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Increase the utilisation of fly ash with electrostatic precipitation

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Abstract

The basic idea in this study is to look into the possibilities of reducing the heavy metal concentrations of fly ash by means of electrostatic precipitation. The utilisation of fly ash as fertiliser is hampered by its high concentrations of heavy metals, which are highly variable. Fly ash fractionation experiments were done using electrostatic precipitators at four power plants. Based on the results, the concentrations of heavy metal are at their lowest in the first collector chamber and highest in the last chamber. The concentration of cadmium in fly ash used as fertiliser can be reduced by as much as 70% by applying electrostatic precipitation fractionation. The removal of other heavy metals is not as efficient as that of cadmium. The results show that electrostatic precipitation is an adequate method in the fractionating of fly ash to be used as a fertiliser or soil amendment.

Keywords: Electrostatic separation; Sizing; Classification; Flue dusts; Recycling

1. Introduction

Heating-energy plants and power plants in Finland generate approx. 400,000 tonnes of ash of biofuel origin per year. The amounts of such ash will increase in the future as increasing amounts of biofuels are used. Wood and peat ash can be spread onto forest lands or arable land as fertiliser or as soil improvement material, and with the purpose of adding calcium to the soil. The use of ash has been constrained by factors such as its dust content and heavy metal concentrations; the latter having in many cases exceeded the maximum permitted levels imposed in Finland on soil improvement substances (Table 1).

In 2001, the utilisation rate of coal ash (84%) was considerably higher than that of peat and mixed fuel ash (43%). Wood fly ash utilisation rates have been considerably lower, being about 6% in 1997.

The extraction of heavy metals from fly ash could enable its more efficient utilisation. Currently, it appears that manipulating the power plant fuel quality is the only method available for this purpose. This means that we must know the combustible fuel's exact consistency, and which materials increase the ash-contained Cd concentrations, and then screen out the cadmium containing materials.

Small amounts of fly ash are used as a fertiliser both in agriculture and in forestry. Generally, various ash types are more suitable as a soil improvement material than fertilisers in agriculture because the amounts of soluble plant nutrients in ash are fairly low. Peat ash is used mainly as a phosphate fertiliser and wood ash in liming of mineral soils and as a basic and support fertiliser in the growing of cereal crops. The liming and fertiliser effects of ash in the soil depend on the concentrations of calcium and nutrients in ash, on the solubility of nutrients in the ash and the soil, and on soil properties, e.g. acidity and nutrient concentrations (Orava et al., 2004; Silfverberg, 1996). Table 2 shows the heavy metal concentrations of four ash types.

Many substances contained in ash are in extremely poorly soluble forms. As the heavy metals (e.g. cadmium,

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Table 1
Maximum permitted concentrations of heavy metals in soil improvement materials and in fly ash from power plant A (Orava, 2003)

Element	Power plant A: fly ash (mg/kg)			Maximum permitted concentration (mg/kg)
	Year 2002	Year 2001	Year 1999	
Mercury (Hg)	<2.5	0.31	–	2.0
Cadmium (Cd)	2.69	5.05	6.3	3.0
Arsenic (As)	18.34	19.73	35	50
Nickel (Ni)	–	–		100
Lead (Pb)	56.59	106.5	52.7	150
Copper (Cu)	86.7	290.1	178	600
Zinc (Zn)	189.7	376.9	706	1500

Table 2
Heavy metal concentrations of various ash types (Palola, 1998)

