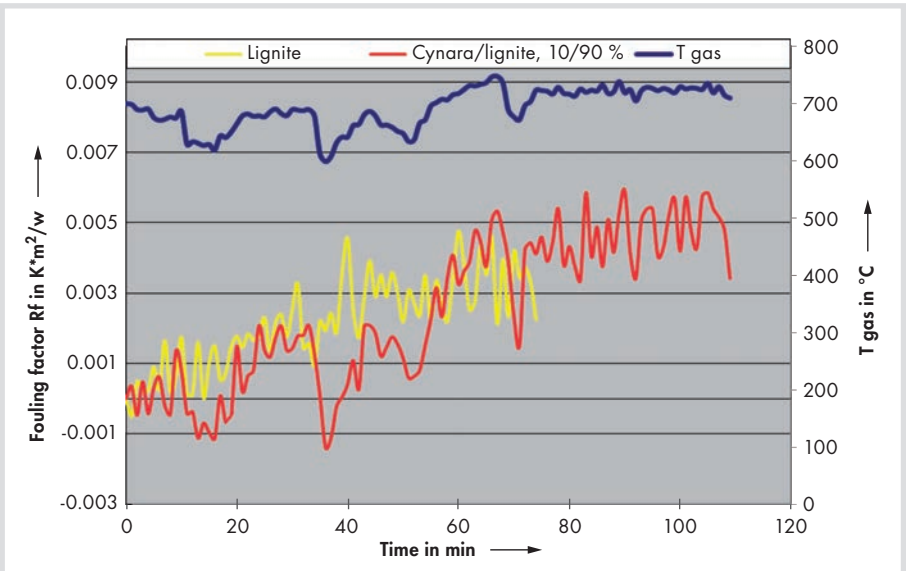

Fig. 4. Online heat flux measurement translated in fouling factor; comparison 100 % lignite and 10/90 cynara/lignite scenario.

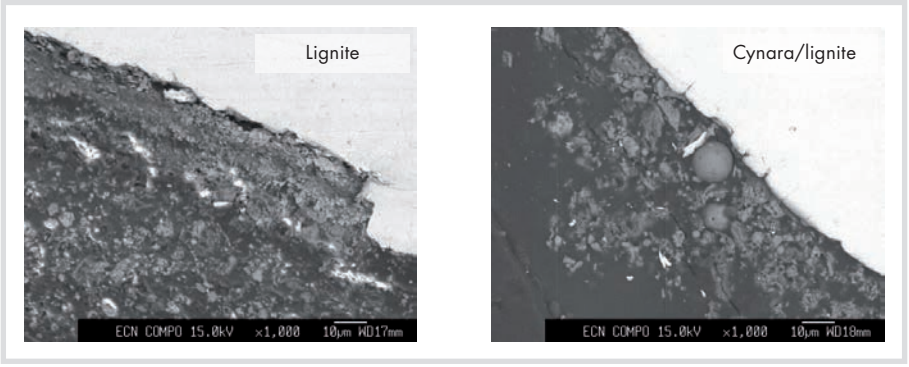

Fig. 5. SEM/EDX images of deposited ash on substrate B27 – lignite; substrate B28- 10/90 cynara/lignite combustion scenario.

