



## PSO Project 10085

### Final Report – Co-Firing of Coal and RDF in Suspension

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**PSO Project 10085:**  
**Final Report – Co-Firing of Coal and RDF in Suspension**

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## Abstract

Co-combustion of refuse derived fuels (RDF) with coal in pulverized coal-fired power plants can potentially increase the electrical efficiency of utilizing RDF and reduce the formation of some harmful pollutants such as dioxins. The objective of this project was to provide a general assessment of the technical issues related to co-combustion of coal and RDF, and to improve the fundamental understandings of this subject. The project was carried out in collaboration between the CHEC Research Centre at DTU Chemical Engineering and DONG Energy Power A/S, and was financially supported by Energinet.dk. The project work mainly involved conducting pilot-scale experiments in the CHEC entrained flow reactor, carrying out full-scale aerosol measurements at the Esbjergværket (ESV), doing global equilibrium calculations, and performing thermogravimetric experiments.

Through performing co-combustion experiments in the CHEC entrained flow reactor, the burnout, NO and SO<sub>2</sub> emissions, the transformation of ash forming species, the formation of deposits, and the partitioning of trace elements during co-combustion of coal and solid recovered fuel (SRF) were studied systematically. The effect of different coal properties, SRF properties, and mass share of SRF on co-combustion was investigated. Besides, global equilibrium calculations were conducted to interpret the results of the entrained flow experiments. The formation of fine particles during co-combustion of coal and SRF was also investigated, through performing full-scale aerosol measurements at the Esbjergværket (ESV). The influence of co-combustion on the concentration and composition of the fine particles was evaluated, and the impact on the dust emissions was discussed. In addition, a fundamental study on the interactions of coal and different waste materials during pyrolysis was conducted through thermogravimetric experiments. In general, the results obtained from this project have significantly improved the understandings of fuel conversion, ash transformation, ash deposition, and pollutant formation during co-combustion of coal and refuse derived fuels. These results have also provided essential knowledge regarding the fuel selection and process optimization of co-firing refuse derived fuels and coal under suspension-firing conditions.

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**A.** Report: Solid fuel interactions in co-combustion – a literature review. H. Wu, P. Glarborg, F. J. Frandsen, K. Dam-Johansen

**B.** Conference paper: Co-combustion of coal and SRF in an entrained flow reactor: a preliminary study. H. Wu, P. Glarborg, F.J. Frandsen, K. Dam-Johansen, P.A. Jensen, B. Sander

**C.** Journal Paper: Co-combustion of pulverized coal and solid recovered fuel in an entrained flow reactor – General combustion and ash behaviour. H. Wu, P. Glarborg, F.J. Frandsen, K. Dam-Johansen, P.A. Jensen, B. Sander

**D.** Journal Paper: Trace elements in co-combustion of solid recovered fuel and coal. H. Wu, P. Glarborg, F.J. Frandsen, K. Dam-Johansen, P.A. Jensen, B. Sander

**E.** Report: A global equilibrium analysis of co-firing coal and solid recovered fuel. H. Wu, P. Glarborg, F.J. Frandsen, K. Dam-Johansen

**F.** Journal Paper: Formation of fine particles in co-combustion of coal and solid recovered fuel in a pulverized coal-fired power station. H. Wu, A.J. Pedersen, P. Glarborg, F.J. Frandsen, K. Dam-Johansen, B. Sander

**G.** Conference paper: Combustion aerosols from co-firing of coal and solid recovered fuel in a 400 MW PF-fired power plant. A.J. Pedersen, H. Wu, F.J. Frandsen, Bo Sander

**H.** Report: Thermogravimetric analysis of combustible waste components. A. Munther, H. Wu, P. Glarborg

## 1. Introduction

This project deals with co-combustion of refuse derived fuels (RDF) with coal at suspension-firing conditions. The main focuses of the project are on the fuel conversion processes and the ash related issues during co-combustion of RDF and coal. The project was carried out in collaboration between the CHEC Research Centre at DTU Chemical Engineering and DONG Energy Power A/S, and was financially supported by Energinet.dk.

Utilization of waste in heat and power production has been long recognized as an effective waste treatment method which can significantly reduce the volume of waste and at the same time generate CO<sub>2</sub>-friendly heat and power. However, traditional waste incineration plants are often suffered from the low electrical efficiency and the formation of some harmful pollutants such as dioxins. Based on the extensive experiences of co-firing biomass and coal in Denmark,<sup>1,2</sup> it has been pointed out that co-combustion of refuse derived fuels with coal in a pulverized coal-fired power plant could potentially increase the electrical efficiency of utilizing waste and meanwhile reduce the formation of dioxins. On the other hand, this approach may induce several technical problems such as increased ash deposition and corrosion rate, decreased fuel burnout, deactivation of the SCR catalysts, increased emission of trace elements and fine particles, and the generation of low quality fly ash. In order to gain more insights into co-combustion of refuse derived fuels and coal as well as facilitate its application in practice, the following subjects have become the main focuses of this project:

- The carbon burnout, NO formation and SO<sub>2</sub> formation during co-combustion of refuse derived fuels and coal was investigated through performing pilot-scale experiments in the CHEC entrained flow reactor. The influence of different waste share, waste properties and coal properties was evaluated.
- The transformations of the ash forming species and the formation of deposits during co-combustion of refuse derived fuels and coal were studied through conducting pilot-scale experiments and performing global equilibrium calculations.
- The effect of co-combustion on the formation/emission of fine particles and trace elements was investigated through a full-scale test at the Esbjergværket (ESV) and the pilot-scale experiments in the CHEC entrained flow reactor.
- The fundamental interactions of different waste materials and coal during pyrolysis were investigated through thermogravimetric experiments.

