Study on Mass Transfer of Ash during Bamboo Powder Combustion

Kazuma TAKATA※1, Nao UMEHARA※1, Shohei OKUBO※1, Ken-ichiro TANOUΕ※1†, Morihisa YOKOTA※1※2, Toyoaki NIKI※2, and Yoshihiko NINOMIYA※3

(Received April 16, 2020)

In this study, mass transfer of ash during bamboo powder combustion on a flat flame is investigated experimentally and numerically. The bamboo powder combustion consisted of volatiles emission, volatiles combustion, char formation, char combustion, and finally ash formation. The mass of ash formed was about 3 wt% that of raw bamboo powder. The mass of ash decreased with the equivalence ratio \( \Phi \) for flat flame combustion. Part of the ash fused and then adhered to the Inconel mesh for wrapping of bamboo powder as bottom ash, flowing through the mesh. The mass adhered to the Inconel mesh depended strongly on the equivalence ratio \( \Phi \). The fusion tendency of the atmospheric oxidization ash agreed qualitatively with Liu’s standard bamboo ash fusion test. On the other hand, as ash fusion started locally in this work, it suggests that the concentration of metal oxides of the atmospheric oxidization ash was not uniform. For the atmospheric oxidization ash at 600 °C, K2Si2O5, KAISO4, Na2CaP2O7, Mg2SiO4, K2SO4, and Fe2O3 were predicted to be the major eutectic materials. At 1120 °C, only Fe2O3 remained and the liquid components accounted for about 95%. On the other hand, the major eutectic materials for the combustion ashes of \( \Phi = 0.85 \) and \( \Phi = 1.0 \) at 1260 °C were MgO and Fe2O3, respectively. Therefore, the predicted eutectic materials of the combustion ash were changed appropriately in comparison with those for the atmospheric oxidization ash because of the fusion and disappearance of some metal oxide components during combustion.

Key Words

Bamboo powder combustion, Ash fusion behavior, Equivalence ratio, Thermodynamic equilibrium simulation

---

※1 Yamaguchi University
2-16-1, Tokiwadai, Ube-shi, Yamagushi 755-8611, Japan
※2 Ube Industries, Ltd.
1978-96, Kogushi, Ube-shi, Yamaguchi 755-8633, Japan
※3 Chubu University
1200, Matsumoto-cho, Kasugai-shi, Aichi 487-8501, Japan
†Corresponding author: tano@yamaguchi-u.ac.jp
1. Introduction

The application of woody biomass plays an important role in efforts to minimize the dependence on non-renewable energy sources such as fossil fuels. The most important merit of woody biomass is that, although woody biomass releases carbon into the atmosphere when it is burned to process into energy, replanting the trees will absorb the same amount of carbon from the atmosphere into the forest eco-system. This is what is called "carbon neutrality." Among woody biomasses, bamboo has the advantage that it grows fast, but it is often sourced from neglected bamboo groves and has the disadvantage that bamboo damage is likely to occur. Therefore, it is very important to consider the effective use of bamboo.

Power generation technologies using biomass as an energy resource can be roughly divided into electricity generation by direct combustion and electricity generation by gasification. Furthermore, direct power generation processes can be divided into the single-firing method and the mixed-firing method. The firing method is a power generation method by using only biomass directly as a fuel. On the other hand, the co-firing method, which is applicable at existing coal-fired power plants, is where a mixture of biomass and coal is used as the fuel. In this method, there is the advantage that it is possible to reduce the amount of coal used in the power generation process.

For co-firing of coal and biomass, there are two problems that need to be solved. Firstly, the high heating value for biomass is about 0.5 times that for coal. In order to solve this first problem, a technique called torrefaction, a semi-carbonization method, which increases the heating value by heating at 200-300 °C and releases volatile components that do not contribute to combustion, has been studied. The second problem is that biomass is different from coal in that it contains ash with a low melting point and contains a large amount of sodium oxide (Na$_2$O), potassium oxide (K$_2$O), etc., which is a problem that forms ash blocks called clinker and hinders combustion. Regarding this second problem, there are different types of low-melting metal oxides and concentrations available for each type of biomass, and various studies have been conducted. Some studies have investigated the increase in ash fusion temperature due to the addition of high-melting-point compounds.

