



Fate of Phosphorus During Co-Combustion of Solid Biofuels

Patrycja Piotrowska, Maria Zevenhoven, Mikko Hupa
Process Chemistry Center
Abo Akademi University
Turku, Finland

Kent Davidsson, Lars-Erik Amand
Department of Energy and Environment
Division of Energy Technology
Chalmers University of Technology
Gothenburg, Sweden

Edgardo Coda Zabetta, Vesna Barisic
R&D Department
Foster Wheeler Energy Oy
Varkaus, Finland

Presented at
20th International Conference on Fluidized Bed Combustion
Xian City, China
May 18 – 20, 2009

FATE OF PHOSPHORUS DURING CO-COMBUSTION OF SOLID BIOFUELS

Patrycja Piotrowska^{*1}, Maria Zevenhoven¹, Mikko Hupa¹,
Kent Davidsson², Lars-Erik Åmand²,
Edgardo Coda Zabetta³, Vesna Barišić³

¹ Process Chemistry Centre, Åbo Akademi University, Turku, Finland

² Department of Energy and Environment, Division of Energy Technology, Chalmers University of Technology, Gothenburg, Sweden

³ R&D Department, Foster Wheeler Energia Oy, Varkaus, Finland

* corresponding author: ppiotrow@abo.fi

Abstract: Recent studies show that deposit formation and agglomeration in fluidized bed boilers may be aggravated by a high phosphorus content besides alkali metals, chlorine and sulphur in a fuel. This paper presents the fate of phosphorus during co-combustion of wood chips and wood pellets with rapeseed cake pellets, a high phosphorus fuel in a 12MW CFB boiler. 12 hour tests with 12% and 18% (energy basis) of rapeseed cake with wood were performed with and without limestone addition. All fuels were characterised by means of standard fuel analyses combined with chemical fractionation. Retrieved ash samples were analysed using wet chemical analysis complemented with SEM/EDXA. Gaseous alkali metal chlorides as well as HCl and SO₂ were measured upstream of the convective pass at a flue gas temperature of 800°C where also the deposit samples were collected with a deposit probe. The composition of deposits was studied with SEM/EDXA. Analyses of bed material particle cross-sections showed phosphorus compounds present within a K-silicates matrix between the agglomerated sand particles, indicating direct attack of gaseous potassium compounds on the bed surface followed by adhesion of rich in phosphorus ash particles. Build-up of the deposits took place mainly on the windward side of the probe; where up to 14wt-% of phosphorus was present. SEM/EDXA shows that rapeseed cake addition caused an increase of K, Na besides P indicating presence of low melting phosphate salts in the deposits. During limestone addition in the deposit samples the increase of Cl could be noticed however no significant change in P content was observed. This paper shows that agglomeration and fouling when co-firing rapeseed cake may be linked to its high content of organically bonded phosphorus - phytic acid salts; together with high content of water soluble fraction of alkali metals chlorides and sulphates in the fuel mixture.

Keywords: rapeseed cake, co-combustion, phosphorus, agglomeration, fouling

INTRODUCTION

In order to save fossil fuels and prevent global warming, biomass, the main one among renewable sources of energy, have been given increased attention. Challenges connected with biomass combustion in fluidized bed boilers, are caused by ash chemistry which may induce agglomeration, fouling and corrosion. It is commonly known that alkali metals, chlorine and sulphur are the main factors lowering the first melting temperature of ash (Hupa M., 2008; Jenkins B.M. et al., 1998). However, recent studies showed that these problems may be aggravated by a high phosphorus content in the fuel (Barišić V. et al., 2008; Coda Zabetta E. et al., 2008; Lindström E. et al., 2007; Nevalainen H. et al., 2008). An interesting example of a fuel rich in phosphorus, alkali metals and chlorine is Rapeseed Cake, a residue from the production of Rapeseed Methyl Ester (RME). Interactions of phosphorus with other ash forming elements during combustion are not fully understood and are subject of this paper.

The work is a continuation of a study on the role of limestone in preventing agglomeration and slagging during CFB combustion of high-phosphorus fuels (Barišić V. et al., 2008). Here the investigation covers both agglomeration and deposit formation during co-combustion of a mixture of wood chips and wood pellets with rapeseed cake pellets. Results are supplemented with gaseous chlorides, sulfates, and alkali metal chlorides present in the beginning of the convective pass.

