Morphology of Woody Biomass **Combustion** Ash and
Enrichment of Potassium Components by Particle Size
Classification

Norio Maeda^{1,2)}, Takaaki Katakura²⁾, Tomonori Fukasawa²⁾,
An-Ni Huang²⁾, Takashi Kawano³⁾, Kunihiro Fukui²⁾

¹⁾Environmental Engineering Department, TAKUMA CO.,
LTD.
2-2-33 Kinrakuji-cho, Amagasaki, Hyogo 660-0806, Japan

²⁾Department of Chemical Engineering,
Graduate School of Engineering, Hiroshima University
1-4-1 Kagamiyama, Higashi-Hiroshima, Hiroshima
739-8527, Japan

³⁾ Energy Engineering Department 1, TAKUMA CO., LTD.
2-2-33 Kinrakuji-cho, Amagasaki, Hyogo 660-0806, Japan

The name and address of the responsible author;
Dr. Kunihiro FUKUI
Department of Chemical Engineering,
Graduate School of Engineering, Hiroshima University,
1-4-1, Kagamiyama, Higashi Hiroshima 739-8527, Japan
Tel & Fax: +81-82-424-7715
E-mail: kfukui@hiroshima-u.ac.jp

ABSTRACT

The mass balance of the ashes and their potassium component was investigated when different biomass fuels were incinerated using a fluidized bed furnace and stoker furnace, respectively. The properties of the ashes were analyzed, and the dependence of the potassium content in the ash upon its particle size was also examined. Very little K is exhausted in the flue gas, and nearly all is included in the ashes. The stoker furnace is thought to be more appropriate than the fluidized bed furnace to obtain bag filter ash, which has the highest potassium concentration. Moreover, the potassium content in the ash decreased with increase in its **mass** median diameter. To enrich the potassium concentration in the ash, a method was proposed for collecting the finer ash selectively using a particle-size classification technique. Using it, ash having more than 35% of K concentration could be successfully obtained at factory scale. It was also confirmed that the enriched potassium bag filter ash, and the chemical fertilizer manufactured from it, completely satisfy the official specifications fixed by the Fertilizers Regulation Act in Japan.

Keywords:

Combustion ash; Particle size; Size classification;
Potassium; Woody biomass boiler; Enrichment; Japanese
cedar; Oregon pine

1. Introduction

The promotion of energy conservation and the introduction of renewable energy have become of considerable importance as the issue of global warming has increased in severity [1,2]. It is essential to reduce atmospheric levels of greenhouse gases such as carbon dioxide for reduction of global climate change. Specifically, after the Great East Japan Earthquake in 2011, the government of Japan began to consolidate the utilization of renewable energy for electric power generation. It also established the Feed-in Tariff Scheme for Renewable Energy in 2012 [3,4]. This scheme promotes power generation using woody biomass, and the power generation capacity of woody biomass power plants in Japan rose to 2.5 million kW in 2014 [5]. This path was selected because carbon dioxide emitted from the combustion of biomass is considered to be carbon neutral [6]. The government of Japan aims to increase its renewable power generation capacity to 3.8 million kW using 6 million m³ of biomass fuel [7]. In order to achieve this target, the cost of power generation must be reduced greatly.

The inorganic components in the biomass are left behind after combustion of biomass in the form of several types of ashes (e.g., cyclone ash, bag-filter ash). In Japan, all types of ashes from the **combustion** of biomass must be transferred to a final disposal site as industrial waste [8]. The cost of conveyance and land filling is about 20,000

JPY/t, which appears sufficient to inhibit the spread of the use of woody biomass power plants.

It has been reported that the **combustion** ash produced by the combustion of biomass could be effectively utilized for such as adsorbent material [9], soil improving agent [10], alkali source [11], and others [12,13]. However, these have not been realized at industrial scale. On the other hand, the ash produced by burning plants during agricultural processes has traditionally been used as fertilizer because it contains a high concentration of potassium components. Because the **combustion** ash of woody construction waste material includes high concentrations of harmful heavy-metal components such as Pb, Cd, Cr, Cu, and Fe [14,15], it is difficult to utilize it. However, the **combustion** ash obtained from the combustion of wood from forest thinning, unutilized wood, and virgin woody biomass could be used as the raw material for making fertilizer because it contains very low concentrations of heavy metals [16,17]. Specifically, chemical fertilizer manufacturing companies could pay for **combustion** ash with potassium content of 25% or more as a valuable raw material. This scheme not only could reduce the cost of power generation but would also contribute to the recycling of an essential resource (potassium).