For biomass ash research, biomass was ashed in an oxidizing atmosphere at around 600 °C or 800 °C according to the standards of each country such as ASTM E870-82, GB/T212-2001, CEN-TS 15920, DIN EN ISO 18122, GB/T 28731-2012, BS EN ISO 18122:2015, and so on. Then, the metal oxides, ash fusion temperature, and eutectic materials of the standard biomass ash were measured or estimated by X-ray fluorescence (XRF), thermal microscopy, and X-ray diffractometer (XRD), respectively. In recent years, estimation of eutectic materials by chemical thermodynamic equilibrium calculation instead of XRD has also been studied as a promising method. The ash melting point is roughly determined by the composition ratio of K$_2$O, SiO$_2$, and CaO. Polparg, Elbistan lignite, hazelnut shell, rice husk, etc., in which the proportion of CaO or SiO$_2$ is higher than the other two oxides, have been shown to have a deformation temperature of over 1300 °C. For example, eutectics formed from lignite ash were CaO, Ca(OH)$_2$, CaSO$_4$, Na$_2$Si$_2$O$_5$-H$_2$O, K$_2$SiO$_3$, K$_2$(S$_2$O$_7$)$_2$, and SiO$_2$. On the other hand, corn cob, wheat straw, sunflower, corn stalk, bagasse, cotton stalk, wheat stalk, bamboo, etc., whose CaO ratio was lower than the other two oxides, generally have a deformation temperature below 1000 °C. However, the oxide composition of bamboo ash varies greatly for K$_2$O: 31-50%, SiO$_2$: 7-24%, and CaO: 2-6%, and its deformation temperature also changes from 800 °C to 1280 °C. Therefore, it is expected that their values for bamboo will differ greatly depending on the place of origin and location.

The eutectics formed from bamboo ash with an ash deformation temperature of 950 °C were K$_2$SO$_4$, Mg$_4$(PO$_4$)$_6$, and MgCO$_3$, while the eutectics formed from bamboo ash with an ash deformation temperature of 1280 °C were (K, Na)$_3$Na(SO$_4$)$_2$, K$_2$SO$_4$, CaS, and Ca(HPO$_4$)$_2$.

Although, for previous reports, ash fusion and eutectic materials with different heating temperatures of ash formed under the standard ashing procedure have been studied, there is no report on the relationship between standard ash and ash mass transfer during actual biomass combustion.

The purpose of this study is to investigate the mass transfer of ash during the combustion of bamboo powder, which contains a large amount of potassium oxide and therefore readily produces clinker. Specifically, temperature in a bamboo-packed bed and the mass of ash during combustion were measured, and the material balance of bottom ash and fly ash after combustion was investigated. Furthermore, we observed the fusion behavior of bamboo ash prepared with reference to JIS K7250-1, JIS P8251, and JIS Z7302-4, analyzed the oxide composition using XRF, and predicted the eutectic materials by thermodynamic equilibrium calculation.

2. Experimental

2.1 Bamboo powder combustion

Fig. 1 shows the total setup of the experimental apparatus for bamboo powder combustion. The apparatus
consisted of a supply section of methane and air, a mixing section, a bamboo-powder-packed bed, and an exhaust blower. The flow rates of methane and air were controlled by a mass flow controller (SEC-E40, HORIBA STEC). The accuracies of the mass flow controllers are 3% of full scale flow rate 10 SLM. A mixing section filled with glass beads and alumina beads was prepared in a stainless steel cylindrical container having a diameter of 76.3 mm and a length of 340 mm. An Inconel mesh A (#18, wire diameter = 0.5 mm) was installed on the mixing section to make a flat flame.

