

CO-FIRING OF BIOMASS AND OTHER WASTES IN FLUIDISED BED SYSTEMS

I. Gulyurtlu, H. Lopes, D. Boavida & P. Abelha, DEECA – INETI, Portugal
J. Werther; E.-U. Hartge & R. Wischnewski, TU Hamburg-Harburg, Germany
B. Leckner, L.-E. Åmand & K. Davidsson, Chalmers Univ. of Techn. - Sweden
P. Salatino, R. Chirone, F. Scala & M. Urciuolo, Dipartimento di Ingegneria Chimica –
Università di Napoli Federico II and Istituto di Ricerche sulla Combustione – CNR, Italy
J.F. Oliveira, N. Lapa, J. Morais, Unidade de Biotecnologia Ambiental, Universidade
Nova Lisboa, Portugal
N. Heidenhof, Stadtwerke Duisburg , Germany
D. Dugwell, N. Paterson, R. Kandiyoti, Imperial College, UK
M. Schiavetti, F. Donatini, ENEL, Italy
Y. Yurum, A.G. Dumanli, FENS, Sabanci University, Istanbul, Turkey

Abstract

A project on co-firing in large-scale power plants burning coal is currently funded by the European Commission. It is called COPOWER. The project involves 10 organisations from 6 countries. The project involves combustion studies over the full spectrum of equipment size, ranging from small laboratory-scale reactors and pilot plants, to investigate fundamentals and operating parameters, to proving trials on a commercial power plant in Duisburg. The power plant uses a circulating fluidized bed boiler. The results to be obtained are to be compared as function of scale-up. There are two different coals, 3 types of biomass and 2 kinds of waste materials are to be used for blending with coal for co-firing tests.

The baseline values are obtained during a campaign of one month at the power station and the results are used for comparison with those to be obtained in other units of various sizes. Future tests will be implemented with the objective to achieve improvement on baseline values. The fuels to be used are already characterized. There are ongoing studies to determine reactivities of fuels and chars produced from the fuels. Reactivities are determined not only for individual fuels but also for blends to be used. Presently pilot-scale combustion tests are also undertaken to study the effect of blending coal with different types of biomass and waste materials. The potential for synergy to improve combustion is investigated. Early results will be reported in the Conference.

Simultaneously, studies to verify the availability of biomass and waste materials in Portugal, Turkey and Italy have been undertaken. Techno-economic barriers for the future use of biomass and other waste materials are identified. The potential of using these materials in coal fired power stations has been assessed. The conclusions will also be reported.

Introduction

Concerns over climate change, driven by the ever-increasing release of greenhouse gases, particularly CO₂, has resulted in the Kyoto Agreement; a global attempt to bring down emissions to the levels of 1990. Achievement of the desired reductions presents a formidable challenge to the whole world today. The EU is very committed to fulfilling its own obligations within the framework of the Kyoto Agreement, and is providing strong financial incentives for the development of technological solutions, both short- and long-term, to decrease CO₂ emissions from within its borders. The use of biomass as a renewable, CO₂ neutral, energy source as replacement for fossil fuels, forms a central pillar of the EU short-term strategy for meeting the Kyoto obligations.

The COPOWER project integrates 10 organisations from 6 Member States with the aim of developing a comprehensive understanding of process synergy during co-firing of coal with biomass and wastes, in circulating fluidized bed systems. The project involves combustion studies over the full spectrum of equipment size, ranging from small laboratory-scale reactors and pilot plants, to investigate fundamentals and operating parameters, to proving trials on a commercial power plant in Duisburg. Two types of coals have been selected for co-firing tests; the Colombian coal regularly used on the Duisburg plant, and a Polish coal used in many power stations across the EU. Three biomass types are being investigated; wood waste; straw, which is important in Northern Europe; and olive bagasse, in Southern Europe. Two non-toxic wastes are being investigated; sewage sludge, both dried and wet; and meat-and-bone-meal, MBM.