Furthermore, studies have been done of the chemical compositions and physical properties of **combustion** ashes obtained from burning various biomass fuels at a number of

different furnaces in Europe [18,19]. The dependence of the chemical composition in the **combustion** ash on its particle size has been also studied, which reveals that the volatile component is concentrated in ash having relatively smaller particle size [16,20,21]. However, these important findings concerning biomass as a resource have been little reported in Japan [22].

Accordingly, in this study, with respect to two types of furnaces and biomass fuels, the mass flow of the ashes and the material balance of the potassium component between the biomass fuel and the ashes produced were investigated. Based on the effect of the particle size of the ash on its potassium concentration, a method to separate the ash-fraction having the most condensed potassium using the particle-size classification technique was proposed. Moreover, this proposal was substantiated by factory-scale experiments using an actual biomass-fueled boiler plant.

2. Materials and methods

2.1 Performance of biomass furnace and ash sampling

The mass flow and the material balance between the biomass fuel and produced ashes were examined when the biomass fuels were combusted in two types of furnace. **Figure 1** demonstrates the schematic diagram of biomass fuel **boiler plants** equipped with different combustion technologies. A fluidized bed combustion furnace and a

stoker furnace are installed in Plant A and Plant B, respectively. As listed in **Table 1**, the fluidized bed combustion furnace had a combustion chamber volume of 280 m³. The gas temperature at the exhaust port of this furnace was maintained at 790 °C. During the time that the boiler generated 39 t/h of high-temperature steam (3.14 MPa, 305 °C), the gas temperature decreased to 330 °C. In contrast, the stoker furnace had a combustion chamber volume of 110 m³, and the gas temperature at its exhaust port was kept at 890 °C (considerably higher than that of the fluidized bed furnace). During the time that the boiler of the Stoker furnace generated 20 t/h of high-temperature steam (1.86 MPa, 310 °C), the gas temperature decreased to 350 °C. The stoker furnace in Plant B gives a larger temperature difference between the exhaust port of the furnace and the outlet of the boiler than does the fluidized bed furnace. This means that the gas from the stoker furnace, which includes various volatile components, is cooled more rapidly than that from the fluidized bed furnace.

The properties of the biomass fuel incinerated by each furnace are listed in **Table 2**. Raw sawdust and bark of Oregon pine was the biomass fuel fed into the fluidized bed combustion furnace (at 15,800 kg/h) in Plant A, and it was incinerated to ashes. At Plant B, 5,470 kg/h of dry sawdust, bark, and wood chips of Japanese cedar was incinerated in a stoker furnace. Japanese cedar, particularly its dry

sawdust and bark, contains potassium at higher concentration than Oregon pine. As a result, the biomass fuel for the stoker furnace had more than twice the potassium concentration as that for the fluidized bed combustion furnace.

Several tens of kilograms of samples of the biomass fuel and types of ash (boiler, cyclone, and bag filter) were collected from both plants. Samples of the bottom ash and cooling tower ash from Plant B were also collected. The collected samples were manually mixed and homogenized, and then reduced to volumes suitable for various analyses using sample powder dividers.

2.2 Analysis method of biomass fuels and ashes

Representative subsamples of the collected biomass fuels and ashes were analyzed for their content of potassium element. This analysis was carried out in full compliance with “Testing Methods for Fertilizer” standardized by the Food and Agricultural Materials Inspection Center (FAMIC) in the Ministry of Agriculture, Forestry, and Fisheries of Japan [23]. Namely, 5.0 g of sample was converted completely into ash at 550 °C, for over four hours. The ashes obtained were dissolved into hydrochloric acid aqueous solution, and this solution was cooled after boiling for five minutes. The test solution for analysis was acquired by filtrating it. The potassium concentration in the test solution was measured using an atomic absorption

spectrophotometer (Hitachi, 170-50A) using 766.5 and 769.9 nm wavelengths.

The major components of the ash were also identified and quantified using an X-ray fluorescence spectrometer (XRF, Rigaku, RIX3000). The crystalline phase of the ashes was identified using an X-ray diffractometer (XRD, Rigaku, MiniFlex600). The particle size distribution of the ashes was measured by a laser diffraction-scattering particle-size analyzer (Horiba, LA-920), while ashes were dispersed into ethanol by a sonicator.

