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Published in:
4th European Combústion Meeting

Publication date:
2009

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Wu, H., Glarborg, P., Frandsen, F., Dam-Johansen, K., Jensen, P. A., & Sander, B. (2009). Co-combustion of coal and SRF in an entrained flow reactor: a preliminary study. In 4th European Combústion Meeting Technical University of Denmark, Department of Chemical Engineering.

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Co-combustion of coal and SRF in an entrained flow reactor: a preliminary study

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Abstract

Investigations on co-firing of SRF with two kinds of bituminous coal were carried out in an entrained flow reactor. The experimental results showed that co-combustion of coal and SRF increased the unburnt carbon in fly ashes. The emissions of NO and SO₂ were reduced with an increasing share of SRF both due to the low nitrogen and sulphur contents in the SRF and the synergy effects of the fuels. Influences of co-combustion on the deposit formation rate on an air-cooled probe were rather different for the two coals. For COPRIB coal and SRF co-combustion, the deposit formation rate decreased slightly with an increasing share of SRF. For SAKLEI coal and SRF co-combustion, the deposit formation rate showed an increasing trend up to 10 mass percent of SRF, and started to decrease at a higher SRF share. By analyzing the ash samples, it has been found that the concentrations of some trace elements such as Cd, Cu, Pb and Zn were highly enriched in the fly ashes from coal and SRF co-combustion. The effect may be due to there are more organically associated trace elements in SRF than coals, and the high Cl content in SRF may enhance the enrichment of trace elements in fly ashes.

Introduction

With the target of reducing the CO₂ emission, replacing part of the fossil fuel consumption by biomass or waste which is usually considered to be CO₂ neutral has become an attractive option. Among the various technologies that utilize biomass or waste as an energy source, one of the most simple and promising methods is to co-fire biomass or waste together with coal in existing coal-fired power stations [1].

Solid recovered fuels (SRF) commonly refer to non-hazardous waste streams usable for energy recovery in waste incineration or co-incineration plants [2]. In comparison with combustion in waste incineration plants, co-combustion of SRF and coal in pulverized coal-fired boilers could offer several advantages. For example, co-combustion is a cheap approach of treating the increasing amount of waste, since the capital cost for co-combustion in an existing coal-fired boiler is much lower than building a new dedicated incineration plant [3]. Furthermore, the electrical efficiency in a pulverized coal-fired boiler is generally higher than that in a dedicated waste incineration plant. Therefore, co-combustion can have the potential to increase the efficiency of utilizing waste energy [4]. The power generation in a coal-fired boiler is normally significantly larger than that from a waste incineration plant. Hence, the power produced from waste can be increased largely, if co-combustion is applied in coal-fired boilers. The NO_x and/or SO_x emissions from power plants may be reduced by co-combustion, since combustible waste usually contains lower nitrogen and sulphur contents than coals, and the synergy effects between coal and waste may also lead to the reduction of NO_x and/or SO_x emissions [5]. Moreover, compared to the fly ashes from dedicated waste incineration plants which are mostly landfilled, co-combustion of coal and

waste may generate more valuable fly ashes that may be used in cement or concrete production.

Besides advantages, problems and challenges are associated with co-combustion of coal and SRF as well. For example, SRF often contains relatively higher alkali and chlorine contents than coals. When a secondary fuel with high alkali and chlorine contents is co-fired with coal, ash deposition and corrosion problems in the boilers may become more severe [6,7], fly ash qualities may be lower [4,8], and the deactivation of the SCR catalysts may happen very fast [6,8]. In addition, combustible waste from industrial or household often contains much higher trace element contents than coals. Thus, the emissions of trace element may become a large concern for co-combustion of coal and waste [9].

All of the technical problems mentioned above could limit the application of co-combustion of coal and SRF in an existing pulverized coal-fired plant. Therefore, in order to promote coal and SRF co-firing to an industrial scale, it is necessary to evaluate the influences of co-combustion on deposition formation, corrosion, fly ash qualities, and trace element emissions.