The project was achieved by means of performing literature review, conducting laboratory- and pilot-scale experiments, carrying out full-scale measurements in a pulverized coal-fired boiler, and performing global equilibrium calculations. Valuable results have been gained through this project, which have significantly improved the understandings of fuel conversion, ash transformation, ash deposition, and pollutant formation during co-combustion of refuse derived fuels and coal. These results generally provide essential information regarding the fuel selection and process optimization for co-combustion of refuse derived fuels and coal under suspension-firing conditions.

In this report, the results of the project are documented by a number of publications enclosed in Appendix A–H. These publications contain the details of the conducted work, while the short main report provides a summary of the different work and the main conclusions.

## 2. Literature review

The fundamental combustion characteristics of different solid fuels and their interactions during co-combustion under suspension-firing conditions were reviewed through a literature survey. The review covered both the fundamental combustion aspects (such as devolatilization, ignition, burnout and gaseous pollutant formation) as well as the ash related issues (such as ash formation, deposition, corrosion and utilization processes) in co-combustion. The detailed review is provided in **Appendix A**, and a summary is given below.

Coal, biomass and waste materials have some fundamental differences in their devolatilization, ignition, char burnout, and pollutant formation processes. These differences may lead to certain interactions when different solid fuels are co-combusted. In general, the interactions of different solid fuels during the devolatilization stage are insignificant under suspension-firing conditions, although some synergies have been observed under fixed-bed combustion conditions.<sup>3-5</sup> The ignition and flame characteristics during suspension-firing can be greatly influenced when a secondary fuel is co-fired with the primary fuel. As an example, co-combustion of coal with biomass (such as straw or wood) with relatively high moisture content and large particle size has been shown to result in a delayed ignition and a two-stage flame structure.<sup>6,7</sup> The burnout of the solid fuels during co-combustion is to a large extent dependent on the char reactivity of the fuel mixture. Compared to dedicated coal combustion, co-combustion of coal with biomass/waste often results in an improved burnout, which is primarily linked to the relatively high reactivity of the char from biomass/waste. The NO<sub>x</sub> emission during co-combustion is closely related to the amount and association of fuel nitrogen as well as the chemical interactions of the nitrogen species and other gaseous species during combustion. When coal is co-fired with a secondary fuel with relatively low fuel-N content and high volatile content, the NO<sub>x</sub> emission is often found to be reduced, either due to a dilution effect and/or the positive chemical interactions between the volatiles and the nitrogen species. The SO<sub>2</sub> emission in co-combustion is largely dependent on the sulfur content in the fuels. On the other hand, the inorganic elements in the fuels, such as K and Ca, may be able to capture some gaseous SO<sub>2</sub> and reduce the emission.<sup>8</sup>

Ash related issues such as slagging, fouling, corrosion and particulate emissions are of significant concerns in co-combustion of different solid fuels. A primary reason is that biomass and waste materials are usually characterized by significantly larger Cl and alkali contents, and relatively smaller alkali/Si and alkali/S molar ratios than coals (see Figure 1). This implies that the formation of alkali chlorides would be more significant during biomass/waste combustion. On the other hand, co-combustion of biomass/waste with coal may offer an opportunity to reduce the formation of alkali chlorides, through the reactions between the alkali chlorides from the biomass/waste and the silicates and/or sulfur species from the coal. These reactions have been observed during co-combustion of coal with straw.<sup>9</sup> The fundamental mechanisms of these reactions have been studied through laboratory-scale experiments as well as kinetic modeling.<sup>10-12</sup> The influence of these reactions on the formation of fine particles has also been demonstrated through laboratory- and full-scale experiments. The results indicated that the formation of submicron aerosols could be significantly reduced when biomass was co-fired with coal. The effect of co-combustion on the formation of deposits was investigated extensively, based on different secondary fuels such as straw, wood, and waste materials. In general, when a biomass/waste with high deposition tendency (such as straw) is co-fired with coal, the deposition tendency of the fly ash would be significantly reduced compared to dedicated biomass/waste combustion, primarily due to chemical effect of the coal ash. This would also considerably reduce the corrosion potential of the formed deposits. These positive

synergy effects have been observed in different solid fuels, and the knowledge can be applied to optimize the fuel selection during co-combustion.

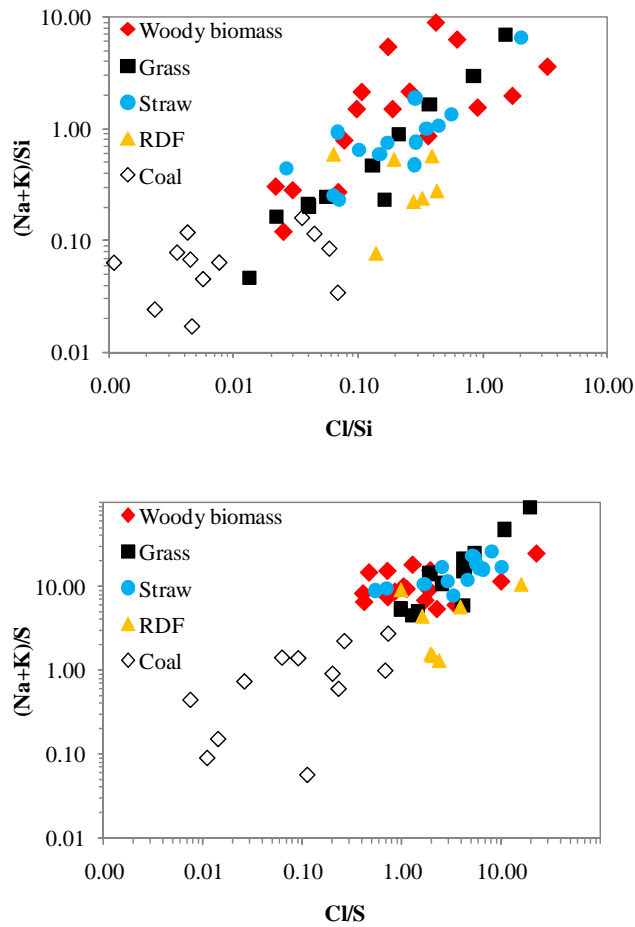


Figure 1 Molar ratios of (Na+K)/Si versus Cl/Si in different solid fuels, and molar ratios of (Na+K)/S versus Cl/S in different solid fuels.