3. Results & Discussion

3.1. Material balance of ashes and their potassium element

The mass balance of the ashes, and their potassium elements contained in them, is listed in **Table 3**. For both boiler plants, the amount of ash calculated from its content in the biomass fuel listed in Table 2 provided near agreement with the total amount of ashes actually produced. The error margins for the boiler plants were 12.4% and 2.7%, which means that our measurement results had adequate reliability. For Plant A, the calculated amount of ash (9.88 kg/ton) was smaller than the total amount of ashes actually produced (11.11 kg/ton), and Plant A had a larger error margin than Plant B. This may be caused by mixing of the fluidized bed sand in the ashes [24]. This phenomenon

is discussed in detail on Figure 6. Moreover, the amount of potassium in the two biomass fuels, as calculated from data listed in Table 2, was 0.62 and 1.34 kg/ton-dried fuel, respectively. On the other hand, the total potassium element contained in all actual ashes were 0.70 and 1.28 kg/ton-dried fuel, respectively, which are in absolute agreement with those in the biomass fuel. Accordingly, this result indicates that very little potassium component escapes with the flue gas, and that nearly all of it remains in the ashes. This is because compounds consisting of potassium element can easily devolatilize and to particulate materials due to their relatively low boiling temperature [25,26].

Figure 2 shows the mass fraction of each ash and its potassium component calculated from the data in Table 3. The fluidized bed furnace in Plant A did not discharge the bottom ash, and Plant A had an almost equal mass fraction of the cyclone ash to Plant B. As a result, the mass fraction of the bag filter ash in Plant B was less than half that in Plant A. In contrast, the mass fractions of the potassium component in the boiler ash and the cyclone ash were almost same between two plants. It was also found that the major part of the potassium element was recovered as the bag filter ash. Moreover, the difference in the mass fraction of the potassium in the bag filter ash between Plants A and B was not so large, compared with the mass fraction of the bag filter ash itself. These results mean that,

in the case of Plant B, 50% of the potassium element in all the ashes could be recovered as the bag filter ash, which is a very minor portion, less than 20% of all ashes. However, for Plant A, 70% of potassium element was recovered as the bag filter ash (40% of all ashes). Consequently, it can be seen that Plant B had a much higher concentration of potassium in the bag filter ash than Plant A.

The properties of the cyclone ash and the bag filter ash were analyzed and compared between boiler plants. **Figure 3** shows the external appearance of the cyclone and bag filter ashes in both plants. It also lists the concentration of the potassium element in these ashes. It is confirmed that the ash residue from Plant A contains more brownish-red ashes than that from Plant B. This may be because the abraded or pulverized fluidized bed sand is mixed into the ash. For both plants, the color of the bag filter ash is more whitish gray than that of the cyclone ash. The bag filter ash has a remarkably higher potassium concentration than the cyclone ash. In other words, the ash having relatively smaller particle size has a higher potassium concentration. Moreover, Plant B has higher potassium concentration in both the cyclone and the bag filter ashes than Plant A. **This is caused by the difference in the potassium concentration in the biomass fuel.** One peculiar finding was that the potassium concentration (280 mg/g-dried ash) in the bag filter ash of Plant **B**, was much higher than that (110 mg/g-dried ash) in the ash of Plant **A**. Hence, ash with

higher potassium concentration has a brighter, grayish color.

Figure 4 shows the XRD peak patterns of the cyclone and the bag filter ashes for the two boiler plants. Because the crystalline phase of SiO_2 can be detected only in the ashes of Plant A, this phase may be due to mixing of the fluidized bed sand into the ashes. With respect to Plant A, the potassium in ashes is in the forms of crystallized KCl and K_2CO_3 , while it exists as crystallized KCl and K_2SO_4 for Plant B. Although the crystal structure of the potassium components in the ash is different between the two boiler plants, all components have hydro-soluble crystalline phases. This result indicates that these ashes could be used directly as a raw material for making fertilizer.