Heavy metals (mg/kg)	Coal ash	Peat ash	Wood ash	Bark ash
Arsenic (As)	2.3–200	2–200	0.2–60	7–28
Cadmium (Cd)	0.01–250	0.05–8	0.4–40	4–20
Chrome (Cr)	3.6–7400	15–250	15–250	40–81
Copper (Cu)	30–3000	20–400	15–300	57–144
Mercury (Hg)	0.01–80	0.001–1	0.02–1	0.012–0.4
Nickel (Ni)	1.8–800	15–200	20–250	36–52
Lead (Pb)	3.1–1800	5–150	15–1000	53–140
Zinc (Zn)	14–13,000	10–600	15–10,000	1100–5100

lead, nickel) in ash are in very poorly soluble forms, it can be assumed that ash fertilisation will not result in significant heavy-metal impacts, e.g. in water systems, within a short period of time following fertilisation. In the long run, harmful heavy metals may, however, be released from ash in soluble forms and be thereby translocated into the vegetation (Nieminen, 2003). The liming effect of ash lowers the solubility of heavy metals in the soil. Ash may at first raise the cadmium concentration in tree stands, but once tree growth has improved the concentrations of trace elements and heavy metals may fall even below the initial level. The rise in the Cd concentration in some plant species can last for a long time (Moilanen, 2003). Cadmium is considered to be the most harmful of all heavy metals because it remains in the soil, it becomes enriched in food chains, and it is toxic to organisms.

Electrostatic precipitation (Fig. 1) is currently the most common method used in separating the solid matter from power plant flue gases. The advantages of electrostatic precipitation include high collection efficiency (as high as 99.9%) and its suitability for dealing with particles of different sizes (even particle sizes below 1 μm) and variable flue gas volumes. Its further advantages are long service life, good operational reliability, and low operating and maintenance costs (Walsh, 1997; Immonen, 1987).

The functioning of the electrostatic precipitator is significantly dependent on the properties of the fly ash to be collected. The amount and size distribution of the particles to be removed have a significant impact on the functioning of the electrostatic precipitator. Although the collection efficiency of electrostatic precipitator is more or less constant irrespective of the particle mass, the effective migration velocity is lower in the case of small particles. Due to the different charging properties of the particles, the collection efficiency of the particles varies as a function of particle size. The most difficult particle size from the point of view of separation is 0.2–0.5 μm (Nykänen, 1993; Kouvo, 2003).

Fig. 1. Alstom Finland Oy's electrostatic precipitator (Jalovaara et al., 2003).

The concentrations of heavy metal in ash can be reduced by fractionation of the finest ash particles from flue gases by means of multi-chamber electrostatic precipitators. The fractionating properties of the precipitator can be influenced by actions such as restricting and pulsating the current. Our research results have shown that heavy metals are concentrated in fine ash particles (Orava et al., 2004; Orava, 2003). According to the results of Thun and Korhonen (1999), the 3-field electrostatic precipitator was stopped, depending on the operating conditions, 84–95% of the overall amount of ash in the first field, 4–15% in the second field, and approx. 1% in the last field. The cadmium concentration of ash can be reduced at least by 15–25% by means of fractionating the ash using electrostatic precipitators (Orava et al., 2004; Thun and Korhonen, 1999).

Depending on the boiler in question, ashes from bark fuelled and wood chip fuelled power plants (grate boilers) are divided into weight percentage categories as follows: bottom ash 70–90%, cyclone fly ash 10–30%, electrostatic precipitator fly ash 2–8% and dust emissions 0.1–3.0% (Agarwal and Agarwal, 1999). In dust combustion and fluidized-bed combustion, the share of fly ash generation is 80–100%. As much as 75–90% of the heavy metals (Cd and Zn) are contained in the fine particle fraction of the fly ash, which is separated by electrostatic precipitators (Dahl et al.). Fig. 2 sets out the zinc, lead and cadmium contents (mg/kg and m-%) in bottom ash, cyclone ash and electrostatic precipitator fly ash. Based on the figure,

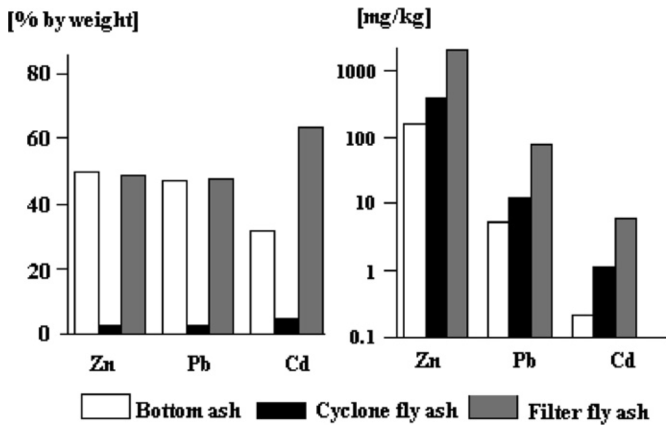

Fig. 2. Heavy metal concentrations and their division as bulk percentage figures in bottom ash, cyclone fly ash and filter fly ash (Agarwal and Agarwal).