Fig. 2 shows an enlarged view of the bamboo-powder-packed bed. Bamboo powder was made uniform to 0.5 mm or less with a sieve and dried at 383 K for 120 min or more with a constant-temperature drier (BNS-112S, ISUZU Corp.). A cylindrical fire brick was wrapped by Inconel mesh B (#60, wire diameter = 0.18 mm) to hold 20 g of bamboo powder and settled on Inconel mesh A. Three titanium circular plates as shown in Fig. 2 were set to measure the mass of adsorbed ashes for bottom ash and fly ash. The diameters of the plate for the bottom ash and fly ash were 10 mm and 20 mm, respectively. The thickness of the plates was 1 mm. The temperature during combustion at a position of 5 mm from Inconel mesh B was measured by an R-type bare thermocouple of 100 μm.

The experimental procedure was as follows.
1) Methane and air of the expected equivalence ratio were supplied, ignited to generate a flat flame, and maintained for about 1 hour.
2) After confirming that the flat flame was stable, a bamboo-powder-packed bed was installed on the top of the flat flame and the combustion experiment was started and continued for a predetermined combustion time. Immediately, temperature measurement with the thermocouple was started, and the combustion gas was discharged by the blower.
3) Volatile components such as tar and hydrocarbons were discharged from the outlet through the blower during bamboo combustion.
4) After expected combustion time , methane and air were stopped.
5) The masses of Inconel mesh B, combustion residue, and three titanium circular plates were measured. In consideration of reproducibility of mass of ash, experiments were conducted twice or more for . The experimental conditions are listed in Table 1. The equivalence ratio is defined by the following equation .

\[
\Phi = \frac{\text{Stoichiometric mass flow rate of oxygen}}{\text{Stoichiometric Mass flow rate of fuel}}
\]

2.2 Bamboo powder ashing and visualization of fusion behavior

In order to prepare an original ash without partly disappearance of ash due to fusion during combustion, bamboo powder was spread thinly on a magnetic dish, placed in a box-type electric furnace, and heated at 600 °C for 4 hours under air atmospheric conditions with reference to JIS K7250-1, JIS P8251, and JIS Z7302-4. The bamboo powder after heating is hereinafter referred to as the original bamboo ash. Fusion behavior of the original bamboo ash was observed using a high-temperature microscope whose heating rate and air flow rate were 10 °C/s and 100 mL/min, respectively.
2.3 Measurement of metal oxide components

The components of metal oxides of the original ash and the combustion residue at $t_c = 60$ min for $\Phi = 0.7, 0.85$ and 1.0 were measured by an X-ray fluorescence analyzer (RIGAKU, ZSX Primus).

2.4 Prediction of eutectic materials

As FactSage 7.1 (GTT-Technologies) has the thermodynamic data for a few thousands of pure materials and hundreds of solutions [39], we could predict the crystalline phases of the ashes by using metal oxide components, which were measured by XRF analyzer at the expected temperature. The calculations were conducted from 600°C to 1300°C every 50°C.

3. Results and Discussion

3.1 Bamboo powder combustion

Fig. 3 shows the time course of temperature and visualization photographs in the bamboo-packed bed during combustion. For an equivalence ratio $\Phi = 0.85$, the temperature increased sharply to $t_c < 5$ min after the start of combustion, reaching about 800°C. At this time, white smoke rose as seen from the visualization photograph. Therefore, in this time period, it is suggested that the emission of volatile matter by pyrolysis of bamboo powder and combustion of volatile matter occur simultaneously.

After that, the temperature asymptotically approached about 900°C at $10 \text{ min} < t_c < 25 \text{ min}$, reaching a nearly constant temperature. From the visualization photograph at this time, it transpired that apart of the char was glowing red. Therefore, it is expected that char combustion occurs mainly in this time period. It was confirmed that the temperature slowly decreased from around $t_c = 40$ min. Char combustion continued afterwards, and it was observed that the amount of ash decreased. Although the maximum temperature strongly depended on the equivalence ratio $\Phi$, the time courses of the temperature for $\Phi = 0.7$ and 1.0 were almost the same as that for $\Phi = 0.85$.