Specific Objectives

The objective of this study is to investigate the impacts of SRF and coal co-combustion on carbon burnout, gaseous emissions, deposit formation, fly ash qualities and trace element emissions in a pilot-scale facility. The results from this study could provide valuable information about the suitable SRF fraction and coal type that may be applied in co-combustion of coal and SRF in a pulverized coal-fired power plant.

Experimental

As shown in Figure 1, co-combustion experiments are carried out in an entrained flow reactor in this study.

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The reactor, which has been used in a number of previous studies [10,11], is designed to simulate the combustion environment of a suspension fired boiler. The setup mainly consists of a gas supplying system, a fuel feeding system, a gas preheater, a flow reactor, a bottom chamber, a particle and gas extraction system, and a deposition system. During the experiment, fuel particles are injected into the reactor together with primary air. To have a comparable residence time for different experiment, the flow rate of the primary air and total air is maintained at 13 NI/min and 95 NI/min respectively. The feeding rate of the fuel particles is controlled by a gravimetric screw feeder, and is adjusted for different experiment in order to keep the excess air ratio to be around 1.35. Upon injection, the fuel particles are mixed with preheated secondary air at the inlet of the flow reactor, and the combustion of the particles takes place in the reactor subsequently. The electrical heated flow reactor used in this study is 2 meters long and has an internal diameter of 79 mm. The temperature of the heating element in the preheater is set to be 900 °C, and the wall temperature of the flow reactor is set to be 1000-1300 °C for all of the experiments.

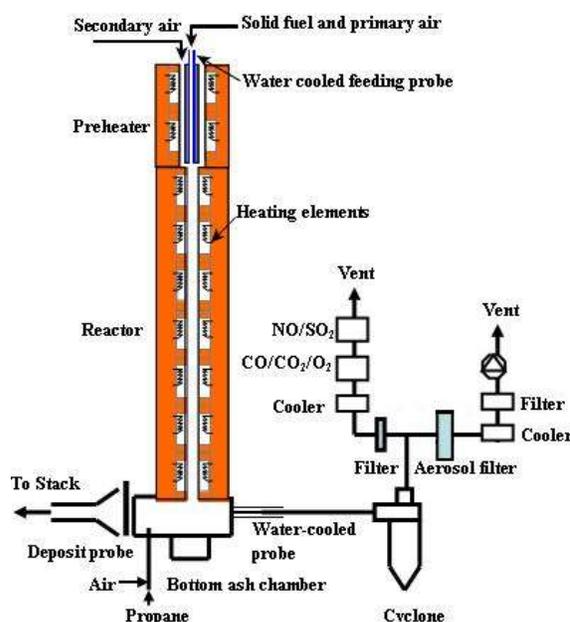


Figure 1. Schematic drawing of the entrained flow reactor.

During combustion experiments, the bottom ashes are collected in a bottom ash chamber. The flue gas from combustion is divided into two parts. As shown in Figure 1, a small part is sampled through a water-cooled probe. Large ash particles are collected by a cyclone with a cut diameter of 2.5 μm , and fine fly ash particles are collected in an aerosol filter using a polycarbonate membrane with a pore size of 0.1 μm . After removal of particles, the sampled flue gas is cooled to remove the water content and the concentrations of CO, CO₂, O₂,

NO and SO₂ are measured by continuous gas analyzers. The majority of the flue gases together with fly ashes flows through a deposit probe and then to the ventilation system. In front of the deposition probe, a propane burner is mounted to control the flue gas temperature to be 800 °C. The air-cooled deposit probe used in this study is made of stainless steel, with an outer diameter of 1 cm and a length of 10 cm. During the experiment, the deposit probe is placed in front of the exit slit of bottom chamber which has a size of 4*8 cm. By adjusting the temperature of the air preheater and the heating tape connected to the probe, surface temperature of the deposit probe is controlled to be 550°C during the experiments.