Figure 5 shows the particle size distributions of the cyclone ash and the bag filter ash obtained from Plants A and B. In both boiler plants, naturally, the particle size of the cyclone ash is larger than that of the bag filter ash. However, Large difference between the two boiler plants was not found in the particle size distribution of the cyclone and bag filter ashes. For example, the mass median diameters of the bag filter ashes in Plants A and B were 4.1 and 5.4 μm , respectively. These results suggest that there is also little difference in the collection efficiency of the multi-cyclones and bag filters of the two boiler plants. Therefore, a difference in particle size between two boiler plants is not causing that the concentration of the

potassium element in the bag filter ash of Plant B is much higher than in that of Plant A. Obviously, this is thought due to the difference in the potassium content of the biomass fuels mainly. However, it is also considered that a difference in the furnace type can affect the difference in the potassium concentration in the bag filter ash between two plants. As mentioned above in Section 2.1, the gas from the stoker furnace in Plant B is cooled more rapidly than that from the fluidized bed furnace in Plant A. In general, rapid cooling makes the size of the condensable material particles smaller [27,28]. Consequently, because the stoker furnace in Plant B has a higher cooling rate, the potassium (which has a relatively low boiling point) is thought to be concentrated in the finer ash of Plant B. This is the reason why the concentration of the potassium element in the bag filter ash for Plant B is much higher than that for Plant A (shown in Figure 3).

Figure 6 shows the components of ashes identified and quantified by XRF. The XRF measurement also revealed that the potassium content in the ash increased as the particle size of the ash decreased, independent of the type of boiler plant. It can be also confirmed that the potassium content in the bag filter ash of Plant B was highest among all types of ash. The ashes of Plant B have relatively higher calcium content than that of Plant A, which may be due to the difference in the tree species used as biomass fuel. On the other hand, the ashes of Plant A contained higher amounts

of silicate, magnesium, and iron elements than those of Plant B. Here, olivine sand, which contains 43% of MgO , 43% of SiO_2 , and 9% of Fe_2O_3 , was used as the fluidized bed sand. Therefore, this is thought due to mixing of the fluidized bed sand in the ashes [24]. The elemental content of them in the ash increased with increasing particle size of the ash (with sources, in order of particle size: bag filter, cyclone, and boiler ashes). These facts clarified that not only the potassium but also other elements in the ash are markedly dependent on its particle size, the kind of biomass fuel, and the type of furnace.

It was assumed that the material balance of the ashes and their potassium content is established independently of the properties of the biomass fuel. Namely, presuming that the mass fraction of each ash and its potassium component shown in Figure 2 does not depend upon the properties of the biomass fuels, the potassium content in the bag filter ash of Plant A was calculated as if the biomass fuel used in Plant B were used in Plant A. In this case, the calculated potassium content in the bag filter ash was 180 mg/g-dried ash, which is much lower than that of Plant B, 280 mg/g-dried ash. From the same process, the potassium content in the bag filter ash of Plant B was 177 mg/g-dried ash (also much higher than that of Plant A), and 110 mg/g-dried ash, when the same biomass fuel as used in Plant A was fed into Plant B. Therefore, the stoker furnace is thought to be always more appropriate than the fluidized

bed combustion furnace for the condensation of the potassium component.

3.2 Enrichment of potassium in ash by size classification

As mentioned above, the ash having smaller particle size was associated with a higher potassium concentration. Accordingly, it was investigated whether the potassium concentration in the ash could be managed by controlling its particle size. From this, arose the idea for a method of enrichment of the potassium concentration in ash by particle size classification.

Figure 7 illustrates the schematic diagram of the enrichment process set up in Plant B. This process consists of a suction probe at the outlet of the boiler, a high-performance cyclone separator, and a bag filter dust collector. A part of the ash collected by the isokinetic sampling method using the suction probe [29] was fed into the cyclone separator. The coarse and fine ash particles classified by the cyclone were collected in the cyclone and the bag filter, respectively. The dimensions of the cyclone separator, and the appearance of the enrichment process set-up, are shown in **Figure 8**. The classification cut size of the cyclone separator was easily varied by changing the width of the cyclone inlet and setting the position of the apex cone in the dust collection box [30-32]. Hence, the particle size of the ashes collected in the cyclone separator and in the bag filter dust collector could be controlled.

Using this equipment, the dependence of the potassium content on the ash particle size was studied. The experimental relationship between the **mass** median diameter of the ash and its potassium concentration are shown in **Figure 9**. The potassium concentration in the ash rapidly decreased with increasing **mass** median diameter; then the concentration continued to decrease gradually to a constant, for particle size $>20\text{ }\mu\text{m}$. It was also found that ash having more than 35% potassium concentration could be acquired successfully. This adequately satisfies the condition that ash provide a valuable raw material for making fertilizer (i.e., more than or equal to 25% potassium concentration).