EXPERIMENTAL SET-UP

Boiler

A 12 MWth CFB boiler, shown in figure 1, was used for the tests. The boiler is large enough to be representative for a semi-industrial CFB boiler and is described in detail elsewhere (*Amand L.-E., 2004*)

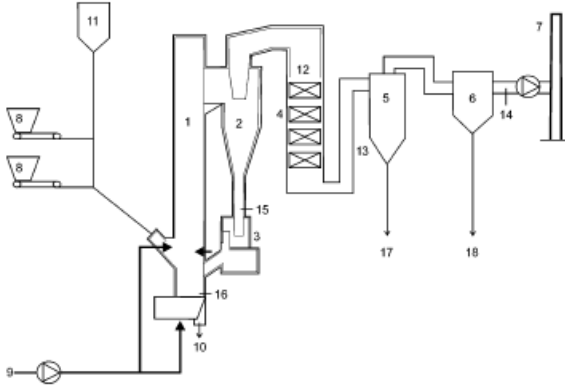


Figure 1 Schematic of the boiler. 1: furnace, 2: primary cyclone, 3: particle seal, 4: convection pass, 5: secondary cyclone, 6: bag-house filter, 7: stack, 8: fuel bunkers, 9: air, 10: bottom material removal, 11: bed sand, 12: measurement spot before convection pass, 13: measurement spot after convection pass, 14: measurement spot after bag-house filter, 15: cyclone leg material sampling spot, 16: bed material sampling spot, 17: secondary cyclone ash sampling, 18: bag-house filter ash sampling.

Combustion experiments

The experimental plan consisted of 4h preliminary tests and 12h tests listed in Table 1. The varied parameters were the rapeseed cake (RC) ratio and the addition of limestone (CaCO_3) to the bed consisting of silica sand. During the tests wood chips (WC) and wood pellets (WP) were used as a base fuel. The highest share of RC was co-combusted during a 4h test here named as WNL45_preliminary. This test was preceded with two other 4h preliminary tests during which 12 and 21% (energy basis) of RC was co-fired respectively. During tests WNL12 and WL18 a RC ratio of 12 and 18% (energy basis) was used, respectively. In the latter test limestone was added. Both tests lasted approximately 12h and were preceded with the reference tests, reference_WNL and reference_WL, when no RC was co-combusted however limestone was used in the latter one. The limestone was taken from Ignaberga in south Sweden. The operational conditions were chosen to represent a typical case of an industrial CFB boiler with a bottom bed temperature of 850°C and an excess air ratio

of 1.2. The flue gas temperature was maintained at the level of 800°C before the convective pass and around 150°C in the secondary cyclone and bag house filter in all tests. Samples from all outgoing solid material streams - namely bed material, secondary cyclone and bag filter, were collected at the end of each test. Deposit samples were collected on steel rings which were fitted on an air-cooling probe situated in the middle of the flue-gas stream before the convective pass. The surface temperature of the steel rings

Table 1 Rapeseed cake and wood co-combustion tests

| test name | test duration [h] | RC ratio [% _{en}] | Fuel load [kg ds/h] | | Ash with fuel ¹ [kg ash/h] | | Lime addition [kg/h] | Bed regen. [kg sand/h] | ash balance ² |
|-------------------|-------------------|-----------------------------|---------------------|-------|---------------------------------------|-------|----------------------|------------------------|--------------------------|
| | | | RC | WP+WC | RC | WP+WC | | | |
| WNL12_preliminary | 4 | 12 | 136 | 1175 | 9,4 | 5,1 | 0,0 | 0,0 | 47,2 |
| WNL21_preliminary | 4 | 21 | 229 | 1048 | 15,9 | 4,5 | 0,0 | 0,0 | 37,2 |
| WNL45_preliminary | 4 | 45 | 524 | 771 | 36,3 | 3,3 | 0,0 | 4,4 | 37,5 |
| Reference_WNL | 16 | 0 | 0 | 1309 | 0,0 | 6,4 | 0,0 | 0,0 | 160,1 |
| WNL12 | 13 | 12 | 135 | 1190 | 9,6 | 4,9 | 0,0 | 0,0 | 66,7 |
| Reference_WL | 14 | 0 | 0 | 1328 | 0,0 | 7,0 | 54,5 | 0,0 | 52,9 |
| WL18 | 12 | 18 | 196 | 1101 | 14,0 | 7,6 | 54,9 | 0,6 | 38,1 |

RC – rapeseed cake; WP – wood pellets; WC – wood chips; %_{en} – percentage on energy basis;

¹ – ash content in the fuel measured at ChUT; ² – $(\text{ash}_{\text{out}} / \text{ash}_{\text{in}}) * 100\%$

was set to 500°C during all three preliminary tests and 480°C in case of other 12h tests to simulate a superheater tube.