Table 1. Properties of the fuels.

| Properties | COPRIB coal | SAKLEI coal | SRF |
|---------------------|-------------|-------------|-------|
| LHV (MJ/kg wet) | 27.44 | 26.04 | 20.62 |
| Moisture (wt% wet) | 3.12 | 3.76 | 4.80 |
| Volatiles (wt% wet) | 37.11 | 24.25 | 73.11 |
| Ash (wt% wet) | 7.07 | 14.72 | 11.52 |
| C (wt% dry) | 72.6 | 70.3 | 49.0 |
| H (wt% dry) | 4.91 | 3.85 | 6.53 |
| N (wt% dry) | 1.44 | 1.76 | 0.86 |
| S (wt% dry) | 0.77 | 0.66 | 0.28 |
| Cl (wt% dry) | 0.002 | 0.004 | 0.68 |
| Si (wt% dry) | 1.8 | 3.4 | 1.7 |
| Al (wt% dry) | 0.84 | 2.40 | 0.61 |
| P (wt% dry) | 0.006 | 0.15 | 0.045 |
| Ca (wt% dry) | 0.13 | 0.86 | 2.30 |
| Na (wt% dry) | 0.046 | 0.014 | 0.25 |
| K (wt% dry) | 0.10 | 0.072 | 0.11 |
| Cd (ppm dry) | 0.24 | 0.03 | 2.1 |
| Cr (ppm dry) | 8.5 | 29.0 | 76.0 |
| Cu (ppm dry) | 6.7 | 11.0 | 290.5 |
| Pb (ppm dry) | 2.7 | 9.6 | 100.0 |
| Zn (ppm dry) | 12.0 | 9.5 | 420.0 |

The fuels used in the experiments are a SRF and two different bituminous coals. The SRF is produced from combustible wastes which mainly consist of paper, wood, and plastics. To be able to feed it into the reactor, the SRF is grinded to an average particle size of 175 μm by a cutting mill and an Alpine® pin mill. The two bituminous coals, i.e. SAKLEI coal and COPRIB coal, are pulverized to a particle size with 90% of the particles lower than 60 μm . Fuel compositions of the SRF and coals are given in Table 1. It is shown that the SRF is significantly rich in some of the trace elements, such as Cd, Cr, Cu, Pb and Zn. Compared to the two bituminous coals, the contents of volatiles, Cl, Na, and Ca are higher in the SRF, while the lower heating value (LHV) and the contents of nitrogen and sulphur are lower in the SRF. For the two coals selected in the experiments, a large difference between them is the ash content. Besides, Al and Si contents are much higher in the SAKLEI coal than in the COPRIB coal.

In this study, two baseline experiments are first performed for the two bituminous coals, and then each of the two bituminous coals is co-fired with 5, 10, 15,

and 20 wt% of SRF. In the co-combustion experiment, SRF and coal particles are premixed in a special mixer. The homogeneity of the fuel mixture is proved by the relatively stable flue gas concentrations observed during the experiment. With the purpose of collecting sufficient deposits and ash samples for analyses as well as avoiding a significant drop of deposits from the probe, the time for an experiment is determined to be 1.5 hour. After an experiment, the deposits on the air-cooled probe and the ashes from the cyclone, aerosol filter, and bottom chamber are collected, weighted and preserved for chemical analysis. To minimize the impacts of the deposits inside the reactor on the experimental results, the entrained flow reactor is heated to 1400°C to perform high temperature cleaning for 20 hours after every experiment.

Results and Discussion

In Figure 2, fuel carbon burnout and percentage of unburnt carbon in the ashes obtained from different co-combustion experiment are shown. The carbon burnout of the fuel or fuel mixture is determined according to the following equation [12]:

$$B_c = \left[1 - \frac{A_0}{100 - A_0} \frac{100 - A_i}{A_i} \right] \times 100 \quad (1)$$

where B_c is the carbon burnout, A_0 is the ash content of the dry fuel, and A_i is the ash content of the extracted fly ash sample. Two assumptions are applied in the calculation of carbon burnout, i.e. the ashes in the fuel are inert during the combustion and the unburnt carbon contents are the same for the bottom ashes and fly ashes. The unburnt carbon content of the ashes is determined by keeping the fly ashes at 750 °C for two hours, according to a procedure described in [13].