### 3. Co-combustion of coal and solid recovered fuel (SRF) in an entrained flow reactor

The CHEC entrained flow reactor is an electrically heated horizontal tube reactor which was designed to simulate the combustion environment of a suspension-fired boiler. In this project, a large number of co-combustion experiments were carried out in the reactor. The objective was to study the influence of co-combustion on fuel conversion, ash transformation, pollutant formation, trace element partitioning, and ash deposition under different fuel/fuel share conditions.

A schematic drawing of the entrained flow reactor is shown in Figure 2. During the experiments, the fuels/fuel mixtures were combusted under well-controlled temperature and gas conditions. The residue ash from the combustion was collected in a bottom chamber, a cyclone and a filter, respectively. The flue gas compositions were analyzed by two gas analyzers. In addition, a well-controlled deposit probe was mounted at the outlet of the reactor, which was used to simulate the deposit formation at the convective section of a boiler.



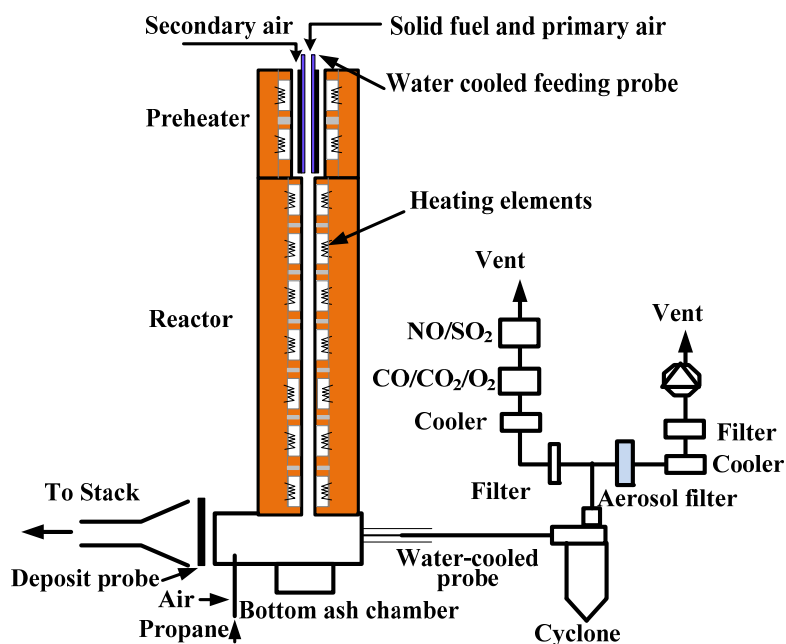


Figure 2 Schematic drawing of the CHEC entrained flow reactor.

Two rounds co-combustion experiments were carried out in the CHEC entrained flow reactor. The first-round experiments were focused on co-combustion of different bituminous coals with a solid recovered fuels (SRF). The second-experiments were emphasized on the impact of SRF properties (particularly the Cl and alkali content) on co-combustion. The experimental results from the two rounds co-combustion experiments are summarized in the following. In addition, the results from global equilibrium calculation are included to interpret the observed experimental results.

### 3.1 First-round co-combustion experiments

Sold recovered fuels (SRF) refers to non-hazardous waste stream usable for energy recovery in waste incineration or co-incineration plants.<sup>13</sup> The first-round co-combustion experiments aimed to provide a preliminary assessment of co-firing coal and SRF under suspension-firing conditions. During the experiments, two different bituminous coals, i.e. a South Africa bituminous coal (SAKLEI) and a Columbia bituminous coal (COPRIB), were co-combusted with a SRF comprised mainly of paper, wood and plastics. The SRF used in the experiments was obtained from the initial full-scale co-combustion tests carried out by DONG Energy Power A/S at the Esbjergværket (ESV) in April 2008. The co-combustion experiments were performed at different SRF mass share conditions (up to 20 wt.%). The detailed information regarding the experiments is given in **Appendix B**.

The results from the first-round experiments showed that when coal was co-combusted with SRF, the unburnt carbon in the fly ash was generally increased. On the other hand, the emissions of NO and SO<sub>2</sub> were reduced with an increasing mass share of SRF, probably due to the low nitrogen and sulfur contents in the SRF as well as the synergy effects of the fuels during combustion. The influence of co-combustion on the deposit formation rate on an air-cooled probe appeared to be different for the two coals. As illustrated in Figure 3, when COPRIB coal was co-fired with SRF, the deposit formation rate decreased slightly with an increasing share of SRF. However, for SAKLEI coal and SRF co-combustion, the deposit formation rate showed a slight increasing tendency up to 10 wt.% of SRF, and then started to decrease at larger SRF shares. Similar

tendencies were also observed for the ash deposition tendency (i.e. deposition flux/ash flux). Analyses of the fly ash composition indicated that the concentrations of Cd, Cu, Pb and Zn were significantly higher in the fly ash from co-combustion, as compared to the fly ash from coal combustion. These trace elements were generally enriched in smaller fly ash particles, and the enrichment factor appeared to be increased significantly during co-combustion. The detailed results and discussions regarding the first-round co-combustion experiments are available in **Appendix B**.