A comprehensive survey of co-firing is presented in an IEA Coal research Publication (1). Most of the experience on co-firing is with units designed to burn pulverized or crushed coal. For existing equipment to do co-firing, it requires retrofitting to be able to handle fuels of varying nature and this could be costly. According to this study by IEA, although large amounts of waste and biomass are claimed to be available, there are debates about the accuracy of the data because the reported data are scarce and inconsistent. Caution should, therefore, be exercised before any co-firing project is undertaken as to the validity and consistency of a particular waste resource and that the waste and biomass can be transported to the plant reliably in the quantities required. Environmental legislation could be the main driving force for encouraging coal-waste-biomass co-firing and market-driven methods should be encouraged. Technology has also an important role to play and according with the IEA study, the combustion technology to co-fire coal, biomass and waste materials is not yet fully developed; emissions, combustion efficiency, and impacts on system performance, such as slagging, and fouling, need to be quantified more fully. It is unlikely that a plant would obtain and burn a single waste or biomass for a prolonged period. It is more likely that plant officials would buy or offer to dispose of a number of wastes available to them locally. Therefore, potential problems and synergies arising from the various combinations need to be identified. In addition, both upstream and downstream impacts are important. Upstream impacts include handling, preparation and storage. Downstream ones include ash deposition, corrosion, and pollutants (reliable prediction of SO₂ and NO_x and reduction in particular, as well as heavy metal emissions). From another IEA publication (2), it is clear that most of the work has been done using coal as the base fuel and admitting relatively small amounts of waste or biomass (no more than 10% of thermal input). Co-firing, especially with 'CO₂-neutral' biomass is a way of displacing coal as a fuel and thus reducing greenhouse gas emissions. Another advantage is a viable solution, largely to the increasing problems of waste disposal. Here, the more stable combustion characteristics and the lesser environmental impacts of coal are used to deal with wastes that otherwise would be landfilled or, if incinerated alone, would lead to more undesirable emissions to the atmosphere.

Coal users in the European Union are under continuing pressure to achieve higher process efficiencies, while minimising emissions of potentially harmful species. Co-utilisation could have a significant impact on reducing the emissions of principal coal pollutants (3) because waste materials usually have very little amounts of S and N, principal elements for pollution formation during coal combustion. Furthermore, these wastes have varying ash content and thus their addition to coal firing could have a bearing on the amount of ash formed during combustion. Waste materials, such as non-recyclable paper, board, packaging material, plastics, etc., need to be compacted before use as a feedstock to reduce the potential for fuel handling storage, and to improve feeding and combustion performance.

The fossil fuels used traditionally for power generation, as well as many of the non-conventional biomass and waste materials now being considered as auxiliary fuels, contain a wide range of elements, in addition to carbon and hydrogen. Their amounts are generally at the trace level, defined as less than 1000 ppm. Trace element release mechanisms are known to be complex but a general understanding of the behaviour of trace elements in fossil fuel combustion has now been

Table 1 – The characterization of fuels used

Sample reference	Polish Coal	Columb. Coal	Straw	Sewage sludge
Moisture %	3.4	8.1	9.4	14.2
Ash %	9.7	11.2	5.5	22.8
Volatile %	31.0	33.4	67.5	54.5
Fixed carbon % **	55.9	47.3	17.6	8.5
Sulphur %	0.47	0.84	0.17	1.18
Chlorine %	0.30	0.06	0.29	0.06
Gross Calorific Value kJ/kg	29200	26750	16730	15940
Net calorific value kJ/kg	28158	25607	15484	14615
Calorific value kJ/kg (DAF) **	33600	33150	19660	25300
Volatile matter % (DAF) **	35.7	41.4	79.3	86.5
Carbon %	72.56	64.29	41.4	36.98
Hydrogen % *	4.2	4.23	5.19	4.62
Nitrogen %	1.22	1.37	0.73	5.03
Oxygen % **	8.45	9.97	37.6	15.2

Analysis basis : as received into laboratory

* Corrected for moisture content

** Calculated using determined values (by difference)

reached, and is well reviewed by Clarke and Sloss (4). More recent work by Miller, Kandiyoti and Dugwell (5) has focussed on non-conventional biomass or waste fuels burned alone or in combination with coal. The co-combustion studies revealed some interesting synergies and the suspicion that the chlorine and/or sulphur content of the fuels have a significant influence on the behaviour of some trace elements during combustion.