As shown in Figure 2, fuel carbon burnout generally decreases with an increasing share of SRF, and this decreasing effect is similar for both of the coals. However, when 5 wt% of SRF is co-fired with coal, the decrease of fuel carbon burnout is almost negligible. In the case that the SRF share is 10 wt% or even higher, the decrease of the carbon burnout becomes very significant. Considering about the unburnt carbon in ashes, for 5 wt% SRF and coal co-combustion, the percentage of unburnt carbon in the ashes is quite close to that from dedicated coal combustion and the value is lower than 5 wt%. However, when the percentage of SRF is raised to 10 wt% or higher, unburnt carbon in the ashes increases significantly to a value much higher than 5 wt%. High percentage of unburnt carbon in the ashes not only leads to low combustion efficiency but also limits the utilization of fly ashes in concrete production [14]. The significant reduction of carbon burnout at a high share of SRF is possibly caused by the significant agglomeration behavior of the grinded SRF particles. With a higher share of SRF, the agglomeration level of the fuel mixture becomes more significantly. These agglomerated fuel particles are more difficult to ignite and combust completely than separated fuel particles, thus lead to low carbon burnout. In addition, with a higher share of SRF, fluctuation during the

feeding of the fuel becomes more significant, and it may have an adverse effect on the fuel carbon burnout as well. The reactivity of the SRF char may also be lower than coal char and result in reduced burnout.

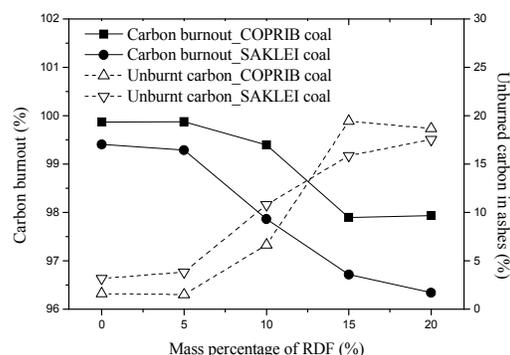


Figure 2. Fuel carbon burnout and percentage of unburnt carbon in ashes during co-combustion of coal and SRF in the entrained flow reactor

The concentrations of NO (dry, 6% O₂) in the flue gas and the percentage of fuel nitrogen emitted as NO during co-combustion of coal and SRF are presented in Figure 3. In the figure, it is clearly shown that the NO emission decreases almost linearly with an increasing percentage of SRF during co-combustion. One obvious reason for the results is that the SRF applied in this study contains lower nitrogen content than the COPRIB and SAKLEI coals. The dilution effect caused by the SRF can reduce the NO emission to some extent. Another trend that can be observed from the figure is the NO emission from SAKLEI coal and SRF co-firing is generally much higher than that from COPRIB coal and SRF co-firing. It is probably also due to the nitrogen content in the SAKLEI coal is higher than that in COPRIB coal.

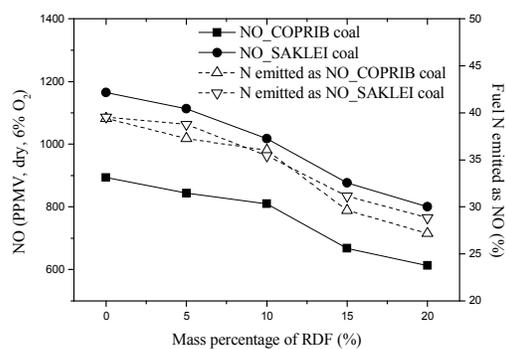


Figure 3. Emissions of NO and the percentage of fuel nitrogen emitted as NO during co-combustion of coal and SRF in the entrained flow reactor.

Besides the NO concentrations, it is shown in Figure 3 that a lower percentage of nitrogen in the fuel is converted to NO when the share of SRF in co-firing becomes higher. It indicates that a positive synergy

effect which can reduce the NO emission exists between the SRF and the two coals. This synergy effect may be caused by the high volatile content of the SRF. It is known that a fuel with high volatile can usually form a highly reduction zone during its devolatilization process. The low oxygen concentration in the reduction zone could inhibit the conversion of fuel nitrogen to NO and result in reduced NO formation [15]. In addition, the lower carbon burnout at higher SRF share may also decrease the NO formation to some extent, since the NO formed from char oxidation may be reduced. Different from the NO concentrations in the flue gas, the COPRIB and SAKLEI coal have quite similar profiles for the percentage of nitrogen emitted as NO at different SRF share.