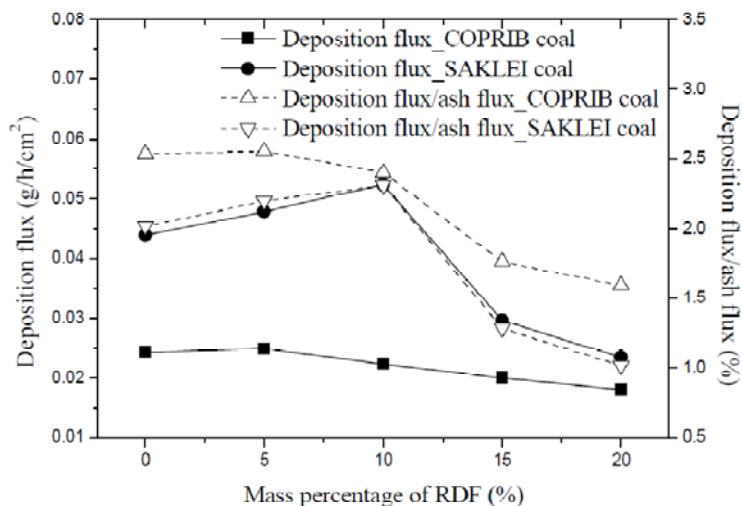


Figure 3 Deposition flux and deposition flux/ash flux during first-round co-combustion of coal and SRF in the entrained flow reactor.

### 3.2 Second-round co-combustion experiments: general combustion and ash behavior

The main objective of the secondary-round co-combustion experiments was to study the effect of different SRF properties (especially the Cl and alkali content) on co-combustion. The experiments were carried out based on a Columbia Bituminous coal (COCERR) and a SRF different from that used in the first-round experiments. Both fuels were collected from the full-scale co-combustion tests carried out at the Esbjergværket (ESV) during December 2008 and January 2009. In order to simulate the variation of SRF properties, different additives (including PVC, NaCl, ammonium sulfate and kaolinite) were mixed with the SRF, and the mixtures were co-combusted with coal in the entrained flow reactor. The details of the experiments can be found in **Appendix C**.

The general combustion and ash behaviors observed during the second-round co-combustion experiments were described and discussed in details in **Appendix C**. In general, it revealed that the fuel burnout, NO and SO<sub>2</sub> emissions in co-combustion of coal and SRF were decreased with increasing share of SRF. The majority of the additives inhibited the burnout, except for NaCl which seemed to have a promoting effect. The impact of additives on NO emission was mostly insignificant, except for ammonium sulfate which greatly reduced the NO emission. For SO<sub>2</sub> emission, it was found that all of the additives increased the S-retention in ash.

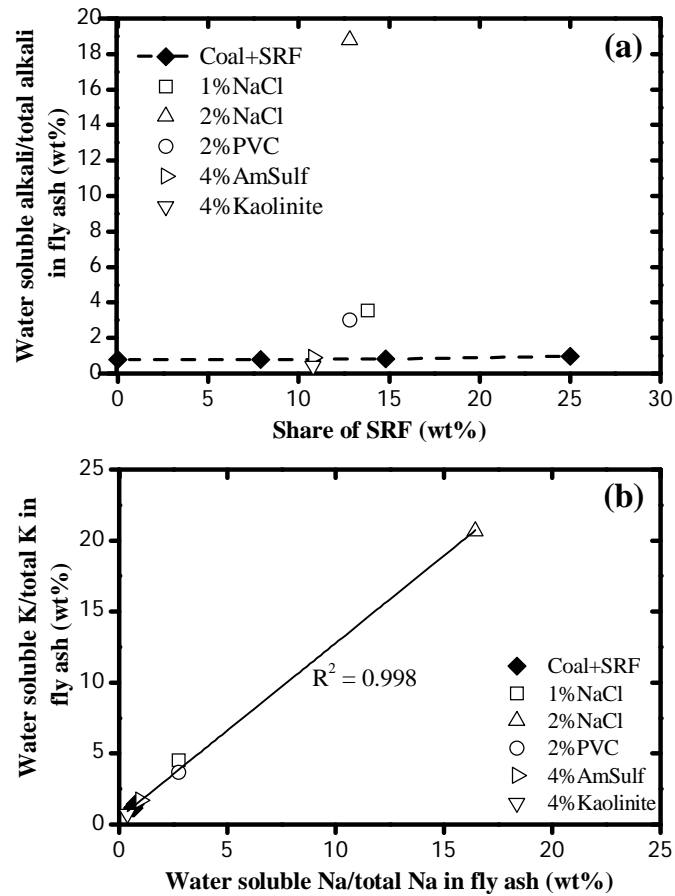


Figure 4 (a) percentage of water soluble alkali in the fly ash from the second-round co-combustion experiments with different share and type of secondary fuels, (b) comparison of the percentage of water soluble K/total K and the percentage of water soluble Na/total Na in the fly ash.

Analysis of the bulk composition of fly ash from different experiments indicated that the majority of S and Cl in the fuels were released to gas phase during combustion, whereas the K and Na in the fuels were mainly retained in ash. As shown in Figure 4a, when co-firing coal and SRF, approximately 99 wt.% of the K and Na in fly ash was present in water insoluble form such as aluminosilicates or silicates. On the other hand, the addition of NaCl, PVC and ammonium sulfate generally promoted the vaporization of Na and K, and resulted in an increased formation of water soluble alkalis such as alkali chlorides or sulfates. The vaporization degree of Na and K was found to be correlated during the experiments (see Figure 4b), suggesting an interaction between the vaporization of Na and K during pulverized fuel combustion. By collecting deposits on an air-cooled probe during the experiments, it was shown that the ash deposition propensity in co-combustion was decreased with increasing share of SRF. The addition of NaCl and PVC significantly increased the ash deposition propensity, whereas the addition of ammonium sulphate or kaolinite showed a slight decreasing effect. The chlorine content in the deposits generally implied a low corrosion potential during co-combustion of coal and SRF, except for the experiments with NaCl or PVC addition.