Despite the above studies, our knowledge of how sulphur and chlorine contents of fuels will affect the release of specific trace elements is still far from complete. However, it is clear that

Table 2 – The composition of ashes of fuels used

Sample reference	Polish Coal	Columb. Coal	Straw	Sewage sludge
SiO ₂	43.2	54.3	55.3	31.0
Al ₂ O ₃	17.4	18.9	1.2	13.8
Fe ₂ O ₃	7.8	7.6	0.5	5.5
TiO ₂	0.6	0.8	0.1	1.3
CaO	7.7	2.5	8.1	18.1
MgO	5.0	2.3	2.1	3.1
Na ₂ O	1.2	0.8	1.7	0.7
K ₂ O	1.5	2.0	16.5	1.2
Mn ₃ O ₄	0.1	0.1	0.1	0.1
P ₂ O ₅	0.3	0.2	3.3	19.7
SO ₃	7.6	2.7	4.3	1.4
Total	92.4	92.2	93.2	95.9
Composition % m.m. as analysed				

* Corrected for moisture content

** Calculated using determined values (by difference)

there is scope for reducing the volatilisation of some key trace elements by judicious blending of fuels to give effective Cl:S ratios. Furthermore, fuel ashes exhibit varying capability for retaining volatilised trace element species, so that further environmental benefits may accrue from fuel blending.

Experimental

The descriptions of installations used by different partners are given in previous publications of the authors. Small-scale laboratory studies are undertaken at Imperial College, University of Naples and University of Sabanci. The pilot facilities are at INETI and the University of Hamburg. The boiler of the Chalmers Technical University is used to obtain results for the verification of those obtained on the pilot installations. The descriptions of installations are given in previous publications of the participating organizations (5, 6, 7, 9, 10). Finally, work is undertaken at the power plant of Stadtwerke Duisburg and a team from the University of Hamburg undertakes measurements for the comparison of results as result of the scale-up. The fuels selected for the tests are Colombian and Polish coals, straw and wood pellets, olive bagasse, sewage sludge and meat and bone meal (MBM). The characteristics of some of these fuels are given in Table 1. The ash compositions of the same fuels are in Table 2.

Results and Discussion

The COPOWER project comprises 5 separate workpackages (WP) addressing different issues related to co-firing. The key features are characterization of selected fuels; combustion behaviour of raw fuels and mixtures; environmental impact; socio-economic assessment; management and optimization of the whole fuel supply chain; and market analysis. The fuel supply chain analysis has been investigated in the scope of WP1 in detail for 3 countries, namely Italy, Portugal and Turkey.

Initial results of WP1 suggest that most Member States have reasonable resources of biomass and waste materials but lack the infrastructure necessary to ensure their regular supply for use as auxiliary fuels. It will be necessary to develop an integrated system of collection, storage and distribution at the national level. This involves many problems, e.g. transport over long distances is very costly due to the low energy density of waste materials. In addition, there is a need to create a well regulated market for the use of biomass and waste for energy production, if sustainability of supply is to be guaranteed. With the exception of the Scandinavian countries and Austria, there is very little tradition of using biomass on a large scale within the EU. Experience and knowledge about the use of biomass for energy is thus limited, and there are no quality control standards for biomass or waste materials for use as fuels. This contrasts negatively with the well-established market for fossil fuels.

The work package 2 (WP2) addresses the characterization of the very basic patterns of fuel devolatilization and combustion in fluidized beds in order to provide the fundamental understanding required to fully exploit synergistic effects in co-combustion. Fundamental aspects like kinetics of fuel devolatilization and char burnout, fuel attrition, generation of primary ash particles and their further attrition, release and partitioning of trace compounds are investigated by a combination of experimental techniques, mostly based on the operation of bench scale FB reactors. The most remarkable features emerged from WP2 so far are:

- Both sludge and straw pellets are characterized by relatively long devolatilization times, 50-90s. These times, related to the pelletized rather than loose nature of these co-fuels, should positively affect lateral spreading of the fuel upon feeding and evenness of volatile matter release across the combustor cross-section;
- Sludge burnout takes place according to a shrinking core conversion pattern, with the formation of a coherent ash skeleton enclosing an unreacted carbon-rich core. This feature is reflected by the PAPSD, i.e. the size distribution of Primary Ash Particles, or PAPs, released after complete burn-off (Figure 1) which exhibits a large population of