Fig. 4 shows the dependence of the mass of combustion residue and the adsorbed ash on Inconel mesh B on the combustion time at $\Phi = 0.85$. The mass of combustion residue was about 3.7 g at $t_c = 5$ min when the emission of volatiles from bamboo pyrolysis and their combustion occurred. The mass of combustion residue decreased with the combustion time, while the adsorbed ash on Inconel mesh B increased with the combustion time. For $20 \text{ min} < t_c < 30 \text{ min}$, the mass of combustion residues had the large scattering. From the observation results, the combustion was almost completed at this time, and the ash formed during the combustion was distributed in the radial direction of the cylindrical container, and the mass of ash decreased.

| Table 1 Experimental conditions for bamboo powder combustion |
|-------------------------------------------------------------|
| Gas component  | Flow rate [SLM] | Equivalence ratio for methane flat flame [-] | Bamboo powder | Input mass [g] | Average particle diameter [μm] | Particle shape | Place of origin |
|----------------|-----------------|-----------------------------------------------|---------------|---------------|-------------------------------|----------------|----------------|
| Air            | 9.2             | 0.7                                           | 20            | 20            | 344                           | Acicular       | Kumamoto Pref. (Japan) |
| Methane        | 0.68            | 0.78                                          |               | 344           | Collectible                  |                |                |
|                | 0.76            | 0.78                                          |               |               |                               |                |                |
|                | 0.82            | 0.85                                          |               |               |                               |                |                |
|                | 0.89            | 0.92                                          |               |               |                               |                |                |
|                | 0.96            | 1                                             |               |               |                               |                |                |

Fig. 3 Time course of temperature on the Inconel mesh and photograph of the bamboo-packed bed during combustion.

Fig. 4 Dependence of the mass of the combustion residue and adsorbed ash on Inconel mesh B on the combustion time.
not only at the center of the container but also at the wall of the container could be smaller than that at the other part of the container. Therefore, it is considered that the reason for the mass scattering of the residue ash at 20 min $< t_c < 30$ min could be not only the shape of the ash on the Inconel mesh but also the amount of ash passing through the Inconel mesh after each experiment. As the combustion time elapsed, their mass approached an almost constant value at $t_c > 45$ min. Therefore, it suggests that char may be included in the combustion residue at $t_c < 45$ min, and we regarded the combustion residue as combustion ash at $t_c = 60$ min.

Table 2 shows the dependence of theoretical adiabatic temperature and mass balance of the ashes at $t_c = 60$ min on the equivalence ratio. The theoretical adiabatic flame temperature can be calculated by the published calculation program. For $\Phi = 0.70$, the theoretical adiabatic temperature was 1565 °C and the mass of combustion ash was almost 2.7 wt% that of the raw bamboo powder, while ash of 5.7% was adsorbed on the Inconel mesh. The masses of ash on titanium plate 1 and plate 2 were higher than that on titanium plate 3 because more bottom ash may be produced than fly ash. The mass of combustion ash for $\Phi \geq 0.78$ was lower than that for $\Phi = 0.70$ because the theoretical adiabatic temperature was higher than that for $\Phi = 0.70$ and then part of the ash fused and adsorbed on the Inconel mesh. As the fusion of ash for $\Phi = 0.92$ and 1.0 may progress because of the increment of the theoretical adiabatic temperature, the mass of ash on titanium plates 1 and 2 was higher than that for $\Phi = 0.85$.

![Fig. 5](image_url)

**Fig. 5** shows photographs of the adhered ash on titanium plate 1. For $\Phi = 0.70$, the ash was very brittle and had a hardness that would break when nipped with tweezers. The higher the equivalence ratio became, the harder the adhered ash became. Furthermore, for $\Phi = 1.0$, the height of the adhered ash was up to about 5 mm as shown in the perspective view of the ash.