Analyses of gases

In the convective pass gaseous HCl and SO₂ were measured with Fourier Transform Infrared (FT-IR) spectroscopy. In addition gaseous alkali chlorides were continuously measured at this position using the In-situ Alkali Chlorides Monitor (IACM) developed by Vattenfall. The instrument uses a sampling time of 5-10 seconds. The detection limit at a 5 meter measuring length (width of the flue gas channel) is 1 ppm for KCl and NaCl (*Kassman H. et al., 2006*). HCl emissions were measured by means of FT-IR and SO₂ with non dispersive ultra-violet (NDUV) analyzer; the results were used for the mass balances calculation over the boiler.

Analyses of fuels and ash samples

Fuel samples (WP, WC and RC) were analyzed using standard fuel analysis and chemical fractionation. Chemical fractionation is a method based on selective consecutive leaching by water (H₂O), 1M ammonium acetate (NH₄Ac) and 1M hydrochloric acid (HCl) (*Baxter L.L., 1994; Benson S.A., 1985; Skrifvars B.-J. et al., 1998; Zevenhoven M. 2001, Zevenhoven M. et al., 2001, 2004*). The increasingly aggressive solvents leach samples into a series of four fractions (including the unleached residue). The untreated samples, the liquid fractions and the remaining solids were analyzed by an external laboratory according to Swedish standards. Ash samples from all outgoing solid material streams were collected and analyzed quantitatively according to ASTM D3683 and ASTM D3682 by the same external laboratory. Additionally semi quantitative analyses of bottom ash and deposit samples (from the windward (0°) side of the deposit ring) were performed by means of SEM/EDX. Hereto, ash samples were mounted on carbon tape and covered with a thin carbon layer. Also the bed material particle cross-sections were studied by means of SEM/EDX spot analyses. Hereto investigated samples of bed material particles were embedded in epoxy and polished with ethanol to obtain cross-sections and smooth surface that was consecutively covered with carbon for SEM/EDXA.

Table 2 Properties of fuels.

| Fuel | | RC | WP | WC |
|------------------|------------|---------|--------|--------|
| Ash ¹ | [% db] | 7,5 | 0,4 | 0,6 |
| HHV | [MJ/kg db] | 22,157 | 20,193 | 19,980 |
| LHV | [MJ/kg db] | 20,672 | 18,873 | 18,665 |
| C | [% db] | 49,900 | 50,600 | 49,900 |
| H | [% db] | 6,900 | 6,100 | 6,000 |
| N | [% db] | 5,100 | 0,100 | 0,200 |
| O (calculated) | [% db] | 29,900 | 42,800 | 43,300 |
| S | [% db] | 0,720 | 0,006 | 0,007 |
| Cl | [% db] | 0,26 | na | na |
| Si | [mg/kg db] | 261,0 | 165,0 | 346,0 |
| Al | [mg/kg db] | 43,4 | 36,5 | 207,0 |
| Fe | [mg/kg db] | 152,0 | 43,9 | 204,0 |
| Ti | [mg/kg db] | 3,6 | 1,8 | 8,4 |
| Mn | [mg/kg db] | 59,7 | 112,0 | 166,0 |
| Ca | [mg/kg db] | 7040,0 | 783,0 | 1100,0 |
| Mg | [mg/kg db] | 4500,0 | 160,0 | 224,0 |
| P | [mg/kg db] | 11500,0 | 55,9 | 120,0 |
| Na | [mg/kg db] | 4660,0 | 28,9 | 49,7 |
| K | [mg/kg db] | 12300,0 | 432,0 | 594,0 |

¹ - ashed at 550⁰ C; ² - calculated; RC-rapeseed cake, WP- wood pellets, WC – wood chips; ar – as received, db – on dry basis; na – not available (below detection limit of 500 ppm)

RESULTS AND DISCUSSION

Fuel analyses

Standard fuel analysis, shown in Table 2, indicates clearly the main ash forming matter constituents of rapeseed cake (RC) pellets are potassium and phosphorous, an additional feature is the high content of chlorine. The ash content is much higher in case of RC compared to WP and WC resulting in up to 11 times higher ash inflow during test WNL45_preliminary (Table 1).