### 3.3 Second-round co-combustion experiments: trace element behavior

The behavior of trace elements during the second-round co-combustion experiments was studied in details in **Appendix D**. The trace elements focused were As, Cd, Cr, Pb, Sb and Zn, since these

elements were significantly enriched in the SRF as compared to the coal. During the experiments, it was found that when coal was co-fired with SRF, the As, Cd, Pb, Sb and Zn content in the filter ash/cyclone ash increased almost linearly with their content in the fuel ash. However, this linear tendency was affected when the fuels were mixed with additives, indicating that the additives may influence the partitioning of trace elements through chemical reactions.

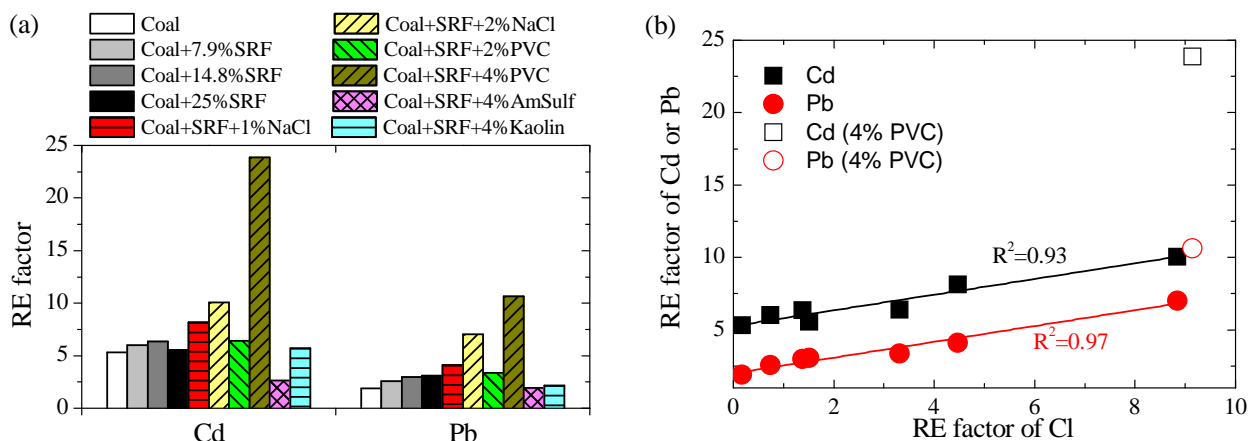


Figure 5 (a) the RE factor of Cd and Pb in the second-round co-combustion experiments (b) comparison of the RE factors of Cd and Pb versus the RE factor of Cl from different experiments (the open symbols denote the results from the addition of 4 wt.% PVC).

The volatility of trace elements during combustion was assessed by applying a relative enrichment (RE) factor (see an example in Figure 5a). In addition, TEM–EDS analysis was conducted to provide qualitative interpretations. The results generally indicated that As, Cd, Pb, Sb and Zn were highly volatile when co-firing coal and SRF, whereas the volatility of Cr was relatively low. Compared to coal combustion, co-firing of coal and SRF slightly enhanced the volatility of Cd, Pb and Zn, but reduced the volatility of Cr and Sb. The Cl-based additives increased the volatility of Cd, Pb and As (indicated by the correlation in Figure 5b), whereas addition of ammonium sulfate generally decreased the volatility of trace elements. Addition of kaolinite reduced the volatility of Pb, while the influence on other trace elements was insignificant. The results implied that trace element emission would be significantly increased when coal is co-fired with SRF, which may greatly enhance the toxicity of the dusts from coal-fired power plant. In order to minimize trace element emission in co-combustion, utilizing SRF with low Cl content and coal with high S and aluminosilicates content would be desirable.

### 3.4 Second-round co-combustion experiments: global equilibrium calculations

Global equilibrium calculations have been performed to study the behavior of ash forming species during co-combustion of coal and SRF. The calculations were carried out by using the software FastSage 6.0, and the calculation inputs were derived from the secondary-round co-combustion experiments of coal and SRF in the entrained flow reactor. The main focus of the calculations was on the distribution of Cl, alkali and S species under different co-combustion conditions. The detailed calculation approaches, results and discussions are available in **Appendix E**.

As illustrated in Figure 6, the equilibrium calculations revealed that co-combustion of coal and 25 wt.% SRF could significantly reduce the formation of NaCl (g) and KCl (g) in moderate temperature (800–1000 °C), as compared to 100% SRF combustion. The simulation results were compared with the experiment results obtained at the same fuel conditions, and qualitative

agreements were achieved. Both results suggested that co-combustion of coal and SRF would be a feasible method to increase the electrical efficiency of utilizing waste, as the aluminosilicates content in the coal could mitigate the ash related problems caused by the relative high chlorine and alkali content in the SRF.