### 3.2 Visualization of the original bamboo ash during fusion

**Fig. 6** shows snapshots of the original bamboo ash on the hot stage that was heated up to 1250 °C. At 600 °C, the ash locally melted. When the temperature increased from 700 °C to 1000 °C, ash melting progressed slowly. Thereafter, ash melting was almost completed at about 1100 °C. The fusion tendency in this study agreed qualitatively with Liu's standard bamboo ash fusion test whose deformation temperature (DT), softening temperature (ST),

| $\Phi$ | Theoretical Adiabatic flame temperature [°C] | Combustion ash [g] | Inconel mesh B [g] | Titanium plate 1 [g] | Titanium plate 2 [g] | Titanium plate 3 [g] |
|-------|---------------------------------------------|--------------------|--------------------|----------------------|----------------------|----------------------|
| 0.70  | 1365                                        | 0.53               | 0.039              | 0.037                | 0.003                | < 0.001              |
| 0.78  | 1693                                        | 0.41               | 0.044              | 0.020                | 0.043                | < 0.001              |
| 0.85  | 1796                                        | 0.38               | 0.187              | 0.029                | 0.025                | < 0.001              |
| 0.92  | 1885                                        | 0.41               | 0.053              | 0.028                | 0.033                | < 0.001              |
| 1.0   | 1953                                        | 0.40               | 0.068              | 0.043                | 0.036                | < 0.001              |

![Fig. 5](image_url)

**Fig. 5** Photographs of the adhered ash on titanium plate 1 as a) top view and b) perspective view
hemispherical temperature (HT), and flow temperature (FT) were 950 °C, 1038 °C, 1136 °C, and 1181 °C, respectively. On the other hand, the three fusion temperatures (ST, HT, and FT) for Zhu's standard bamboo ash were higher than those for Liu's ash because their temperatures for bamboo differed greatly depending on the place of origin and location. Furthermore, as ash fusion started locally in this work, it suggests that the concentration of metal oxides in the original bamboo ash is not uniform.

3.3 Measurement of metal oxide components and prediction of eutectic materials of the original bamboo ash and the combustion ash

Fig. 7 shows the chemical compositions of the original bamboo ash, Zhu's bamboo ash, combustion ash at \( \Phi = 0.85 \), and combustion ash at \( \Phi = 1.0 \). The major components of the original bamboo ash were SiO\(_2\), K\(_2\)O, P\(_2\)O\(_5\), MgO, CaO, Na\(_2\)O, Fe\(_2\)O\(_3\), Al\(_2\)O\(_3\), and SO\(_3\). Comparing the original bamboo ash with Liu's bamboo ash, there were mass percentage differences for SiO\(_2\), K\(_2\)O, Na\(_2\)O, Fe\(_2\)O\(_3\), and Cl because the alkali components differed not only according to the bamboo parts but also the bamboo.
production place. On the other hand, the mass percentage of K₂O after bamboo combustion increased by about twice that of the original bamboo ash even if the equivalence ratio was changed as shown in Figs. 7c) and 7d). The reason may be that Na₂O, Al₂O₃, and part of SiO₂ fused and then flew down through the Inconel mesh.

Fig. 8 shows the calculation result between the mass percentage of the solid components and the temperature using the chemical composition in Figs. 7a), 7c), and 7d). For the original bamboo ash in Fig. 8a), the major eutectic materials at 600 °C were K₂Si₂O₅, KAlSiO₄, Na₂CaP₂O₇, Mg₂SiO₄, K₂SO₄, and Fe₂O₃, while the liquid components