it may be stated, for example, that electrostatic precipitator fly ash has a higher Cd content than cyclone ash, which is partly due to the fact that, compared to cyclones, electrostatic precipitators separate smaller particles that contain the majority of heavy metals. In this case, the portion of the fly ash that is suitable for use as a fertiliser, in terms of its consistency, remains at the cyclone (Obernberger and Biedermann, 1997).

The electrostatic precipitator can more effectively fractionate fly ash than the traditional methods when a mechanical classifier (cyclone) is connected before the ash reaches the precipitator. Fig. 3 shows a basic layout drawing of a power plant fired by using biofuels and which is provided with a multi-cyclone before the electrostatic precipitator. As much as 75–90% of the heavy metals (Cd and Zn) contained in fly ash are bound to the fine fly ash fraction separated by the electrostatic precipitator (Dahl et al., 2002).

Properly designed and adjusted electrostatic precipitation is in principle, capable of separating that fraction of the flue gases, which contains the greatest amount of heavy metals but only a fraction of the overall amount of ash. The heavy metal concentrations in the main part of the ash can thus be reduced to below the maximum permitted concentrations.

2. Materials and methods

The fractionating trials with fly ash were performed at four power plants (A, B, C and D). The electrostatic precipitators were operated at the power plants at different voltage levels and samples were taken from the ESP's various fields. All the samples taken from the electrostatic precipitators were taken from the ash feeders located under the electrostatic precipitators before the ash was fed into the silo. The samples were analysed for the presence of Pb, Cu, Zn, Ni, As and Cd using the graphite method and particle size determination was done using a Malvern device.

Power plant A uses peat, forest chip and oil and the by-products of the mechanical wood processing industry as its fuels. The boiler capacity available to the power plant is 150 MW. The fractionating trials were performed with the power plant's current 3-field electrostatic precipitator.

Power plant B uses two boilers, one a Pyroflow circulating fluidized-bed boiler (capacity 55 MW) and the other a fluidized-bed boiler (capacity 42 MW). The trials were carried out using the fluidized-bed boiler. The power plant's principal fuel is milled peat with wood fuels, soot and aluminium oxide mixed in with it. The fly ash from both boilers is conveyed via 2-field electrostatic precipitators to a common ash silo.

Power plant C is equipped with two power plant boilers. Boiler 1 is a fluidized-bed boiler with a fuel capacity of 267 MW. Boiler 2 is a Pyroflow circulating fluidized-bed boiler with a fuel capacity of 315 MW. The tests were performed using the Pyroflow circulating fluidized-bed boiler. The fuels used at the power plant were mainly milled peat and various wood fuels. Both boilers are equipped with 3-field electrostatic precipitators from which the boilers' fly ash is blown pneumatically to a common ash silo.

The electrical power generated by power plant D's fluidized-bed boiler plant is 77 MW and its heating capacity is 246 MW. The fuels used in the fluidized-bed boiler are