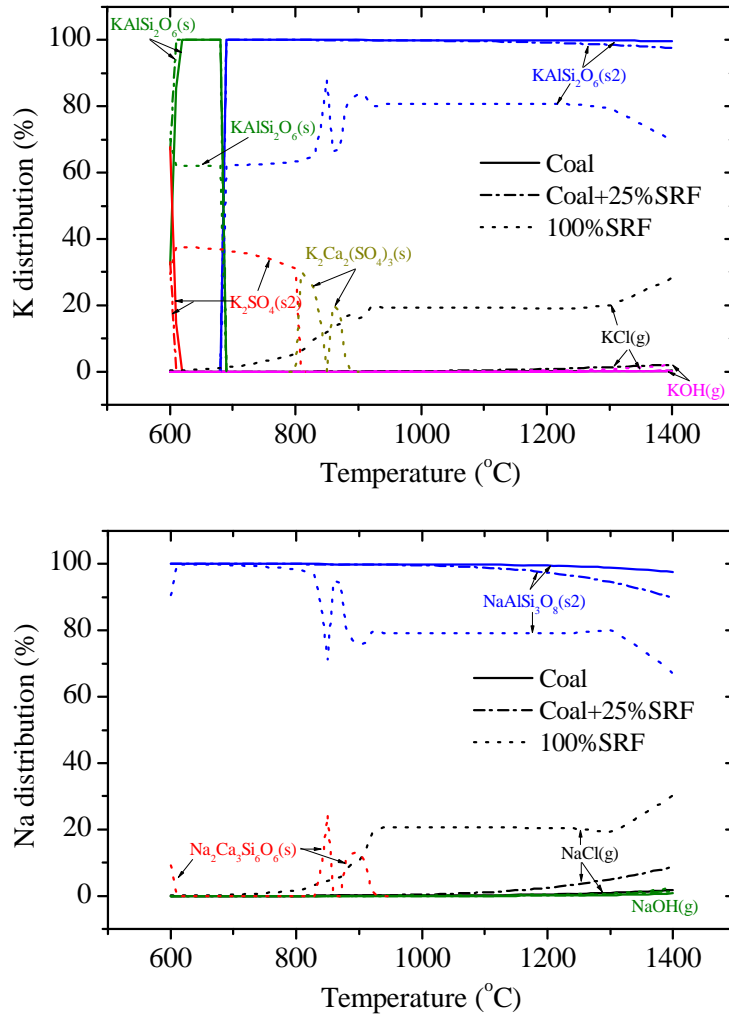


Figure 6 Equilibrium distributions of K, Na, S and Cl species in dedicated coal combustion, co-combustion of coal and 25 wt.% SRF, and 100% SRF combustion.

The influence of different SRF quality on the behavior of co-combustion was evaluated through adding PVC and NaCl to the fuel mixture. Both the simulation and experimental results indicate that formation of NaCl (g) and KCl (g) at temperatures above 1000 °C is significantly increased with the addition of PVC and NaCl. And a large fraction of the formed NaCl (g) and KCl (g) is not converted to aluminosilicates during the flue gas cooling in the experiments, probably due to the kinetic limitations. The results suggest that it is important to control the chlorine and alkali content in SRF, in order to facilitate co-combustion of coal and SRF in practice.

#### 4. Aerosol formation in co-combustion of coal and SRF at Esbjergværket

Full-scale tests on co-combustion of coal and SRF have been carried out by DONG Energy Power A/S in the Esbjergværket (ESV), during December 2008 and January 2009. As part of a comprehensive measurement program, the fine particles formed in the plant were sampled by using a low-pressure cascade impactor, and the collected samples were analyzed by Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM), both equipped with Energy Dispersive Spectroscopy (EDS). This work aimed to explore the impact of SRF co-combustion on the formation of fine particles, based on the particle size distribution, morphology and element compositions of the fine particles from the plant. The detailed results and discussions of the fine particle measurement are given in **Appendix F and Appendix G**. A summary of these results is given below.

As shown in Figure 7, the fine particles from dedicated coal combustion and co-combustion both showed an ultrafine mode centered at approximately 0.1  $\mu\text{m}$ . Compared to coal combustion, co-combustion of coal and SRF generally increased the formation of submicron particles, especially the ultrafine particles below 0.2  $\mu\text{m}$ . On the other hand, the mass concentration of the supermicron particles appeared to be decreased when coal was co-fired with SRF.

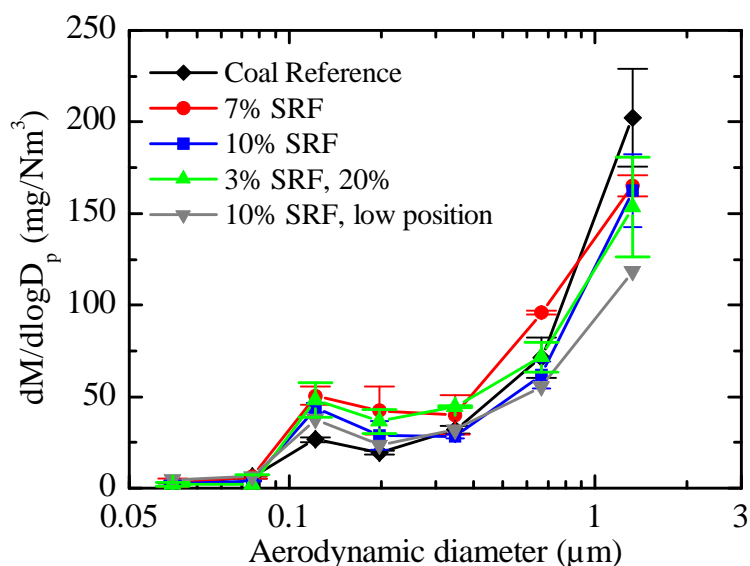


Figure 7 Mass-based particle size distribution from coal combustion and co-firing of coal and SRF at different conditions.

The morphology of the particles (see the TEM pictures in Figure 8) indicated that supermicron particles from co-combustion were primarily formed from the melting of minerals. The ultrafine particles were generated through homogeneous nucleation and coagulation of the vaporized inorganic species, while for the particles in between supermicron and ultrafine particles, condensation of the vaporized species or aggregation of the nucleates on the existing spherical submicron particles may also be an important formation mechanism.