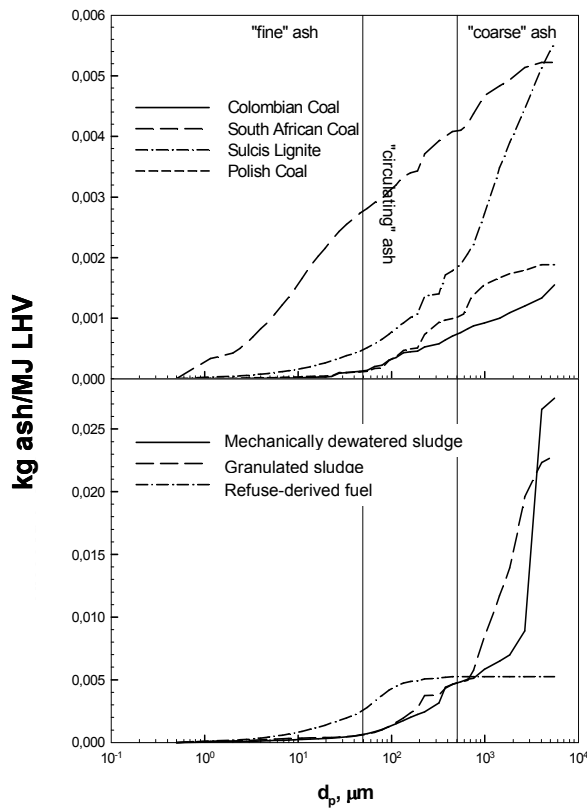


Fig. 1: Cumulative primary ash particle size distribution (PAPSD) of coals and biogenous fuels per unit low-heating value.

operation and environmental emissions. The focus is here on full-scale tests in the Duisburg power station which are supported by work on the 12 MW Chalmers boiler and by laboratory and pilot-scale investigations.

During October and November 2005 a twelve-day test was performed in the Duisburg with an initial three-day period of coal firing followed by a three-day period with co-firing of sewage sludge, another three-day period with co-firing of sewage sludge and wood pellets and finally a

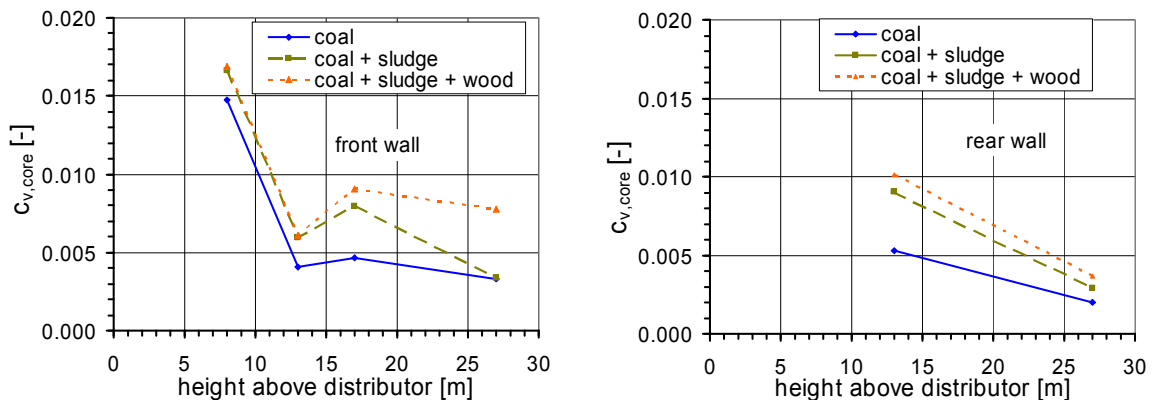


Fig.2: Solids volume concentrations $c_{v,core}$ measured outside the wall zone in the Duisburg combustor under different operating conditions.

ash particles in the mm-sized range. At the same time secondary attrition of PAPs is extensive, the attrition constant k_a defined according to [9] being $4.7 \cdot 10^{-7}$. The combined effect of PAPs release and of secondary attrition of PAPs leads to the expectation that this fuel should contribute significantly to the build-up of bed material in the circulating range.

- Combustion of straw pellets in beds of sand was always associated to formation of ash-sand agglomerates, even when combustion was carried out at temperatures as low as 600°C . Further investigation is required to assess the combustion mode in beds of different materials, like spent sorbent or ash.

The work package 3 is concerned with the co-firing trials on different scales of operation. The general goal is to find synergies with different mixtures of fuels in order to optimize the plant