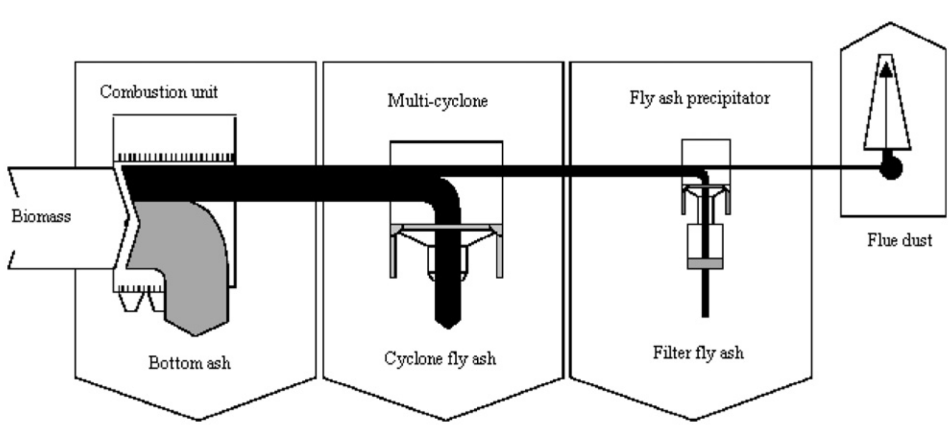

Fig. 3. The ash fractions produced by a biofuel-fired power plant (Agarwal and Agarwal).

mainly milled peat and wood waste. The fly ash is separated from the flue gases by means of a 3-field electrostatic precipitator.

3. Results

During trials with power plant A's electrostatic precipitator (trials 1–7) the fuel used was composed 49% peat and 51% wood fuels. The ash funnels of fields' 1–3 of the electrostatic precipitator were sampled and analysed (Fig. 4).

On the basis of the results, the Cd concentration was at its lowest in field 1 of the electrostatic precipitator and at its highest in field 3. This is due to the bigger fly ash particles accumulating in field 1 and field 3 containing ash with the smallest particles. The Cd concentration in field 1 varies within the range of 2.2–3.6 mg/kg and in the last field within the range of 7.2–12.4 mg/kg. Concentrations are affected by properties such as the ESP voltage, fuel quality, and flue gas flow rate. In almost every electrostatic precipitator's field 1 the Cd concentration is below the permitted maximum limit (3.0 mg/kg) set down for ash intended for fertiliser use.

During trial runs, the electrostatic precipitator fields' CBO ratio (cycle block in operation) was controlled within the range 0–12. The value 0 means that all the half-cycles of the field in question are currently active, and for example, the value 2 means that only a third of the half-cycles are active. Thereby the CBO value declares how many sequential half-cycles are closed, that is, how often the separator's supply current is pulsated. In the present research, the CBO value was controlled by the Micro-Kraft controller whose main task is to keep the voltage near to the breakdown voltage.

The most important thing is to be able to influence and change the properties of field 1 in the electrostatic precipitator. The first field enables the production of fly ash with heavy metal concentration levels that make it suitable as a fertiliser, for example.

Fig. 5 shows how the electrostatic precipitator's CBO ratio control for field 1 affects the fly ash Cd concentration levels. Among other things, the increasing or decreasing number of electrostatic precipitator field flashovers is excluded from this control.

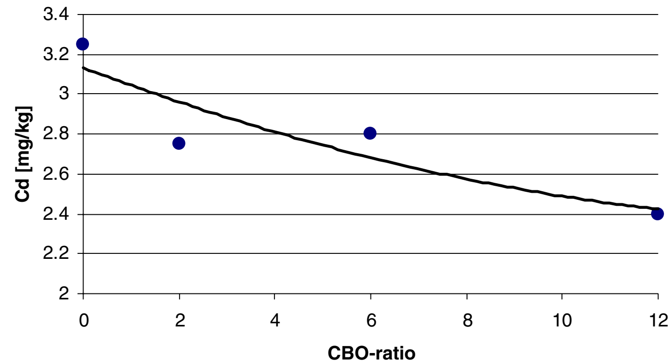

Fig. 5. The effect of the CBO ratio from electrostatic precipitator field 1 on fly ash Cd concentrations (mg/kg) during trial runs with peat fuel.

The more field half-cycles there are deactivated, the lower the heavy metal content of the fly ash being generated. Cd concentration variations are also caused by fuel quality variations, in addition to the control itself, among other factors.