The influences of co-combustion of coal and SRF on the SO₂ emissions are shown in Figure 4. The figure indicates that concentration of SO₂ in flue gas decreases when the percentage of SRF used in co-firing increases. An important reason for the observed decreasing trend is that the SRF used in this study contains lower sulphur content than both of the coals. Therefore, there is a dilution effect of the SRF which can reduce the SO₂ concentration in flue gas.

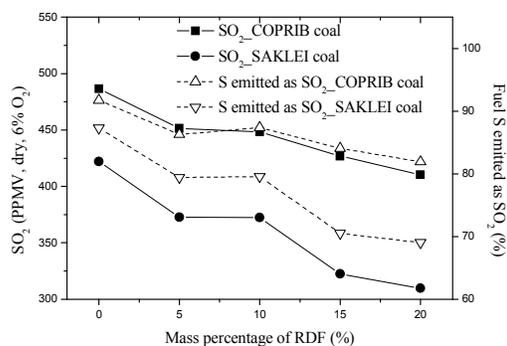


Figure 4. Emissions of SO₂ and the percentage of fuel sulphur emitted as SO₂ during co-combustion of coal and SRF in the entrained flow reactor.

To neglect the dilution effect caused by the low sulphur content of the SRF, percentages of sulphur in the fuel emitted as SO₂ during different co-firing experiment are compared in Figure 4. According to the figure, it is found that the percentage of sulphur emitted as SO₂ decreases when the share of SRF in the fuel mixture increases. A main reason for the result could be the high Ca and Na contents in the SRF which can react with the SO₂ and retain the sulphur in ashes. This is confirmed by the analyses on the fly ash and bottom ash samples which show the ashes from co-combustion experiments generally contain higher sulphur content than those from coal combustion experiments. The retention effects of the alkali and alkaline metals on SO₂ emissions have also been observed in other co-combustion experiments [3,10,16]. Besides, the low carbon burnout at a high SRF share may also play a role in the reduction of SO₂ emission, since a part of the

sulphur combined with char can not be oxidized at low carbon burnout.

However, compared to the linear trend shown in Figure 3, the data in Figure 4 shows a lower linearity. A possible reason is that the deposits inside the reactor are capable of absorbing part of the SO₂ formed during the experiments. These deposits, which can not be completely removed by high temperature cleaning, may lead to some inaccuracies in measuring the SO₂ emissions from the experiments. Other interferences, such as a slight condensation of water in the sampling tubes, may also cause certain inaccuracies in the measurement of SO₂ concentration.

According to the results shown in Figure 4, it can be concluded that coal properties can largely affect the SO₂ emission during co-combustion of coal and SRF. Because of the low sulphur content in the SAKLEI coal, emission of SO₂ is general lower in SAKLEI coal and SRF co-combustion than in COPRIB coal and SRF co-combustion. In addition, since the Ca content in the SAKLEI coal is relatively higher than that in the COPRIB coal, the percentage of sulphur in the fuel emitted as SO₂ is also lower for SAKLEI coal co-combustion. Therefore, in terms of SO₂ emission, SAKLEI coal appears to be more preferable to be used in co-combustion than COPRIB coal.

To evaluate the impacts of coal and SRF co-firing on the deposit formation in the convective part of a boiler, an air-cooled deposition probe is applied to collect the deposits formed during the experiments. The flue gas temperature in the experiment is controlled to be a value similar to the temperature in the convective part of a boiler, and the surface temperature of the deposition probe is similar as that of a superheater tube. Through observing the deposits formed during the experiment, it is found that the deposits formed on the probe mainly consist of two parts. The major part of the deposits, which locates at the windward side of the deposit probe, is mostly generated by inertial impaction of large fly ashes particles. This part of the deposits is normally very loose and can be removed from the probe easily. The other part of the deposits, which appears as a thin layer around the deposit probe, would be primarily formed by the condensation of inorganic vapors and thermophoresis of fine fly ash particles. This part of the deposits is usually much more difficult to remove than the part mainly appears at the windward side of the probe.