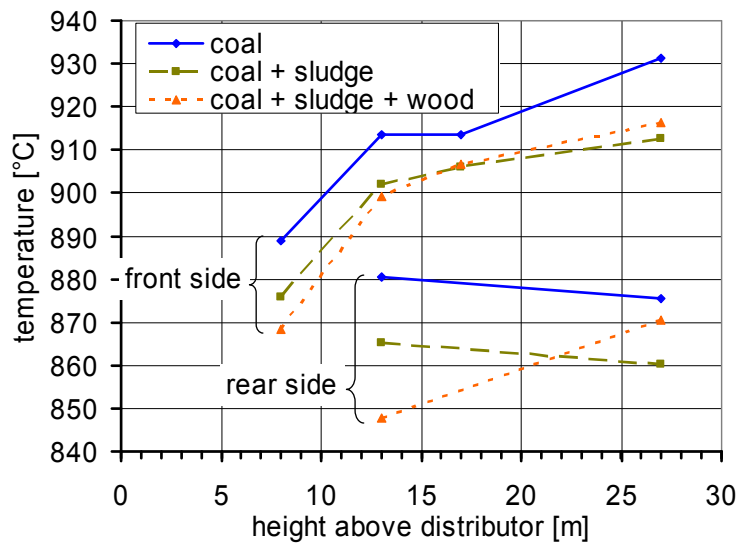


Fig.3: Local temperatures in the Duisburg boiler during the tests.

three-day period of coal firing. The mass flows were 360 t/h coal, 35.3 t/h coal plus 4.1 t/h sludge, and 30.0 t/h coal plus 4.3 t/h sludge plus 6.9 t/h wood, respectively. The boiler was always kept near 100 % load. Flue gas concentrations were measured at the stack, ash samples were taken from various points in the plant and local measurements with gas suction probes, solids suction probes and capacitance probes were performed by the TUHH group at various locations inside the combustion chamber. Full details of this measurements campaign may be found in Wischniewski et al. (2006).

Although it will take some time to fully evaluate the bulk of information gathered during this time first preliminary conclusions may be drawn already. They indicate that indeed co-firing of waste and/or biomass may provide synergies for both the operation of the boiler and the emissions. As an example Fig. 2 shows plots of the solids volume concentration measured by means of capacitance probes at different heights above the distributor in the upper part of the combustion chamber. The measurements were made outside the wall zone of increased solids concentration. It is shown that under co-firing conditions the solids volume concentration increased. Since the solids inventory in the combustion chamber was kept constant by the control system this means that the vertical distribution of the bed solids is changed such that through the addition of sludge or sludge and wood more solids were kept in the upper part of the combustion chamber (and less remained in the bottom bed). The reason could be a change in the ash particle size distribution. This hypothesis finds support from results obtained by the Naples group within WP2 concerning the generation of primary ash particles from sludge and biomass pellets and their secondary attrition. The increased solids holdup in the upper part has an important consequence for the operation of the boiler which is seen from Fig. 3. In Fig. 3 the local temperatures in the upper part of the combustion chamber are plotted against the height above the distributor. Besides the fact that the temperatures measured near the rear wall are generally lower than those measured near the front wall (an explanation is given in Wischniewski et al. (2005)), it was observed that under co-firing conditions the temperatures were generally lower than for pure coal firing. There could be two reasons for the lowering of the temperature. The one is that the increased solids holdup in the upper part under co-firing conditions is associated with an increase of the external solids circulation rate G_s which since most of the heat is extracted in two external fluid bed heat exchangers provides a more efficient cooling of the combustion chamber. About 15 % of the heat released in the combustion chamber is extracted via heat exchanger panels hanging from the top of the combustion chamber. These panels are starting at a height of roughly 20 meters above the gas distributor. The increased solids volume concentration in this part of the combustion chamber