Fig. 6 shows how the electrostatic precipitator's filter voltage affects the Cd concentration level of field 1. The heavy metal concentration level increases in accordance with the rising voltage. This is due to the fact that higher voltages can more effectively separate fine particles that also contain heavy metals. The filter voltage level indicates the field's actual status more effectively than does the CBO ratio. Among other things, it also takes into account any electric breakdowns that occur within the field.

Fig. 7 shows the particle size classes (μm) D10 and D50 of fields 1–3 resulting from trials 5, 6 and 7. D10 is a particle size with respect to which 90% of the sample's particles are larger and 10% are smaller. D50 is a halving particle size class, or the particle size with respect to which sample's particles are larger and smaller in the ratio of 50/50.

On the basis of this figure, the smaller-sized particles tend to be concentrated in the last field and the bigger-sized particles in the first field of the electrostatic precipitator.

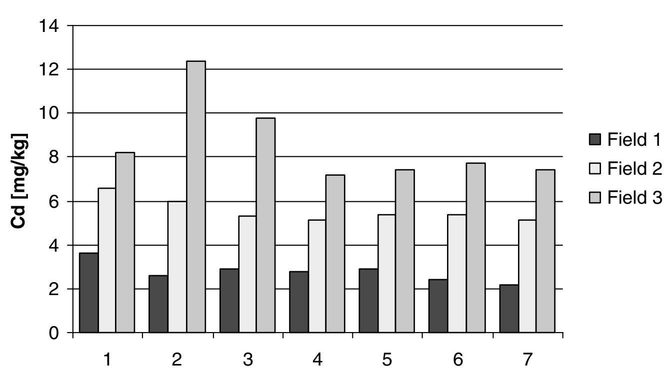

Fig. 4. Cd concentrations (mg/kg) of the fly ash in fields (1–3) during trial runs (1–7) with peat fuel when using the electrostatic precipitator.

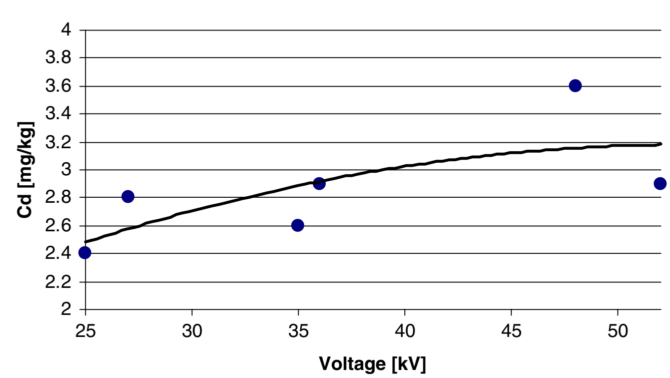

Fig. 6. The effect of the filter voltage level (kV) from electrostatic precipitator field 1 on fly ash Cd concentrations (mg/kg) during trial runs with peat fuel.

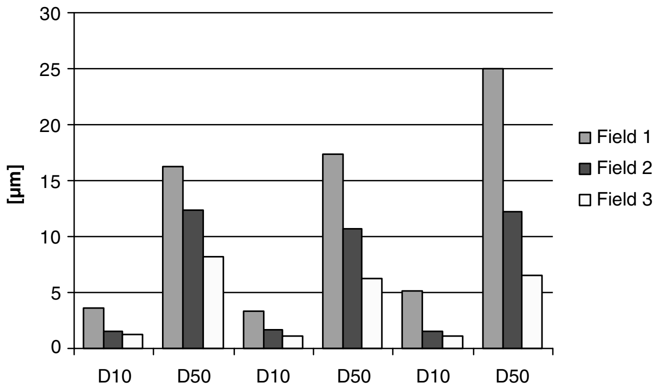

Fig. 7. The particle size classes (µm) D10 and D50 of the fly ash in the electrostatic precipitator's fields 1–3.