![Fig. 8 Relationship between eutectic materials and equilibrium temperature predicted by FactSage for a) original bamboo ash, b) combustion ash of \( \Phi = 0.85 \), and c) combustion ash of \( \Phi = 1.0 \)]
accounted for about 8%. As Na2CaP2O7 and K2Si2O7 were fused at 900 °C, the liquid components reached about 61%. At 1120 °C, only Fe2O3 remained as the eutectic material and the liquid components rose to about 95%. On the other hand, for the combustion ash of $\Phi = 0.85$ in Fig. 8b), the major eutectic materials at 900 °C were Ca2Fe2O5, MgO, K2SO4, and KAlO2, while the liquid components accounted for about 83%. At 1120 °C, K2SO4 and KAlO2 were fused at 1120 °C and a part of Ca2Fe2O5 was changed into CaFeO4. At 1260 °C, only MgO remained as the eutectic material and the liquid components reached about 98%. For the combustion ash of $\Phi = 1.0$ in Fig. 8c), the major eutectic materials at 900 °C were Fe2O3, MgO, K2SO4, KAlSiO4, Na2CaP2O7, Mg2SiO4, K2SO4, and Fe2O3 were predicted as the major eutectic materials. At 1120 °C, only Fe2O3 remained and the liquid components reached about 95%. On the other hand, the major eutectic materials for the combustion ash of $\Phi = 0.85$ and $\Phi = 1.0$ at 1260 °C were only MgO and Fe2O3, respectively. Therefore, the predicted eutectic materials for the combustion ash were changed as appropriate when compared with those for the atmospheric oxidization ash because of the fusion and disappearance of some metal oxide components during combustion.

Acknowledgements

The present work was financially supported by Tanikawa Fund Promotion of Thermal Technology, and contract research expenses of Chugai Ro, Co. Ltd. The crushed bamboo particles were sent by Bamboo Energy Co. Ltd. The authors also give special thanks to Mei Noguchi, Masayuki Fujita and Kanna Hirao for conducting the temperature and mass of ash measurements.