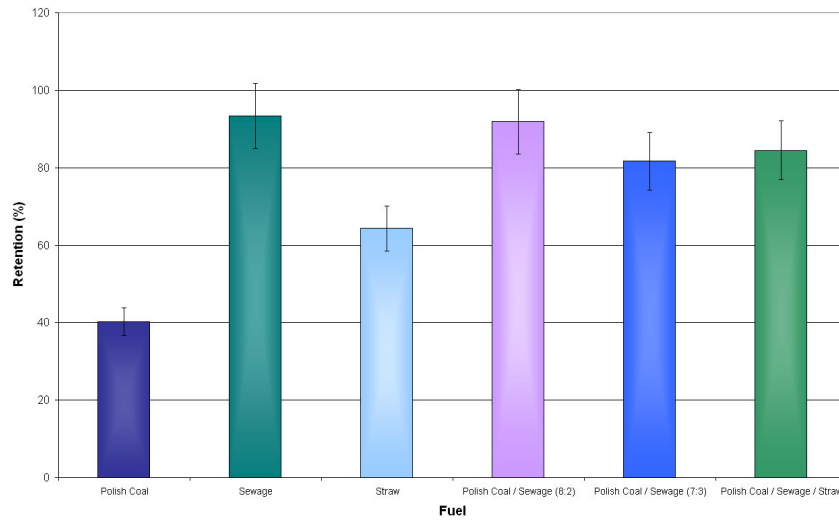


Fig. 4: Molybdenum retention in ash as a function of fuel type

will have as a consequence a higher bed-to-wall that transfer coefficient which is a common experience for CFB boilers (Breitholtz et al., 2001). The same will be valid for tube bundles hanging in the combustion chamber and so the increased heat transfer coefficient will contribute to the lowering of the temperature in the upper part of the combustion chamber. It can be concluded that with the present choice of the waste (and wood) the co-firing provides us with an excellent synergy effect in that co-firing increases the bed-to-wall heat transfer and lowers the combustion temperature. As a practical consequence co-firing of a suitable waste may allow the operator to increase the load for given temperature levels or to lower the temperature in the combustion chamber if this is desirable for ash melting reasons, for example.

Another synergy effect was found by the team at Imperial College, London. They found that under co-firing conditions the retention of a number of heavy metals in the ash was significantly increased. An example, Fig. 4 shows the retention of molybdenum as a function of the fuel type. Similar synergy effects were observed for As, Cr, Mn, Ni and Hg. Be and Se showed no effect.

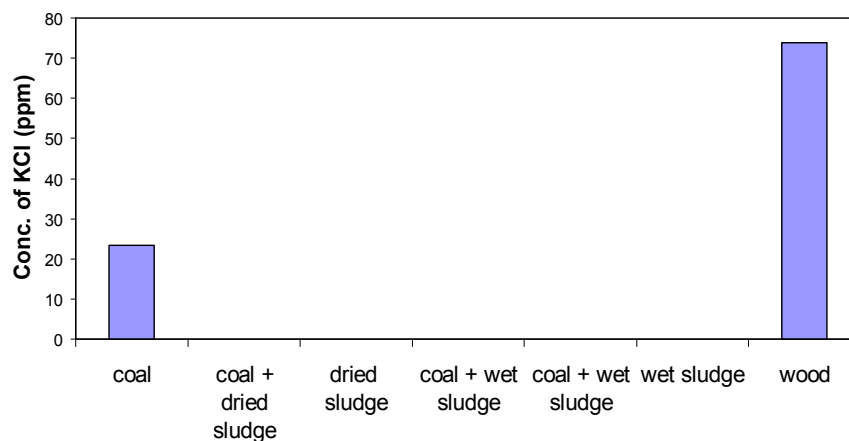


Figure 5: KCl(g)-concentrations at super heater position for different fuel combinations. In all cases the input of K was aimed at 100 mol/h by addition of straw pellets (except for the cases with wet sewage sludge, which contains high levels of alkali). The stoichiometric Cl/K was held at 1 by addition of PVC to the furnace. The theoretical level of KCl (g) (corresponding to complete conversion of K and Cl to KCl) is roughly established to 65 ppm.

However, it has to be admitted that Cd, Cu and V showed minor negative synergy and Pb and Zn even exhibited significant negative synergy which means that the retention of these heavy metals in the ash was decreased under conditions of co-firing. However, as stated above, these results are still preliminary and further investigations have to be performed.

A different series of co-combustion tests was performed in the Chalmers boiler to focus on the synergy effects related to alkali chlorides. An on-line alkali chloride monitor was used at a normal superheater position in the boiler (before the convection flue gas pass) for the monitoring of gas phase KCl and NaCl. Figure 5 shows the sum of the concentrations of the two alkali chlorides, KCl and NaCl for various cases where potassium (K) was added by co-firing straw pellets. A reference case using only wood fuels (straw pellets, wood chips and wood pellets) resulted in concentrations of KCl of more than 70 ppm. This is far too much for long time operation without causing severe fouling and corrosion problems when the gas phase alkali chlorides condensate on the superheaters. By substituting the wood pellets and wood chips with coal as base fuel the KCl level is lowered to about 20 ppm. Adding municipal sewage sludge either together with the coal or alone as wet mechanical sludge or predried completely removes the KCl from the gas phase. The explanation for this positive synergy effect could be:

- The sulphur content in coal and the sewage sludge helps avoiding the formation of KCl by forming K_2SO_4 .
- The clay minerals in coal (aluminia silicates) could promote the formation of potassium aluminia silicates.
- Sewage sludge contains zeolites from detergents. Zeolites are a synthetic form of aluminia silicates. The presence of zeolites in sewage sludge could be the reason for the effective (100%) capture of KCl from biomass by the formation of potassium aluminia silicates.

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