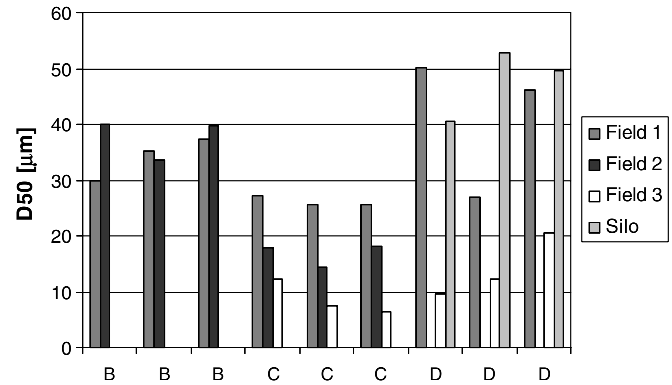

Fig. 10. Fly ash particle sizes in various blocks of the electrostatic precipitator, particle size category (µm) D50.

These small particles have the highest concentrations of heavy metals (Fig. 8). The figure shows that the permissible Cd concentration level for use as a fertiliser is exceeded in particle size category <16 µm.

The cadmium concentrations were at their highest at power plant D (Fig. 9). This was due to the bigger share of wood fuel in the fuel when compared to the other power plants. Following fractionation, the cadmium concentration of the ash accumulated in field 3 of the electrostatic precipitator was at best five fold compared to field 1.

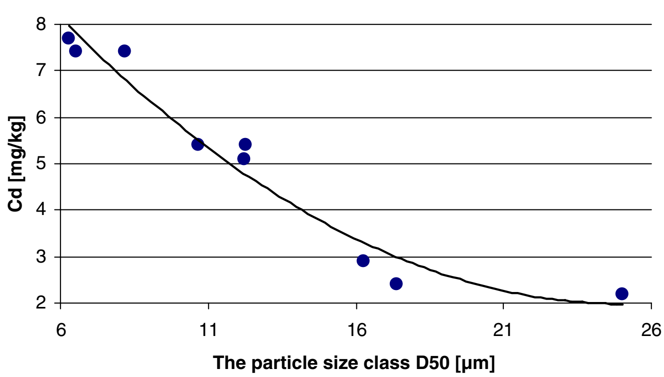

Fig. 8. Cd concentration levels (mg/kg) and particle size (µm) D50 during trial runs with peat fuel.

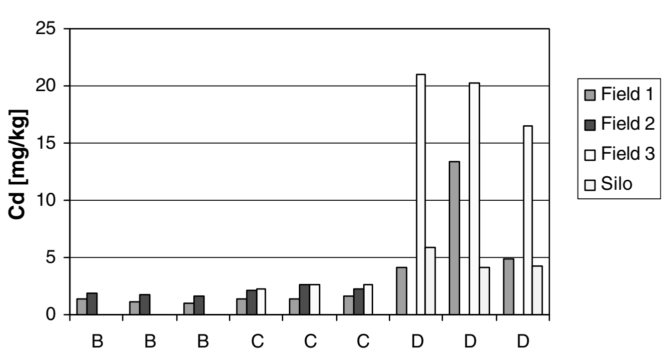

Fig. 9. Cd concentrations of the fly ash in the various fields of the electrostatic precipitator (limit value 3 mg/kg) at power plant B, C and D.

Despite this, in these tests it was not possible to effectively fractionate the ash at power plant D.

According to the results the Pb, Cu and Ni concentrations are not problematic from the viewpoint of fractionation. With respect to these metals, fly ash can be used as a fertiliser without fractionation being necessary. Zn, As and Cd concentrations may exceed the permitted limit values and thereby cause problems for the fertiliser use of fly ash. With respect to these metals, the use of the fly ash as a fertiliser depends on the composition of the fuel and on the effectiveness of fractionation.

Fig. 10 shows the analysed particle sizes from various blocks at power plants B, C and D. Based on this figure, it may be stated the coarsest dust remains in electrostatic precipitator field 1.