The yields of the ash having the enriched potassium concentration were also examined. **Figure 10** shows the dependence of the **enrichment factor** of the potassium element on the collection efficiency in the bag filter. This collection efficiency corresponds to the yield of the enriched potassium ash. Here, the **enrichment factor** was defined as the potassium concentration ratio of the finer ash collected in the bag filter, to the ash fed into the cyclone separator, of which the average concentration was about 20%. The **enrichment factor** decreased with the collection efficiency of the bag filter dust collector monotonously. This indicates that the ash having higher concentration of potassium could be acquired in spite of reduction in its yields. For instance, the yields of ash

having 35% potassium concentration (corresponding to a **enrichment factor** of 1.75) was calculated to be 28%. These results reveal that the enriched potassium ash can be obtained by selectively segregating the fine ash (small particle sizes) using the size classification approach.

The enriched potassium ash cannot be utilized as raw material for the fertilizer when it contains harmful heavy metal components at concentrations in the higher than the regulatory limits. In Japan, the official specifications fixed by the Fertilizers Regulation Act must be satisfied. The official specification for by-product compound fertilizer is as follows [33]: less than 0.75 ppm of cadmium and 20 ppm of arsenic per 1.0% of the maximum concentration among nitrogen, phosphoric acid, and potassium components in the fertilizer. For chemical fertilizer, the official specifications are as follows [33]: in addition to the regulation of cadmium and arsenic, less than 200 ppm of titanium, 30 ppm of lead, 500 ppm of chromium; and 50 ppm of nickel and 0.5 ppm of mercury, per 1.0% of the maximum concentration among nitrogen, phosphoric acid and potassium components in the fertilizer.

Table 4 lists the concentrations of heavy metal components of biomass **combustion** ash enriched to 35% potassium, and the fertilizer made from it and phosphoric acid. The official specifications for by-product compound fertilizer and the chemical fertilizer obtained from their properties are also listed in Table 4. The analyzed

concentrations of all regulated items were much lower than the regulatory limits. That is, the enriched ash and the fertilizer made from it and phosphoric acid completely satisfied the official specifications for both by-product compound fertilizer and chemical fertilizer. Therefore, it is concluded that the enriched ash with high potassium concentration could be used as the raw material for making fertilizer.

4. Conclusions

The material balance and potassium components in residual ash from different two types of combustion processes, and starting with two different biomass fuels, were investigated. The influence of the particle size of the ash on its potassium content was clarified, and a method to enrich the potassium concentration in the ash using a particle-size classification technique was proposed. Moreover, the enriched potassium ash could be used as raw material for making fertilizer. The results obtained can be summarized as follows:

1. The amount of ash calculated from its content in the biomass fuel was in near agreement with the total amount of ashes actually produced, independent of the type of boiler plant. The amount of potassium in the biomass fuel is in absolute agreement with the total amount of

potassium contained in all the ash actually produced. This means that very little potassium escaped with the flue gas, and that nearly all of it remained within the ashes.

2. Most of the potassium is recovered as the bag filter ash, and the difference in the mass fraction of K in the bag filter ash between both plants was not so large, compared with the mass fraction of the bag filter ash itself. This leads to the result that the stoker furnace gives a much higher concentration of potassium components in the bag filter ash than the fluidized bed furnace.
3. Although the crystal structures of potassium components in the cyclone and bag filter ashes are different between the two boiler plants, all components have hydro-soluble crystalline phases.
4. There is little difference between the two boiler plants, in the particle size distribution of the cyclone and the bag filter ashes.
5. The ashes of the boiler plant with the fluidized bed combustion furnace contain higher content of silicate, magnesium, and iron, which might be induced by mixing of the fluidized bed sand in the ashes.
6. According to the mass balance results, the stoker furnace is thought to be always more appropriate than the fluidized bed combustion furnace for condensing the potassium components in the bag filter ash.
7. The potassium concentration in the ash decreases

- rapidly with increasing **mass** median diameter of ash particles, then at $>20\text{ }\mu\text{m}$, the K concentration continues to decrease gradually to a constant.
8. As the **enrichment factor** of K in the ash increases, its yields decline. However, enriched potassium ash can be obtained by collecting the finer ash (smaller particle sizes) selectively using a particle-size classification technique.
 9. Because the enriched potassium ash and the fertilizer made from it completely satisfy the official specifications for both by-product compound fertilizer and chemical fertilizer, the enriched potassium bag filter ash could be used as raw material for making fertilizer.