Results from the chemical fractionation are presented in Figure 2. This figure shows the elemental composition of the fuel divided into four obtained fractions, facilitating the comparison between the chemical compositions of the co-combusted fuels. Leaching with water releases simple soluble salts, usually volatile alkali compounds, with ammonium acetate the ion exchangeable part of the fuel ash forming matter is released; in the final step the acid soluble inorganic salts are leached while in the rest (insoluble) fraction mainly silicates are

present but also sulphur and chlorine when covalently bonded to the organic structure of the fuel. The chemical fractionation results show that the difference between woody biomass and rapeseed cake is not

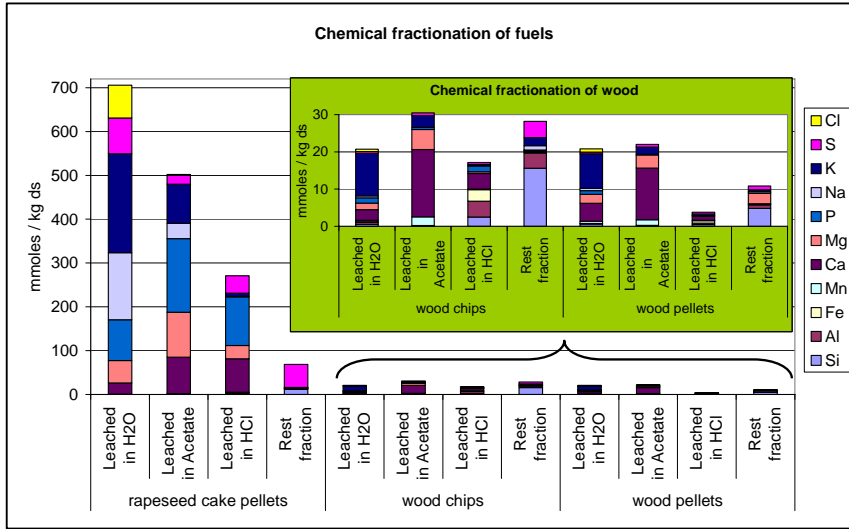


Figure 2 Chemical fractionation results of co-combusted fuels.

only the ash content. Woody biomass ash forming matter consists mainly of potassium leached in water and calcium leached by ammonium acetate indicating its association with carboxylic groups of hemicelluloses and calcium oxalate (Werkelin J., 2008; Zevenhoven M., 2001). Only a small amount of phosphorus is found present in the fraction leached by water and hydrochloric acid.

In rapeseed cake high shares of phosphorus are present. This phosphorus is leached in all three procedure steps, indicating different associations. A large part of the rapeseed cake ash forming matter is leached by water indicating simple salts like alkali chlorides, sulphates and phosphates (Werkelin J., 2008; Zevenhoven M., 2001). As shown in previous studies (Pontoppidan K. et al., 2007) around 70% of total phosphorus present in rapeseed cake can be associated with phytic acid (myo-inositol hexaphosphate) and its degradation products (mainly inositol pentaphosphate). These phosphorus compounds are probably found in the ammonium acetate and hydrochloric acid fractions. The solubility depends strongly on the type of complexes the phytic acid is forming with cations and proteins (Cheryan M., 1980, Shahidi F., 1990). In the hydrochloric acid fraction mainly calcium, magnesium, but also iron, zinc and manganese were found next to phosphorus.

In rapeseed cake high shares of phosphorus are present. This phosphorus is leached in all three procedure steps, indicating different associations. A large part of the rapeseed cake ash forming matter is leached by water indicating simple salts like alkali chlorides, sulphates and phosphates (Werkelin J., 2008; Zevenhoven M., 2001). As shown in previous studies (Pontoppidan K. et al., 2007) around 70% of total phosphorus present in rapeseed cake can be associated with phytic acid (myo-inositol hexaphosphate) and its degradation products (mainly inositol pentaphosphate). These phosphorus compounds are probably found in the ammonium acetate and hydrochloric acid fractions. The solubility depends strongly on the type of complexes the phytic acid is forming with cations and proteins (Cheryan M., 1980, Shahidi F., 1990). In the hydrochloric acid fraction mainly calcium, magnesium, but also iron, zinc and manganese were found next to phosphorus.