References

1) Gustavsson, L.; Svenningson, P., Energy Conversion and Management, 37(6-8), 1211-1216 (1996)
2) Chávez, V.; Macdonald, S. E., Forest Ecology and Management, 271, 19-26 (2012)
3) Scurlock, J. M. O.; Dayton, D. C.; Hames, B., Biomass Bioenergy, 19, 229-244 (2000)
4) Deshmukh, R.; Jacobson, A.; Chamberlin, C.; Kammen, D., Biomass Bioenergy, 55, 163-174 (2013)
5) Sami, M.; Annamalai, K.; Wooldridge, M., Prog.: Energy Combust. Sci., 27(2), 171-214 (2001)
6) Rousset, P.; Aguilar,C.; Labbé, N.; Commandré, J-M., Bioresour. Technol., 102(17), 8225-8231 (2011)
7) Chen, W.-H.; Du, S.-W.; Tsai, C.-H.; Wang, Z.-Y., Bioresour. Technol., 111, 433-438 (2012)
8) Chen, W.-H.; Peng, J.; Bi, X. T., Renew. Sustain. Energy Rev., 44, 847-866 (2015)
9) Acharya, B.; Sule, I.; Dutta A., Biomass Conv. Bioref., 2, 349-369 (2012)
10) Tumuluru, J. S.; Sokhansanj, S.; Wright, C. T.; Hess, J. R.; Boardman, R. D., A Review on Biomass Torrefaction Process and Product Properties. Proceedings of Symposium on Thermochemical Conversion; Oklahoma, USA, Aug 2, 1-14 (2011)
11) Vassilev, S. V.; Baxter, D.; Vassileva, C. G., Fuel, 117(A), 152-183 (2014)
12) Niu, Y.; Tan, H.; Hui, S., Prog. Energy Combust. Sci., 52, 1-61 (2016)
13) Jenkins, B. M.; Baxter, L. L.; Miles Jr, T. R.; Miles, T. R.,
14) Zevenhoven-Onderwater, M.; Backman, Rainer; Skrifvars, B.-J.; Hupa, M., *Fuel*, 80(10), 1489-1502 (2001)
15) Toscano, G.; Corinaldesi, F., *J. Agric. Eng.*, 41(2), 13-19 (2010)
16) Öhman, Marcus; Boström, Dan; Nordin, A., *Energy Fuels*, 18(5), 1370-1376 (2004)
17) Wang, Q.; Han, K.; Wang, J.; Gao, J.; Lu, C., *Renew. Energy*, 113, 428-437 (2017)
18) Wang, L.; Skjevrak, G.; Hustad, J. E.; Skreiber, Ø., *Energy Fuels*, 28(1), 208-218 (2014)
19) Clery, D. S.; Masona, P. E.; Rayner, C. M.; Jones, J. M., *Fuel*, 214, 647-655 (2018)
20) Roberts, L. J.; Masona, P. E.; Jones, J. M.; Gale, W. F.; Williams, A.; Hunt, A.; Ashman, J., *Biomass Bioenergy*, 127, 105284 (2019)
21) Wang, L.; Hustad, J. E.; Skreiber, Ø.; Skjevrak, G.; Gronlia, M., *Energy Procedia*, 20, 20-29 (2012)
22) Llorente, M. J. F.; García, J. E. C., *Fuel*, 84(14-15), 1893-1900 (2005)
23) Haykiri-Acma, H.; Yaman, S.; Kucukbayrak, S., *Fuel*, 89(10) 3063-3068 (2010)
24) Wang, L.; Hustad, J. E.; Gronlia, M., *Energy Fuels*, 26(9), 5905-5916 (2012)
25) Li, Q. H.; Zhang, Y. G.; Meng, A. H.; Li, L.; Li, G. X., *Fuel Process. Technol.*, 107, 107-112 (2013)
26) Niu, Y.; Tan, H.; Wang, X.; Liu Z.; Liu, H.; Yang L.; Tongmo, X., *Bioresour. Technol.*, 101(23), 9373-9381 (2010)
27) Wang, S.; Jiang, X. M.; Han, X. X.; Wang, H., *Energy Fuels*, 22(4), 2229-2235 (2008)
28) Wang, L.; Dibdiiakova, J., *Chem. Eng. Trans.*, 37, 37-42 (2014)
29) Boström, D.; Skoglund, N.; Grimm, A.; Boman, C.; Öhman, M.; Broström, M.; Backman, R., *Energy Fuels*, 26(1), 85-93 (2012)
30) Kowalczyk-Juśko, A., *J. Ecol. Eng.*, 18(6), 200-204 (2017)
31) Rizvi, T.; Xing, P.; Pourkashanian, M.; Darvell, L. I.; Jones, J. M.; Nimmo, W., *Fuel*, 141, 275-284 (2015)
32) Liu, Z.; Zhang, T.; Zhang, J.; Xiang, H.; Xiaomeng Y.; Wanhe, H.; Fang, L.; Bingbing, M., *Energy*, 161, 517-522 (2018)
33) Reinmöller, M.; Schreiner, M.; Guhla, S.; Neuroth, M.; Meyer, B., *Fuel*, 253, 930-940 (2019)
34) Zhu, Y.; Hu, J.; Yang, W.; Zhang, W.; Zeng, Kuo Yang, H.; Du S.; Chen, H., *Energy Fuels*, 32(4), 5244-5251 (2018)
35) Fang, Xi.; Jia, L., *Bioresour. Technol.*, 104, 769-774 (2012)
36) Du, S.; Yang, H.; Qian, K.; Wang, Xi.; Chen, H., *Fuel*, 117(B), 1261-1287 (2014)
37) Xiang, H.; Yang, J.; Feng, Z.; Hu, W.; Liang, F.; Ni, L.; Gao, Q.; Liu, Z., *ACS Omega*, 4(21), 19246-19254 (2019)
38) Mizutani, Y., *Nensho kogaku* 3rd edition, Morikita shuppan, 2002
39) http://www.factsage.com/
40) https://www.morikita.co.jp/exclusive/download/28