Acknowledgements

This work was carried out as the grant-aided project by the Forestry Agency of the Ministry of Agriculture, Forestry, and Fisheries of Japan in 2014, and was also partially supported by the Matching Planner Program of the Japan Science and Technology Agency in 2016.

The authors acknowledge valuable discussions with Dr. Katsunori Noguchi (Katakura & Co-op Agri) and Mr. Hidenao Matsuoka (Chugoku Mokuzai).

References

- [1] D.J. Arent, A. Wise, R. Gelman, The status and prospects of renewable energy for combating global warming, *Energy Economics* 33 (2011) 584-593.

- [2] R.S. Dhillon, G. von Wuehlisch, Mitigation of global warming through renewable biomass, *Biomass and Bioenergy* 48 (2013) 75-89.

- [3] P. Sun, P. Nie, A comparative study of feed-in tariff and renewable portfolio standard policy in renewable energy industry, *Renewable Energy* 74 (2015) 255-262.

- [4] K. Sasauchi, Selection of Technical Systems Suitable for Small Scale Biomass Power Generation under the FIT scheme, *Journal of the Japan Institute of Energy* 94 (2015) 1188-1193.

- [5] T. Kimura, Status of, and Issues concerning, Biomass Power Generation in the Framework of FIT, *Journal of the Japan Institute of Energy* 94 (2015) 1204-1209.

- [6] A. Repo, A. Ahtikoski, J. Liski, Cost of turning forest residue bioenergy to carbon neutral, *Forest Policy and Economics* 57 (2015) 12-21.

- [7] T. Miura, Current Status of Biomass Energy Utilization, *Journal of Waste Resource Recycling* 21 (2010) 11-17.
- [8] N. Tanigaki, Y. Ishida, M. Osada, A case-study of landfill minimization and material recovery via waste co-gasification in a new waste management scheme, *Waste Management* 37 (2015) 137-146.
- [9] Q. Feng, Q. Lin, F. Gond, S. Sugita, M. Shoya, Adsorption of lead and mercury by rice husk ash, *Journal of Colloid and Interface Science* 278 (2004) 1-8.
- [10] B.B. Park, R.D. Yanai, J.M. Sehm, D.K. Lee, L.P. Abrahamson, Wood ash effects on plant and soil in a willow bioenergy plantation, *Biomass and Bioenergy* 28 (2005) 355-365.
- [11] A. Peys, H. Rahier, Y. Pontikes, Potassium-rich biomass ashes as activators in metakaolin-based inorganic polymers, *Applied Clay Science* 119 (2016) 401-409.
- [12] V.K. Gupta, C.K. Jain, I. Ali, M. Sharma, V.K. Saini, Removal of cadmium and nickel from wastewater using bagasse fly ash—a sugar industry waste, *Water Research* 37 (2003) 4038-4044.

- [13] C. Leiva, A. Gomez-Barea, L.F. Vilches, P. Ollero, J. Vale, C. Fernandez-Pereira, Use of Biomass Gasification Fly Ash in Lightweight Plasterboard, *Energy & Fuels* 21 (2007) 361-367.
- [14] O. Ortiz, J.C. Pasqualino, F. Castells, Environmental performance of construction waste: Comparing three scenarios from a case study in Catalonia, Spain, *Waste Management* 30 (2010) 646-654.
- [15] M. Takeuchi, H. Kawahara, L.P. Gupta, M. Itouga, H. Sakakibara, H. Ohta, T. Komai, Y. Ono, Chemistry of fly ash and cyclone ash leachate from waste materials and effects of ash leachates on bacterial growth, nitrogen-transformation activity, and metal accumulation, *Journal of Hazardous Materials* 165 (2009) 967-973.
- [16] R. Budhathoki, A. Vaisanen, Particle size based recovery of phosphorus from combined peat and wood fly ash for forest fertilization, *Fuel Processing Technology* 146 (2016) 85-89.
- [17] A. Demeyer, J.C.V. Nkana, M.G. Verloo, Characteristics of wood ash and influence on soil properties and nutrient uptake: an overview, *Bioresource Technology* 77 (2001) 287-295.