Table 3 Elemental distribution over outgoing ash fractions – inflow of the element is defined to be 100%

| | Test name | Ash fractions [%] | | | | |
|------|-----------|-------------------|----|----|----|----|
| | | BA | SC | BF | E | Δ |
| P | WNL12 | - | 21 | 4 | - | 75 |
| | WL18 | 1 | 23 | 4 | - | 72 |
| K+Na | WNL12 | - | 22 | 8 | - | 70 |
| | WL18 | 2 | 22 | 12 | - | 64 |
| Mg | WNL12 | - | 30 | 13 | - | 57 |
| | WL18 | 2 | 26 | 8 | - | 64 |
| S | WNL12 | - | 9 | 12 | 40 | 40 |
| | WL18 | 2 | 5 | 7 | 1 | 85 |
| Cl | WNL12 | - | 4 | 17 | 60 | 18 |
| | WL18 | - | 7 | 28 | 5 | 60 |

BA – bottom ash; SC – secondary cyclone; BF – bag filter; E- emissions;

$$\Delta = (100\% - \frac{Out_i}{In_i} \%) = \text{accumulation} + \text{error}$$

boiler happened, and the restart was not possible until the particle seal and tube from the cyclone was cleaned from large agglomerates. The boiler was started with fresh bed material after which reference test,

Mass balance and distribution of ash in the CFB boiler

In all of the tests the fuel load was kept at a level of about 6 MW. The ash balance has been calculated for each test and results are presented in Table 1. For the calculation all the incoming and outgoing inert flows were used. Ash forming matter entering the boiler with fuels but also silica entering as fresh bed material and ash produced by limestone addition were considered to constitute the incoming streams. In order to determine the limestone ash flow, the assumption that it fully converts to CaO to form CaSO₄ was made. The closure of the ash balances is shown in Table 1 as the ratio between the total ash outgoing flows to the total ash incoming flows in the percentage form. The closure for RC co-combustion tests was poor indicating ash accumulation in the system. This was proven after the 4 hour tests that resulted in heavy build up of agglomerates in the particle seal of the boiler. A total shut down of the boiler happened, and the restart was not possible until the particle seal and tube from the cyclone was cleaned from large agglomerates. The boiler was started with fresh bed material after which reference test,

reference_WNL, was performed. The mass balance closure for reference_WNL of 160% suggests that ash still present elsewhere in the boiler was removed during the reference case.

Elemental flows were calculated using the quantitative analyses of the incoming and outgoing inert streams. The inflow of the particular element was defined as 100%, and thus the elemental distribution over outgoing streams could be calculated. Results are shown in Table 3. During test WNL12, a forced agglomeration test was performed by shutting off bed regeneration and bottom ash removal (indicated with a “-“ in Table 3). The concentration of chlorine in bottom ash samples could not be analyzed due to method detection limit (500 ppm). Na and K show a similar behaviour in the boiler and are considered here as a combined fraction of alkali metals. The values presented in Table 3 give an indication of the pathway that ash forming matter is taking through the boiler. It can be seen that high phosphorus and alkali metals accumulation in the boiler and/or convective pass took place. The rest was found in the secondary cyclone ash. In contrast, sulfur and chlorine form small particles that were captured in the bag filter or were emitted in the form of sulfur dioxide or hydrogen chloride. During test with lime addition (WL18), next to obvious sulfur and chlorine retention, a small increase of K+Na in the bag filter fraction occurred, most probably caused by increased formation of alkali metal chlorides as shown in Table 4.