At power plant B, C and D, the electrostatic precipitator was controlled by adjusting the current value. Nevertheless, the electrostatic precipitator's productive capacity depends on its voltage level. The proportion between the voltage and the current is not symmetric. When the current level was reduced by 50%, the voltage level merely decreased by 10–20%. In addition, there were considerably fewer breakdowns when the current's setpoint value was reduced. These were the reasons why the average voltage value did not change to a sufficient degree between the various tests, so as to affect the electrostatic precipitator's separation efficiency. This means that the various current adjustments made to the electrostatic precipitator did not have a significant effect on heavy metal concentrations during the trial runs.

4. Conclusions

The chemical and physical properties of combustion-generated ash, as well as the resulting ash volumes, depend on the combustible fuels' composition and quality. The combustion technology and the parameters applied, such as the temperature, combustion rate and air supply volumes, plus the boiler condition and the ash recovery systems also contribute to the resulting ash quality. In view of the fly ash properties, the ash separation equipment is of particular importance since its flue gas borne finest fraction is the crucial one, with regards to the ash composition.

The fine particles of fly ash are frequently enriched by heavy metals. The extensive variation of its heavy metal concentration level makes fly ash problematic to use in practice. Fly ash may contain heavy metal concentrations that exceed the statutory limits for its use as a fertiliser. The most problematic heavy metal in wood-based fly ash is cadmium. In Finland, its currently valid statutory limit value is 3 mg/kg. Wood-based ash exceeds this limit value.

In several cases, heavy metal emissions may be reduced by process technological methods. These include the minimisation of gas emission volumes, waste gas collection, the use of air recirculation, efficient use of raw materials and energy, and the use of raw materials and fuels with minimal heavy metal concentrations. In addition, the quality of fly ash may be manipulated through fractionation. Fractionation is geared towards separating the fractions with high fine particle densities and high heavy metal concentrations from the portion that is suitable for practical applications.

The fractionation trials demonstrated that the heavy metal concentrations are at their lowest in field 1 of the electrostatic precipitator and at their highest in field 3. The heavy metals are enriched in the small particles of the ash. The fly ash particles having the biggest particle size accumulate in the first field while the last field has more of the ash-containing small particles. Due to this, the dust accumulated in field 1 contains less heavy metal. The concentrations of heavy metals in the ash are affected by properties such as the ESP voltage, fuel quality, and flue gas flow rate.

Ni, Pb and Cu are the heavy metals, whose concentrations do not exceed the limit values imposed on wood and peat ash intended to be used as fertiliser. Fractionation is not necessary with respect to these metals considering the present permit conditions. However, fractionation clearly lowered the fly ash concentrations of these metals.

Zn, Cd and As are the metals, whose concentrations may exceed the limit values. Cd and Zn can cause problems when burning wood whereas the problem in peat burning is As. However, the concentrations of these metals significantly depend on the fuel being used. Especially in the case of wood, Cd and Zn concentrations vary a great deal. In regard to Zn, fractionation always resulted in concentrations below the permit limit values. Cd was the most problematic metal of all and it was not always possible to bring its concentrations below maximum permitted concentrations even after making adjustments to the electrostatic precipitator's settings. The cadmium concentrations of ash due to be used as a fertiliser can be reduced by as much as 70% by fractionating the ash using an electrostatic precipitator. The concentrations of the other heavy metals do not diminish quite as much. Arsenic concentrations were always brought to levels below the maximum permitted limits, but making adjustments to the electrostatic precipitator may be necessary if the arsenic concentration of the peat is high. If various by-products formed in industry or wastes are used as fuels, there is no single overall assessment available regarding the concentrations of heavy metals.

Based on the test results obtained, it may be stated that electrostatic precipitators' increasing CBO ratio values will decrease the separation efficiency in the case of fine particles. The heavy metal concentration level increases in accordance with the rising voltage. This is due to the fact that higher voltages can more effectively separate fine particles that also contain heavy metals. This means that electrostatic precipitators' separation efficiency may be influenced by adjusting their maximum voltage setpoint values and CBO ratio values. These adjustments may decrease the efficiency of field 1, thus enabling the minimisation of heavy metal concentrations accumulating in the resulting ash. Correspondingly, heavy metal emissions with fine particle concentrations may be reduced by making the electrostatic precipitator's final field more effective.