[18] R. Poykio, H. Ronkkomaki, H. Nurmesniemi, P. Peramaki, K. Popov, I. Valimaki, T. Tuomi, Chemical and physical properties of cyclone fly ash from the grate-fired boiler incinerating forest residues at a small municipal district heating plant (6 MW), *Journal of Hazardous Materials* 162 (2009) 1059-1064.

[19] R. Rajamma, R.J. Ball, L.A.C. Tarelho, G.C. Allen, J.A. Labrincha, V.M. Ferreira, Characterisation and use of biomass fly ash in cement-based materials, *Journal of Hazardous Materials* 172 (2009) 1049-1060.

[20] C. Lanzerstorfer, Model based prediction of required cut size diameter for fractionation of fly ash from a grate-fired wood chip incineration plant, *Fuel Processing Technology* 92 (2011) 1095-1100.

[21] C. Lanzerstorfer, Cyclone fly ash from a grate-fired biomass combustion plant: Dependence of the concentration of various components on the particle size, *Fuel Processing Technology* 131 (2015) 382-388.

[22] T. Sano, S. Miura, H. Furusawa, S. Kaneko, T. Yoshida, T. Nomura, S. Ohara, Composition of inorganic elements and the leaching behavior of biomass combustion ashes discharged from wood pellet boilers in Japan, *Journal of Wood Science* 59 (2013) 307-320.

[23] FAMIC (Food and Agricultural Materials Inspection Center),

http://www.famic.go.jp/ffis/fert/sub6_data/bunsekihou4.html (2016).

[24] R.P. Giron, B. Ruiz, E. Fuente, R.R. Gil, I. Suarez-Ruiz, Properties of fly ash from forest biomass combustion, *Fuel* 114 (2013) 71-77.

[25] S. Du, H. Yang, K. Qian, X. Wang, H. Chen, Fusion and transformation properties of the inorganic components in biomass ash, *Fuel* 117 (2014) 1281-1287.

[26] D. Wu, Y. Wang, Y. Wang, S. Li, X. Wei, Release of alkali metals during co-firing biomass and coal, *Renewable Energy* 96 (2016) 91-97.

[27] A. Williams, J.M. Jones, L. Ma, M. Pourkashanian, Pollutants from the combustion of solid biomass fuels, *Progress in Energy and Combustion Science* 38 (2012) 113-137.

[28] K. Inkaew, A. Saffarzadeh, T. Shimaoka, Modeling the formation of the quench product in municipal solid waste incineration (MSWI) bottom ash, *Waste Management* 52 (2016) 159-168.

[29] B. Reinhardt, A. Cordonnier, P. Florent, Use of an isokinetic sampling probe. Results in a cyclone, Powder Technology 101 (1999) 81-90.

[30] H. Yoshida, Y. Nishimura, K. Fukui, T. Yamamoto, Effect of apex cone shape on fine particle classification of gas-cyclone, Powder Technology 204 (2010) 54-62.

[31] H. Yoshida, Y. Kwan-Sik, K. Fukui, S. Akiyama, S. Taniguchi, Effect of apex cone height on particle classification performance of a cyclone separator, Advanced Powder Technology 14 (2003) 263-278.

[32] H. Yoshida, Effect of apex cone shape and local fluid flow control method on fine particle classification of gas-cyclone, Chemical Engineering Science 85 (2013) 55-61.

[33] FAMIC (Food and Agricultural Materials Inspection Center),
<http://www.famic.go.jp/ffis/fert/kokuji/60k0284.htm>
(2016).

Figures and Tables

Figure 1 Schematic diagram of biomass fuel boiler plants equipped with different combustion technologies.

Figure 2 Mass fraction of each ash and its potassium component for Plants A and B.

Figure 3 External appearance of the cyclone and bag filter ashes in Plants A and B, and their potassium concentration.

Figure 4 XRD peak patterns of cyclone and bag filter ashes in Plants A and B.

Figure 5 Cumulative size distribution of cyclone and bag filter ashes produced in Plants A and B.

Figure 6 Components of ashes in Plants A and B measured by XRF.

Figure 7 Schematic diagram of the enrichment process set up in Plant B.

Figure 8 Dimensions of the cyclone separator and the appearance of the enrichment process set up.

Figure 9 Relationship between the mass median diameter of ash particles and their potassium concentration (K_2O Basis)

Figure 10 Dependence of the enrichment factor of the potassium element on the collection efficiency in the bag filter dust collector.

Table 1 Specifications of furnace and boiler in Plants A and B.