The role of P in agglomeration

In Figure 3a) a rapeseed cake ash particle found in the bottom ash sample during test WNL45_preliminary

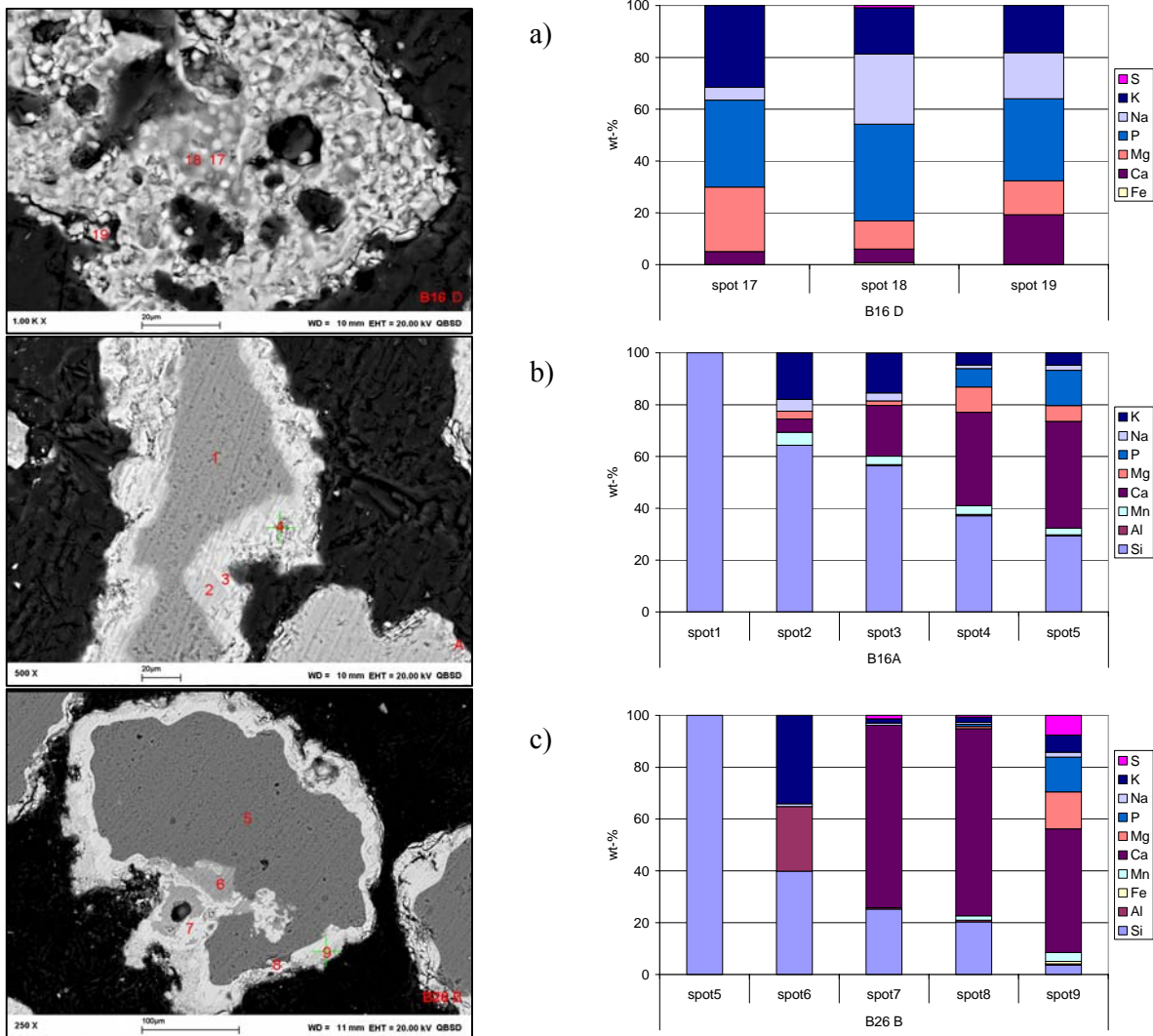


Figure 3 Bed material cross-sections a) RC ash particle - Test WNL45_preliminary, b) bed material particle - WNL45_preliminary, c) bed material particle - Test WL18.

is shown. Within the ash particle the high concentration of phosphorus next to alkali metals can be noticed (about 35 wt-%) indicating that formation of low melting RC ash particles could take place (*Lindström et al., 2007*). The analyses of bed material cross-sections as shown in Figure 3b) indicate a reaction of potassium compounds with bed material forming low melting alkali silicates (*Öhman M. 1999*) followed by adhesion of RC ash particles rich in phosphorus. Probably among others potassium phosphates reacted with silica initiating agglomerates formation *Barišić V. et al. (2008)*. The formation of low melting potassium-calcium-silicates during biomass combustion was discussed by *Öhman M. (1999)* and seems to be valid also in the present co-combustion tests. Addition of limestone changed the combustion behavior by decreasing agglomeration tendency (Figure 3c). The sand particles were coated with a calcium rich layer preventing low melting potassium-silicates formation. This is in agreement with studies done by *Barišić et al. (2008)* regarding the same experiments.