No overall values can be given for the parameters of electrostatic precipitators used in fractionation. The heavy metal concentrations of the fuels used can vary a great deal and the fractionation required cannot be determined unless the fuel in question has been analysed.

References

Agarwal, A.K., Agarwal, G.D., 1999. Recent technologies for the conversion of biomass into energy, fuels, and useful chemicals. TER Information Monitor on Environmental Science 4 (1), 1–12.

Dahl, J., Obernberger, I., Brunner, T., Biedermann, F., 2002. Results and evaluations of a new heavy metal fractionation technology. In: Gratefired Biomass Combustion Plants as a Basis for an Improved Ash Utilisation. 12th European Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection, 17–21 June 2002, Amsterdam, The Netherlands, vol. 1. pp. 690–694.

Immonen, O., 1987. Electrostatic precipitators. Particle Emissions PPP-Seminar 11–12 March 1987, Suomen akatemia. Poltto-Palaminen-Päästöt-tutkimusyhteistyö. Teknillinen korkeakoulu, Energiatekniikan laitos.

Jalovaara, J., Aho, J., Hietamäki, E., Hyytiä, H., 2003. Best available techniques (BAT) in small 5–50 MW combustion plants in Finland. Finnish Environment Institute. The Finnish Environment 649, 126.

Kouvo, P., 2003. Formation and control of trace metal emissions in co-fired of biomass, peat, and wastes in fluidised bed combustion. Lappeenranta University of Technology. Acta Universitatis Lappeenrantaensis (148), 75.

Moilanen, M., 2003. Tuhkalannoituksen ympäristövaikutukset – sienet, marjat ja riistan ravinto. In: Proc. of Tuhka suometsien kasvattamisessa – seminaari, 5.6.2003, Metsäteho, Helsinki, 6p.

Nieminen, M., 2003. Ravinteiden ja raskasmetallien liukeneminen tuhkalannoitteista. In: Proc. of Tuhka suometsien kasvattamisessa – seminaari, 5.6.2003, Metsäteho, Helsinki, 1p.

Nykänen, J., 1993. Lentotuhkahiukkasten agglomeroinnin vaikutus sähkösuodattimen suhteellisiin hankintakustannuksiin. Teknillinen korkeakoulu, lisensiaattityö, 76p.

Obernberger, I., Biedermann, F., 1997. Fractionated heavy metal separation in biomass combusting plants – possibilities, technological approach, experiences. 1997 Institute on Chemical Engineering, Technical University on Graz, Austria, 14p.

Orava, H., 2003. Lentotuhkan fraktiointi sähkösuodattimella ja Ion Blast-menetelmällä. Lappeenrannan teknillinen yliopisto, Energia- ja ympäristötekniikan osasto, diplomityö, 106p.

Orava, H., Matilainen, A., Halinen, A., Tontti, T., Nordman T., 2004. Kompostista ja tuhkasta rakeistamalla lannoitevalmistetta. Mikkelin ammattikorkeakoulu. A: Tutkimuksia, 118p.

Palola, S., 1998. Tuhkien ominaisuudet, hyötykäyttö sekä hyötykäytön edellytykset. Kirjallisuusselvitys. Jyväskylä: Vapo Oy/Tutkimusosasto, 63p.

Silfverberg, K., 1996. Nutrient status and development of tree stands and vegetation on ash-fertilized drained peat lands in Finland. Metsäntutkimuslaitoksen tiedonantoja 588, The Finnish Forest Research Institute, Research papers.

Thun, R., Korhonen, M. (Eds.), 1999. Sihti 2, Energia- ja ympäristöteknologia, Tutkimusohjelman vuosikirja 1998, Projektiesittelyt. VTT Symposium 191.

Walsh, M., 1997. Kivihiili- ja turvevoimalaitosten sivutuotteet ja niiden hyötykäyttö. Energia-alan keskusliitto ry Finergy, tutkimusraportti nro 2, 89p.