The elemental composition of the particles from coal combustion showed that S and Ca were significantly enriched in ultrafine particles and P was also enriched considerably. However, compared to supermicron particles, the contents of Al, Si and K were depleted in the ultrafine particles. The observed high volatility of Ca was attributed to the high combustion temperature and

relative low oxygen condition in the boiler which may promote the vaporization of Ca during char oxidation. The discrepancies on the observed volatilities of Ca and alkalis between some laboratory experiments and full-scale measurements were discussed. The composition of the fine particles from co-combustion was generally similar to those from coal combustion. However, as shown in Figure 9, the ultrafine particles from co-combustion had slightly higher Ca, P, and K contents, and lower S content. The practical implications related to the fine particle formation in co-combustion of coal and SRF were discussed based on the full-scale results.

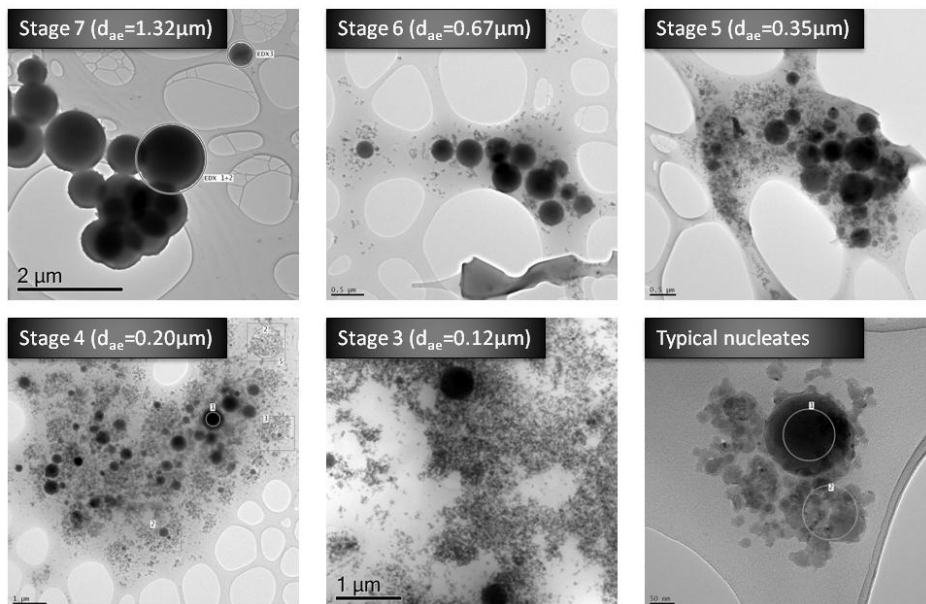


Figure 8 Morphology of the particles collected from co-combustion of coal and 7% (thermal basis) SRF.

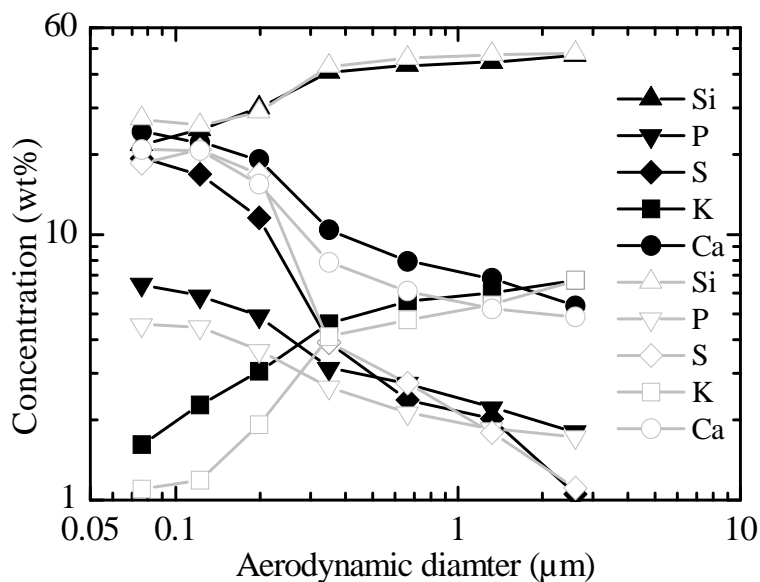


Figure 9 Comparison of the particle elemental compositions from co-combustion of coal with 7% SRF (solid symbol) and coal combustion (open symbol).

## 5. Study on co-pyrolysis of coal and different waste materials

With the purpose of optimizing co-combustion of coal and refuse derived fuel, it is desirable to be able to predict the combustion behavior of the fuel mixture. Since pyrolysis is an important sub-step of combustion which influences the volatile release and char reactivity, it is essential to characterize the pyrolysis behavior of coal and refuse derived fuels, particularly the interactions among these fuels when they are pyrolyzed together. With this objective, co-pyrolysis of coal and different waste components was studied through performing experiments in a STA (simultaneous thermal analyzer). The investigated waste components were wood, paper, polypropylene (PE) and polyvinyl chloride (PVC). The major conclusions of this study are given in the following, and the details are available in **Appendix H**.

According to the thermogravimetric analyses, significant interactions were observed when PVC was co-pyrolyzed with wood, paper or coal. A typical example is given in Figure 10. It is shown that during co-pyrolysis of wood and PVC, the two expected low-temperature DTG (derivative thermogravimetric) peaks from pure wood and PVC are fused into one single peak, with  $T_{\text{peak}}$  close to the expected PVC-peak. Besides, a decreased final weight loss is also observed from the TG-data. The observed interactions are presumably linked to the HCl released from PVC which may have acted as a catalyst for the dehydration and decomposition of the cellulose components in wood.<sup>14</sup> Similar interactions were also observed during co-pyrolysis of paper and PVC. However, for co-pyrolysis of coal and PVC, it appeared that the decomposition of PVC occurred at higher temperatures, when it was mixed with coal. Besides the strong interactions mentioned above, some interactions were also observed between PE & wood, PE & PVC, PE & paper and PE & coal, but to a smaller degree. No interactions were found between coal & wood, coal & paper, and wood & paper. Since PVC was the only waste component which interacted strongly with coal, the interaction between coal and a real waste mixture was likely similar to the interaction observed between PVC & coal. In other words, without the presence of large amount of PVC, the interactions between coal and waste mixture might be negligible during co-pyrolysis, thus separate/non-interactive models would be adequate to describe the co-pyrolysis processes.