Table 4 Measurements at the beginning of convective pass.

| Test name | RBU | KCl+NaCl | HCl | SO ₂ |
|-------------------|-----------------------|---|-----|-----------------|
| | [g/m ² *h] | [ppm _v dry flue gas, 6% O ₂] | | |
| WNL45_preliminary | 16,9 | 114 | 171 | 140 |
| WNL_reference | 1,2 | 1 | 0 | 0 |
| WNL12 | 2,6 | 14 | 44 | 52 |
| WL18 | 6,3 | 49 | 44 | 3 |

The role of P in deposit formation

Rates of deposit build-up (RBU) presented in Table 4 indicate that co-firing of wood with RC showed high fouling rates; rapeseed cake addition from 0–45 % on energy basis caused an increased RBU most probably due to alkali chloride condensation. However, the deposit formation was also aggravated by fine phosphates particles as shown in Figure 4 where the elemental analysis done with the

use of SEM/EDX is presented. Figure 4 shows not only an increase of K, Na in the deposit samples but also of P (14 wt-%). Increased concentration of (KCl+NaCl) in the dry flue gas entering the convective pass can be noticed during test WL18 (Table 4). This could be a result of limestone addition which by binding S didn't allow sulfation of (KCl+NaCl) (*Kassman H. et al., 2006*) and as a consequence higher RBU were observed. Unexpectedly no influence of limestone addition can be noticed on HCl entering the convective pass (Table 4) most probably due to measurement uncertainties. Limestone addition seemed to have no impact on the amount of phosphorus (Figure 4) present in the deposits.

CONCLUSIONS

Co-firing of wood with rapeseed cake in a circulating fluidized bed boiler caused both agglomeration and fouling. About 18% of rapeseed cake on energy basis could be co-fired with wood when limestone is added to the bed.

Analyses of bed material particle cross-sections showed a reaction of potassium compounds with bed material forming a K-Si rich layer that was probably partly molten followed by adhesion of ash particles rich in phosphorus. Limestone addition prevented low melting potassium-silicates formation via coating of sand particles with a calcium rich layer. Rapeseed cake addition caused an increased rate of deposit build-up (RBU) but also higher emissions of HCl (g) and SO₂ (g).

The chemical composition of rapeseed cake, mainly consisting of water soluble alkali metals, -chlorides and organically associated phosphorus gives a good indication of agglomeration and fouling tendencies. However, detailed studies are required to better understand the leaching mechanism of phosphorous compounds for this particular case.

The fate of phosphorus during combustion in fluidized bed boiler needs to be further investigated.

Acknowledgements

This study was carried out as part of the SAFEC project. The financial support by the Academy of Finland, the Graduate School of Chemical Engineering is gratefully

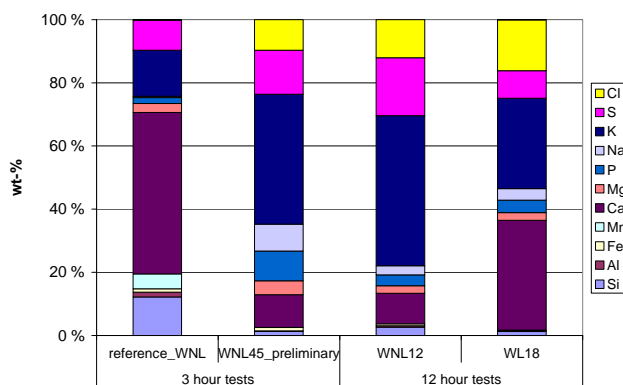


Figure 4 Windward side deposits composition.

acknowledged. This research was partly financed by ChemCom, a mainly TEKES financed project at the Process Chemistry Centre at Åbo Akademi University. Other funders are Andritz Oy, Foster Wheeler Energia Oy, International Paper Inc., Metso Power Oy, Oy Metsä-Botnia Ab, Clyde Bergemann GmbH, and UPM-Kymmene Oy. Results of IACM could be used with a permission of Vatenfall AB, which is highly appreciated. Special thankfulness goes to Matti Hiltunen for his key contribution in the early phases of this work. Linus Silvander, Tor Laurén and Piia Leppäsalo are kindly acknowledged for helping with the experimental work. Akademiska Hus and the measurement team at the CTU are kindly acknowledged for their continuous efforts to operate the boiler.