Table 2 Properties of the biomass fuels used in both boiler plants.

Table 3 Material balance of ashes and their potassium components for both plants.

Table 4 Concentrations of heavy metal components in the ash and its chemical fertilizer with their specifications fixed by the Fertilizers Regulation Act in Japan.

Table 1 Specifications of furnace and boiler in Plants A and B.

	Plant A	Plant B
Furnace type	Fluidized bed combustion furnace	Stoker furnace
Feed rate of biomass fuel	15,800 kg/h	5,467 kg/h
Combustion chamber volume	280 m³	110 m³
Fire floor area	18 m²	14.4 m²
Steam pressure	3.14 MPa	1.86 MPa
Steam temperature	305 °C	310 °C

Table 2 Properties of the biomass fuels used in both boiler plants.

Boiler plant type	Boiler Plant A			Boiler Plant B			
Biomass fuel type	Oregon pine			Japanese cedar			
	Bark	Raw sawdust	Average	Wood chip	Bark	Dry sawdust	Average
Mixing ratio [mass%]	45.3	54.7	100	17.6	62.9	19.5	100
Moisture content [mass%]	51.3	49.1	50.1	14.2	47.3	10.1	34.2
Ash component [mass% - dry]	2.06	0.12	0.99	0.48	2.31	0.37	1.37
Potassium component [kg/ton-fuel-dry]	1.10	0.23	0.62	0.54	1.50	1.50	1.34

Table 3 Material balance of ashes and their potassium components for both plants.

(a) Plant A	Biomass fuel	Foreign matter	Boiler ash	Cyclone ash	Bag filter ash	Total
Amount of ash [kg/ton-fuel-dry]	9.88	0.45	1.32	4.84	4.50	11.11
Potassium component [kg/ton-fuel-dry]	0.62	0	0.03	0.17	0.50	0.70

(b) Plant B	Biomass fuel	Bottom ash	Boiler ash	Cyclone ash	Cooling tower ash	Bag filter ash	Total
Amount of ash [kg/ton-fuel-dry]	13.69	2.04	1.08	7.84	0	2.37	13.33
Potassium component [kg/ton-fuel-dry]	1.34	0.13	0.05	0.43	0	0.67	1.28

Table 4 Concentrations of heavy metal components in the ash and its chemical fertilizer with their specifications fixed by the Fertilizers Regulation Act in Japan.

Heavy metal component	Official specification for by-product compound [ppm]	Enriched potassium ash [ppm]	Official specification for chemical fertilizer [ppm]	Fertilizer from enriched potassium ash [ppm]
Ti	-	-	9600	340
Pb	-	-	1440	158
Cr	-	-	24000	72
Ni	-	-	2400	11
Cd	24	4.56	36	4
As	634	5.25	960	9
Hg	-	-	24	0.5

(a) Plant A

(b) Plant B

Figure 1 Schematic diagram of biomass fuel boiler plants equipped with different combustion technologies.

(a) Amount of ash

(b) Amount of potassium component

Figure 2 Mass fraction of each ash and its potassium component for Plants A and B.

(a) Plant A

(b) Plant B

Figure 3 External appearance of the cyclone and bag filter ashes in Plants A and B, and their potassium concentration.

(a) Plant A

(b) Plant B

Figure 4 XRD peak patterns of cyclone and bag filter ashes in Plants A and B.

Figure 5 Cumulative size distribution of cyclone and bag filter ashes produced in Plants A and B.

(a) Plant A

(b) Plant B

Figure 6 Components of ashes in Plants A and B measured by XRF.

Figure 7 Schematic diagram of the enrichment process set up in Plant B.

Flow rate : 200 ~ 500 m³/h

(a) Dimensions of the cyclone separator

(b) Appearance

Figure 8 Dimensions of the cyclone separator and the appearance of the enrichment process set up.

Figure 9 Relationship between the mass median diameter of ash particles and their potassium concentration (K₂O Basis)

Figure 10 Dependence of the enrichment factor of the potassium element on the collection efficiency in the bag filter dust collector.

Schematic diagram of the enrichment process set up in Plant B.

Relationship between the median diameter of ash particles and their potassium concentration

The potassium concentration in the ash decreases rapidly with increasing median diameter of ash particles.

To enrich the potassium concentration in the ash, a method was proposed for collecting the finer ash (smaller particle size) selectively using a particle-size classification technique at factory scale.