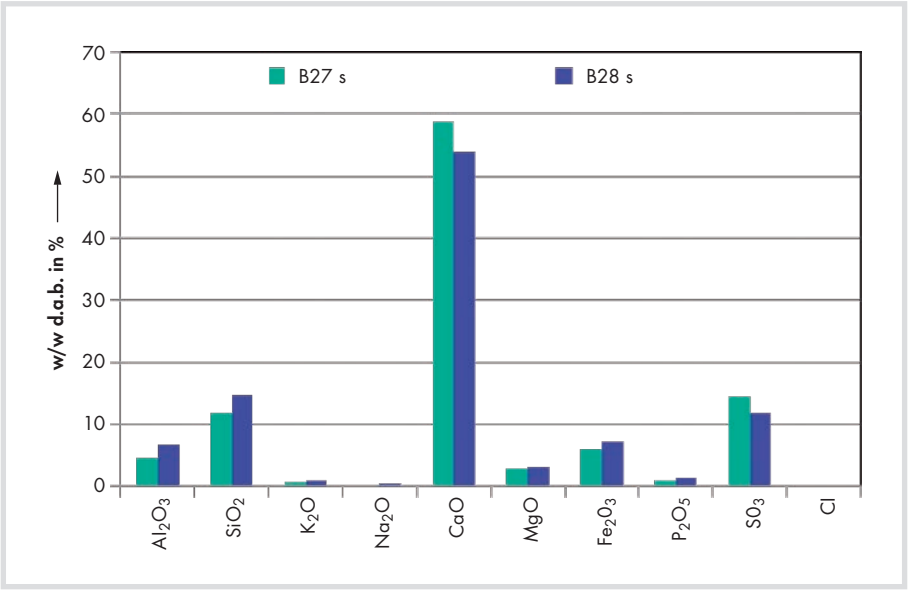

Fig. 6. Major elements concentration; deposited ash substrate B27 – lignite; substrate B28- 10/90 cynara/lignite combustion scenario.

carbon particles were found in the water-cooled probe deposits.

Sulphur was identified not only in the ash layer, but also in the oxide layer of the deposition substrate. It is known that sulphur containing salts in the form of fuel ash, attack the protective oxide film of the heat exchanging material, resulting in a severe chemical damage.

5 % RDF/95 % coal – Fusina, Italy 2011

The fouling- and ash deposition-related tests have been performed at two boiler levels of unit 4 of the Fusina power plant when RDF was co-fired with coal. ECN has been involved in the tests related to the boiler performance in terms of ash formation, slagging, and fouling behaviour of the deposited ashes on heat exchanging areas.

The ash deposition in the boiler employing was measured with ECN's mobile deposition probe in the superheater area of the boiler (at 5th floor – 38 m and 7th floor – 42 m). Besides particulate sampling, flue gas temperature measurements, deposit build up as well as the influence of the deposit on the heat transfer were monitored in real time by means of heat flux sensors. The surface temperature of the deposition coupon simulating SH conditions was set at 500 °C, 570 °C, 630 °C, and 700 °C. The two lower temperatures correspond to steam conditions in the current installations. The temperature 630 °C has been selected as a reference case for a new advanced installation and the highest probe surface temperature has simulated uncooled surfaces. An example of the obtained deposit during the co-firing scenario RDF/coal (5/95) at two boiler levels is shown in Figure 7.

The fouling propensity of studied samples from the Fusina campaign are dependent apart from the fuel/ash chemical composition on the surface temperature of the simulated SH tube and the flue gas temperature. The worst fouling propensities were observed for a sample exposed at 38 m of the boiler and at the highest surface temperature. Obviously the ash deposit collected at 38 m (higher flue gas temperature – Figure 7b)) has been built up relatively fast and it has been severely sintered. While the ash deposits collected on probe during deposition/fouling tests at 42 m are powdery, relatively thin and might be easily removed from the SH surfaces by conventional cleaning.

A significant deposit formation and fouling have been observed at deposition substrate at a surface temperature of 500 °C (Figure 8).

The filter ash deposits were composed of relatively big particles, containing significant amounts of unburnt carbon, aluminosilicates, calcium, and iron. During the first day of the measurement campaign (coal combustion) only the particulate matter in the flue gas has been sampled and analysed. There were no significant differences in chemical composition of collected ashes between 100 % coal combustion and 95/5 (coal/RDF) firing scenario observed.

Also during the deposition test with co-firing of RDF, at various substrate surface temperature no significant changes in the chemical composition can be presented. The collected ash particles were spherical with homogenous composition, containing mainly alumina silicates with Ca, Fe, P, and potassium.

Conclusions

Co-firing biomass with coal in large pulverised coal-fired (PF) boilers is an attractive option to increase biomass utilisation and reduce CO_2 emissions. Nevertheless at high co-firing shares, slagging and fouling are expected to be the major technical bottlenecks.