In order to have a quantitative comparison of the deposits formed at different co-firing experiment, the deposition flux, which describes the amount of deposits that can be formed in an experiment if all of the flue gases are directed to the deposit probe, is calculated for different co-combustion experiment and the results are shown in Figure 5. In the figure, it is clearly shown that the deposition fluxes from SAKLEI coal and SRF co-combustion are generally higher than those from COPRIB coal and SRF co-combustion. A primary reason is that the ash content of the SAKLEI coal is much higher than that of COPRIB coal. Besides the

influences of coal types, it is shown in Figure 5 that the percentage of SRF used in co-combustion has a large impact on the deposition flux as well. For COPRIB coal and SRF co-combustion, it is found the deposition flux generally decreases with increasing percentage of SRF. For SAKLEI coal and SRF co-combustion, the deposition flux increases with increasing percentage of SRF, when the percentage of SRF is not higher than 10 wt%. However, when the SRF share becomes 15 wt% or higher, the deposition flux decreases significantly.

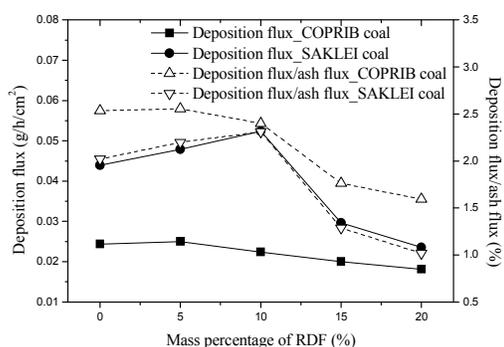


Figure 5. Deposition flux and deposition flux/ash flux from co-combustion of coal and SRF in the entrained flow reactor.

The deposition fluxes shown in Figure 5 mainly depend on two parameters, i.e. the ash flux to the deposition probe and the deposition propensity of the fly ash particles. Due to the different ash contents in SRF and the coals, the ash fluxes from different co-combustion condition are usually different. In order to neglect the effect of ash flux, deposition flux can be divided by the flux of fly ashes out of the slit of the bottom chamber. The parameter of deposition flux/ash flux, which indicates the deposition propensity of fly ashes, is calculated for different co-combustion experiment and is presented in Figure 5. From the figure, it is seen that the profiles of deposition flux/ash flux are similar to the profiles of the deposition flux. It shows that the deposition flux increases with increasing value of deposition flux/ash flux and vice versa, when SRF is co-fired with SAKLEI coal or COPRIB coal. The result indicates that the change of fly ash deposition propensity is a major reason for the decreased or increased deposit formation when difference percentage of SRF is co-fired with coal. The deposition propensity of fly ashes is closely related with their chemical and physical properties. Detailed analyses on the chemical and physical properties of the fly ashes are required in order to understand the variation of the deposition propensity of fly ashes during co-combustion of coal and SRF. However, some other parameters, such as the fluid flow near the deposition probe, may also affect the deposit formation rate to some extent. Therefore, further investigation is required in order to obtain a better understanding on the deposit formation mechanism during co-combustion of coal and SRF.

Table 2 Trace element concentrations in the ashes from SAKLEI coal combustion and 20 wt% SRF and SAKLEI coal co-combustion.

| Trace element (ppm) | Cyclone ash | Aerosol | Aerosol/cyclone ash |
|---------------------|-------------|---------|---------------------|
| SAKLEI coal | | | |
| Cd | 0.12 | 0.72 | 6.00 |
| Cr | 190 | 310 | 1.63 |
| Cu | 55 | 120 | 2.18 |
| Pb | 43 | 110 | 2.56 |
| Zn | 32 | 150 | 4.69 |
| SAKLEI + 20 wt% SRF | | | |
| Cd | 1.4 | 16 | 11.43 |
| Cr | 210 | 380 | 1.81 |
| Cu | 150 | 410 | 2.73 |
| Pb | 100 | 460 | 4.60 |
| Zn | 310 | 1900 | 6.13 |