References:

- Barišić V., Åmand L.-E., Coda Zabetta E. "The role of limestone in preventing agglomeration and slagging during CFB combustion of high phosphorus fuels" World Bioenergy, Jönköping (Sweden), May 2008
- Baxter L.L. "Pollutant emission and deposit formation during combustion of biomass fuels", Livermore (CA, USA), 1994
- Benson S.A., Holm P.L. "Comparison of inorganic constituents in three low-rank coals" Ind. Chem. Eng. Prod. Res. Dev., 24 (1985) 145-149.
- Cheryan M. "Phytic acid interactions in food systems" Critical reviews in food science and nutrition, 13: 4 (1980)
- Coda Zabetta E., Barišić V., Peltola K., Hotta A. "Foster Wheeler Experience with biomass and waste in CFBs" Proceedings of the 33rd Clearwater Conference, Clearwater (Florida, U.S.A.), June 2008
- Hupa M. "Ash behavior in fluidized bed combustion-recent research highlights" Proceedings of the 9th International Conference on Circulating Fluidized Beds, Hamburg (Germany), May 2008
- Jenkins B.M., Baxter L.L., Miles Jr. T.R., Miles T.R. "Combustion properties of biomass" Fuel processing Technology, 54 (1998) 17-46
- Kassman H., Andersson C., Högberg J., Åmand L.-E., Davidsson K., "Gas Phase Alkali Chlorides and Deposits during Co-Combustion of Coal and Biomass", FBC2006-99, Proceedings of 19th International Conference on Fluidized Bed Combustion, Vienna (Austria), May 21-24 2006,
- Lindström E., Sandström M., Boström D., Öhman M. "Slagging characteristics during combustion of cereal grains rich in phosphorus" Energy&Fuels, 21 (2007) 710-717
- Nevalainen H., Leino T., Tourunen A., Hiltunen M., Coda Zabetta E. "Deposits and emissions during the co-combustion of biodiesel residue with coal and biomass in a CFB pilot" Proceedings of the 9th International Conference on Circulating Fluidized Beds, Hamburg (Germany), 2008 May 2008
- Pontoppidan K., Pettersson D., Sandberg Ann-Sofie "The type of thermal feed treatment influences the inositol phosphate composition" Animal feed Science and Technology 132 (2007)
- Shahidi F. "Canola and rapeseed: production, chemistry, nutrition and processing technology", Van Nostrand Reinhold Company Inc. (AVI Book); 1990, ISBN 0-442-00295-5
- Skrifvars B.-J., Blomquist J.-P., Hupa M., Backman R. "Predicting the ash behavior during biomass combustion in FBC conditions by combining advanced fuel analysis with thermodynamic multicomponent equilibrium calculations" Proceedings of the 15th Annual International Pittsburgh Coal Conference, Pittsburgh, (PA, USA), 1998
- Werkelin J. "Ash forming elements and their chemical forms in woody biomass fuels" PhD thesis, PCC, Åbo Akademi University; 2008, ISBN 978-952-12-2125-5
- Zevenhoven-Onderwater M., "Ash-Forming Matter in Biomass Fuels" PhD thesis, Department of Chemical Engineering, Åbo Akademi University; 2001, ISBN 952-12-0813-9
- Zevenhoven M., Skrifvars B.-J., Yrjas P., Hupa M., Nuutinen L., Laitinen R. "Searching for improved characterisation of ash forming matter in biomass", Proceedings of the 16th International Conference on Fluidized Bed Combustion, Reno (NV, USA) 2001
- Zevenhoven M., Yrjas P., Backman R., Skrifvars B.-J., Hupa M. "The Åbo Akademi database-fuel characterization", FBC2005-78093, Proceedings of the 18th International Conference on Fluidized Bed Combustion, Toronto (Ontario, Canada), May 18-23 2005
- Åmand L.-E., Leckner B. "Metal emissions from co-combustion of sewage sludge and coal/wood in fluidized bed" Fuel, 83 (2004) 1803-1821
- Öhman M. Experimental studies on bed agglomeration during fluidized bed combustion of biomass fuels. PhD thesis, Department of Chemistry, Umeå University; 1999, ISBN91-7191-646-6