In this paper, fouling and the ash deposit formation in pulverised fuel boilers of the Rodenhuize, Kardia, and Fusina power plants were studied. It must be noted that

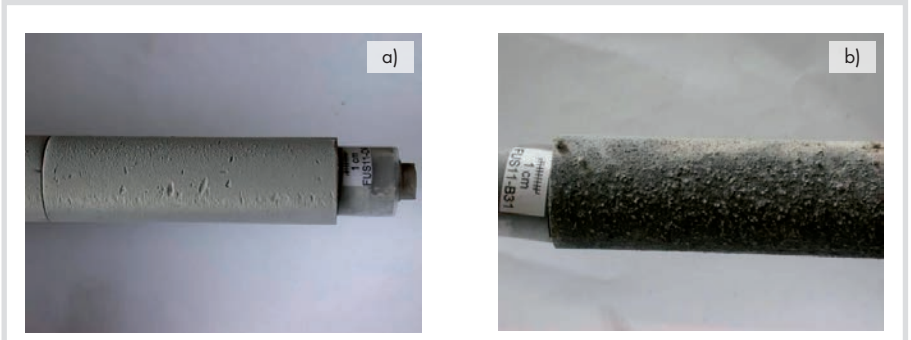

Fig 7. a) deposition test- 42 m; b) deposition test – 38 m; coal/RDF (95/5) scenario.

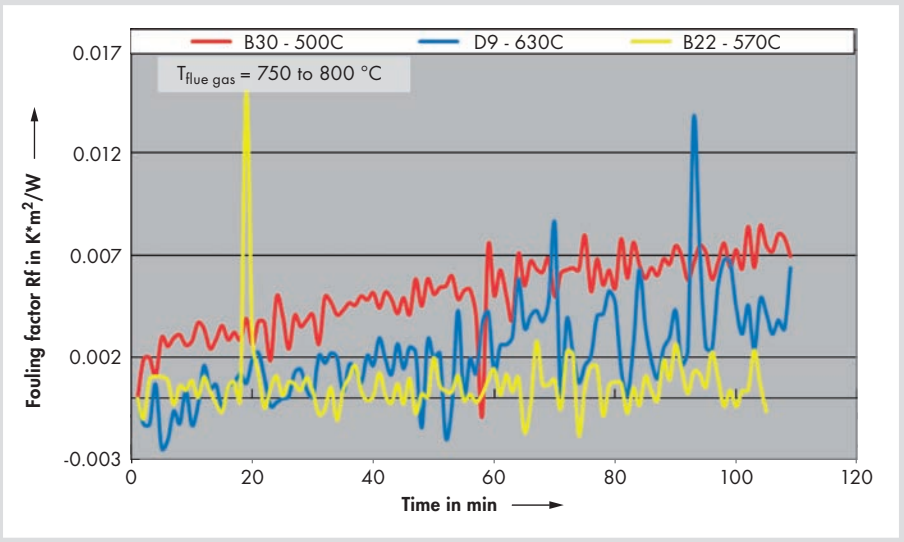

Fig. 8. Online heat flux measurement translated in fouling factor 5/95 RDF/coal; comparison substrate surface temperature 500, 570 and 630 °C.

100 % biomass combustion has been successfully demonstrated in the Rodenhuize power plant and no significant increase of fouling and deposit formation was observed. The ash deposit can be eliminated by optimised cleaning. Fouling propensities related to surface temperature and fuel can be ranked in the following order: bio/coal at 500 °C > bio/coal at 570 °C > 100 % bio 500 °C > 100 % bio at 570 °C. The ash deposits in the convective pass collected during the join measurement campaigns can be identified as loose to bound. There was not a deposit of the slag character observed. A good conformity of the results from short-term large-scale tests using the mobile diagnostic probe has been achieved. This characterisation methodology next to the lab-scale tests can provide valuable information related to the ash deposit formation and fouling prediction in the large-scale power plant boilers.

Acknowledgments

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