Some trace element concentrations in the cyclone ashes (large fly ash particles) and aerosols (fine fly ash particles) from SAKLEI coal combustion and 20 wt% SRF and SAKLEI coal co-combustion are listed in Table 2. In addition, the ratio between the concentrations of trace element in aerosol and cyclone ash, which indicates the enrichment of the trace elements in fine fly ash particles, is calculated and presented in Table 2. From the table, it is obvious that the concentrations of Cd, Cu, Pb and Zn are significant higher in the ashes from co-combustion than those from dedicated coal combustion. Besides, it is shown that the enrichment factors of Cd, Pb, and Zn in fine fly ash particles are much higher under co-combustion condition than those from coal combustion condition. The enrichment of trace elements in fine particles may lead to increased trace elements emissions, since fine fly ash particles are more difficult to remove by particle collection equipment (e.g. ESP) in full scale plants [17].

There are several reasons which may cause the increase of the enrichment factor of a trace element in fine particles. For example, fuels which contain more organically associated trace elements are easier to enrich trace elements in fine fly ash particles [18]. The SRF used in this study contains about 70% of volatiles. Thus, the percentage of organically associated trace elements in SRF is probably higher than that in coal, and results in increased enrichment factor in fine fly ash particles. Besides, it has been found that inorganic elements such as Cl and S can affect the volatilities of trace elements and the partitions of trace elements in ashes with different particle size [19]. The high chlorine content in the SRF used in this study may enhance the enrichment of trace elements in fine fly ash particles.

Conclusion

Co-combustion experiments on SRF and two bituminous coals have been performed in an entrained flow reactor. It was found that the fuel carbon burnout decreased with an increasing percentage of SRF in co-combustion. The unburned carbon in the fly ashes became higher than 5 wt% when the SRF used in co-combustion was 10 wt% or higher. The agglomeration

behavior of SRF was considered to be a main reason for the reduction of burnout at high SRF share.

The concentrations of NO and SO₂ in the flue gas were found to decrease with an increasing share of SRF in co-combustion. The low nitrogen and sulphur contents in the SRF were considered to have a great contribution to the reduced emissions. In addition, the high volatile content in the SRF which could inhibit the formation of fuel NO during fuel pyrolysis process cause the reduction of NO emission to some extent. For SO₂, the relatively high Na and Ca contents in the SRF, which could react and retain SO₂ in the ashes from combustion, was an important reason for reduced SO₂ emissions during co-combustion of coal and SRF as well.

Influences of co-combustion of SRF and coal on deposit formation have been studied by using an air-cooled probe. The results showed that for COPRIB coal and SRF co-combustion, the deposition formation flux decreased with an increasing share of SRF. However, for SAKLEI coal, the deposit formation rate showed an increasing trend up to 10 mass percent of SRF, and then started to decrease at higher SRF share. The deposition propensities of the fly ashes from co-combustion were found to have the similar trends as the deposition fluxes. To understand the deposition behavior during co-combustion of coal and SRF better, further investigations on the chemical and physical properties of the fly ashes were suggested.

Several trace element concentrations in the ashes from SAKLEI coal combustions and SAKLEI coal and 20 wt% SRF co-combustion were analyzed and compared. The results indicated that the concentrations of Cd, Cu, Pb and Zn were significant higher in the ashes from co-combustion than those from coal combustion. Trace element concentrations were enriched in fine fly ashes particles for both coal combustion and co-combustion conditions. For Cd, Pb, and Zn, enrichment factors at fine fly ash particles were found to increase significantly under co-combustion conditions.

Acknowledgements

The work is part of the CHEC (Combustion and Harmful Emission Control) Research Center. The present work is sponsored by The Technical University of Denmark and co-funded by the PSO project. DONG Energy A/S is gratefully acknowledged for providing the SRF used in the experiments.

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