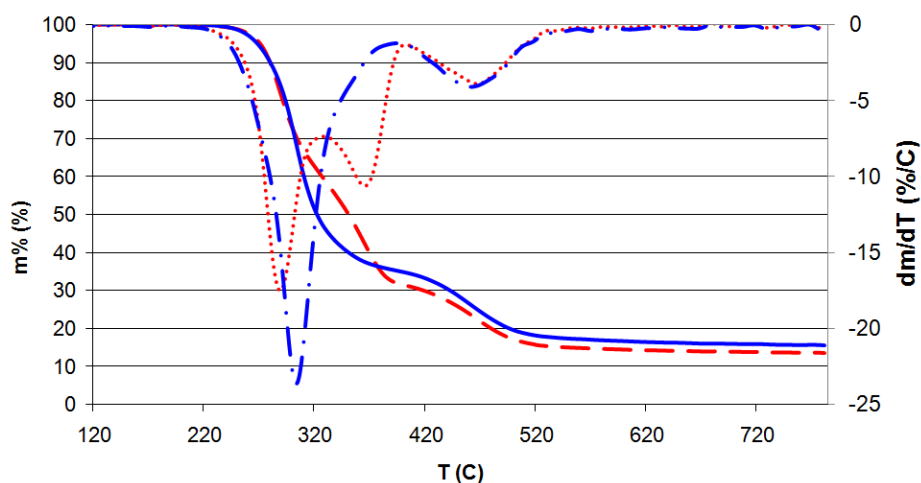


Figure 10 TG-curves for the pyrolysis of calculated wood-PVC (— —) and experimental wood-PVC (—), and DTG-curves for the pyrolysis of calculated wood-PVC (•••) and experimental wood-PVC (•—).



## 6. Conclusion

This project aimed to provide a general assessment of the technical issues related to co-combustion of coal and refuse derived fuels, and to improve the fundamental knowledge on this subject. The project was achieved through conducting pilot-scale experiments in the CHEC entrained flow reactor, carrying out full-scale aerosol measurements at the Esbjergværket (ESV), doing global equilibrium calculations, and performing thermogravimetric experiments.

The results revealed that when coal was co-fired with solid recovered fuels (SRF) in the entrained flow reactor, the burnout was decreased with increasing mass share of the SRF, primarily attributed to the relatively large particle size of the SRF as well as the slightly unstable flame conditions during co-combustion. The NO and SO<sub>2</sub> emissions were reduced when co-firing coal with SRF, due to the low nitrogen and sulfur content in the SRF as well as the positive synergy effects of the fuels during combustion. In most cases, the Cl content in the fly ash was very low (<0.1 wt.%) when coal was co-fired with up to 25 wt.% SRF, indicating that the majority of the Cl in the SRF were released to gas phase during co-combustion. This tendency was observed in the experiments and was also supported by global equilibrium calculations. During co-combustion, the formation of fouling deposits generally appeared to be decreased with increasing mass share of SRF, and the resulting deposits showed a very small Cl content (<0.01 wt.%), suggesting a low corrosion potential on superheater tubes when coal was co-combusted with up to 25 wt.% SRF. On the other hand, if the SRF contained very large Cl and/or alkali content, the formation of alkali chlorides would be significantly promoted, which was both observed in the experiments and in the global equilibrium calculations. This would lead to the formation of large amount of deposits with high corrosion potential. The results indicated that the Cl and alkali content in the SRF should be carefully controlled in order to facilitate co-combustion of coal and SRF in practice.

The trace element concentrations in SRFs are often significantly higher than that in coals. Investigations on the partitioning of typical trace elements during co-combustion of coal and SRF revealed that the As, Cd, Pb, Sb and Zn were highly volatile during combustion, while the volatility of Cr was relatively low. Compared to coal combustion, the volatility of Cd, Pb and Zn was slightly increased in co-combustion of coal and SRF, whereas the volatility of Cr and Sb was to some extent reduced. With the injection of Cl based additives, the volatility of Cd, Pb and Zn was increased significantly. The addition of ammonium sulfate generally decreased the volatility of trace elements, while the addition of kaolinite reduced the volatility of Pb. The results implied that co-combustion of coal and SRF may increase considerably the trace element content in the fly ash, mainly due to the significantly large trace element content in the SRF, but also related to the interactions of the two fuels in co-combustion.

The formation of fine particles during full-scale co-combustion of coal and SRF was investigated by using a low-pressure cascade impactor. The results revealed that co-combustion of coal and SRF generally promoted the formation of ultrafine particles with a concentration peak around 0.1 μm, while the total concentration of PM<sub>2.5</sub> were decreased. Composition analyses generally showed that Ca, S and P were significantly enriched in the ultrafine particles. Compared to coal combustion, the content of Ca, P and K appeared to be larger in the fine particles from co-combustion, whereas the S content was slightly smaller. The emissions of dust from the power plant were significantly increased during co-combustion of coal and SRF, which was presumably related to a reduction of the collection efficiency of the electrostatic precipitator (ESP), rather than the increased formation of ultrafine particles.

The fundamental interactions between coal and different waste materials during the pyrolysis stage were investigated through thermogravimetric experiments. It appeared that PVC was the only waste component which interacted strongly with coal. Therefore the interaction between coal and a waste mixture was likely similar to the interaction observed between PVC and coal. Without the presence of large amount of PVC, the interactions between coal and waste mixture might be negligible during pyrolysis, thus separate/non-interactive models would be adequate to describe the pyrolysis processes in co-combustion.

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