

Estimation of Production and Energy Consumption in Woody Biomass Pulverization Using a Multiple Tube Vibration Mill

Nobusuke Kobayashi* and Yoshinori Itaya

Environmental and Renewable Energy Systems, Gifu University, Yanagido, Gifu-shi, Gifu, Japan

Abstract

The evaluation of the scale-up potential of woody biomass pulverization using a newly developed multiple tube vibration mill (MTVM) was performed. The pulverization ability of a large MTVM was estimated based on the results of a laboratory-scale pulverization experiment. The pulverization pot arrangement was investigated, and the optimum pulverization conditions for woody biomass in MTVM were calculated in terms of the yield of wood powder and energy consumption. The pulverization performance of MTVM was compared to that of a conventional single tube vibration mill, where MTVM is shown to have higher productivity for a given energy consumption, and has the ability of producing high yields with larger pot sizes. Applying the stage grinding method, low-crystallinity wood powder (crystallinity index of cellulose <10%) can be produced around 1.2 t/h with an energy consumption of 1.0 GJ/t-product with an industrial-scale MTVM. The total energy consumption in the woody biomass pulverization process including coarse, middle, and fine grindings is 1.48 GJ/t-product.

Keywords: Pulverization; Scale-up; Woody biomass; Multiple tube vibration mill

Introduction

To effectively use woody biomass, it needs to be pulverized. Fine powders are preferable for improving the reactivity in woody biomass refinery processes such as enzyme saccharification [1-4] or gasification [5-7]. For example, the direct use of fine lignocellulose powder for enzyme saccharification is beneficial for avoiding inhibitor production [8] and excessive use of chemical material. Conversely, it is also well known that energy consumption during fine pulverization is large and increases exponentially with decreasing powder size and crystallinity [9]. For this reason, fine grinding of woody biomass has been avoided in refinery processes.

Many types of pulverization equipment for woody biomass have been developed in an attempt to increase the yield and reduce the energy consumption of the pulverization processes, and scale-up of some of these technologies has also been conducted [10-14]. The authors have also attempted the scale-up of a single tube vibration mill by increasing the pulverization pot size [8]. However, a significant increase in powder production per pulverization pot volume was not observed, but a huge increase in energy consumption was measured due to the pulverization rate decreasing in proportion to the square of the pulverization pot diameter [9]. Therefore, MTVM that could achieve high yield of amorphous cellulose with less energy consumption has been recently developed by the authors [15].

MTVM was developed based on a conventional vibration mill, but the configuration of the pulverization pot was completely different from a conventional single tube vibration mill. Since the size up of the pot diameter in a single tube vibration mill deteriorates pulverization performance, pulverization pot has many small size tubes in a hexagonal pattern in MTVM scale-up. As long as the pulverization tube size is kept small, high pulverization and fracture rates could be retained even though the number of tubes increased [15]. Therefore, powder production increases with increasing number of tubes, and energy consumption per production can be reduced.

Fundamental research and laboratory-scale experiments using a batch-type MTVM have already been performed with woody biomass, and the performance of MTVM was verified [15]. In laboratory-scale pulverization experiments, MTVM showed a large improvement in fine woody biomass pulverization over a conventional vibration

mill. These results suggested that large-scale MTVM was capable of producing wood powder in sufficient quantities with acceptable energy consumption. Therefore, it is necessary to verify the performance of MTVM experimentally using a large-scale unit.

For this reason, the pulverization capability of a large-scale MTVM is estimated from the results of laboratory-scale pulverization experiments where we considered the yield of fine powder and consumed energy per ton of yield. In the estimation, the production rate of wood powder and consumed energy per production were calculated assuming a linear scaling of the size of the MTVM unit. The effect of powder size and crystallinity index of the pulverized wood powder on the pulverization capability is also discussed. Moreover, total energy consumption during a stage grinding process including coarse, middle, and fine grindings with MTVM is also estimated.

Experimental

Laboratory-scale woody biomass pulverization

Woody biomass pulverization in a laboratory-scale experiment was performed with two different batch-type vibration mills (Chuo Kakohki, MB type and VF type). Figure 1 shows a schematic diagram of an MB-type vibration mill. The vibration mill consists of a vibration motor and two pulverization pots on either side of the motor. The VF type has two vibration motors and one large pot in the middle of the motor. For the experiments, different types of pots were designed, the details of which are summarized in Table 1. For the laboratory-scale experiment, seven different pots were prepared with different diameters and number of tubes. The pot diameters ranged between 66 and 375 mm. The multiple tube pot was a new design that bundled 3 to 4 tubes in parallel inside

*Corresponding author: Nobusuke Kobayashi, Environmental and Renewable Energy Systems, Gifu University, Yanagido, Gifu-shi, Gifu, 501-1193, Japan, Tel: 81-58-293-2621; E-mail: nsuke@gifu-u.ac.jp

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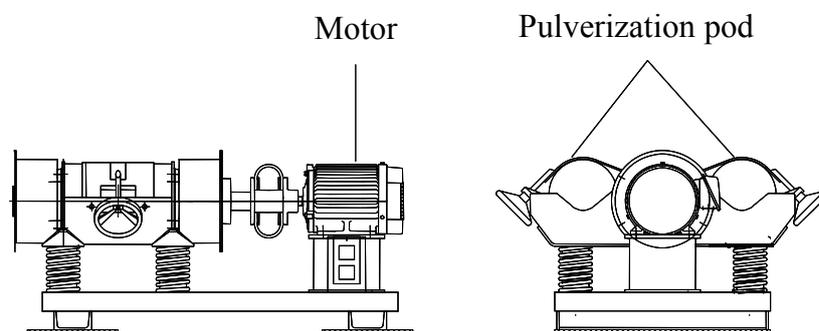


Figure 1: Schematic diagram of batch-type vibration mill (pot type: MB).

Pot type	d66	d74	d107		d145	(d74)3	(d66)4	d375
Mill type				MB				VF
Tube diameter, D_t [mm]	66	74	107		145	74	66	375
Pot diameter, D_t [mm]	66	74	107		145	160	160	375
Number of tubes, n [-]	1	1	1		1	3	4	1
Pot length, L [mm]	225	225	125		225	225	225	600
Total pot volume, V [cm ³]	770	970	1200		3600	2910	3080	66000
Total grinding ball weight [kg]	2.69	3.39	4.10		13.0	10.2	10.8	240
Initial woody powder weight [kg]	0.027	0.034	0.041		0.130	0.102	0.108	2.4
Total weight [kg]	10.4	11.4	8.6		25.0	20.0	22.2	-

Table 1: Specification of pulverization pots and pulverization conditions.

the pulverization pot, where the diameter and length of each tube in the pot is as shown in Figure 2. The difference between conventional single tube vibration mill and MTVM is only the pot configuration: the vibrator itself was the same for both the mills. The (d74)3 pot consisted of three tubes with 74 mm diameters. The (d66)4 pot had four tubes with 66 mm diameters. Note that these tubes were fixed inside the pot and did not pivot during the pulverization process. Pulverization was conducted after filling the pots with the woody biomass feedstock and grinding media. The vibration frequency and amplitude were fixed to 60 Hz and 9 mm, respectively, for all experiments. The pulverization performance differs depending on the grinding medium and diameter: 1 inch (25.4 mm) stainless steel balls were selected for this experiment. From the previous pulverization results [15], the stainless steel balls filled the pot, occupying 80% of the pot volume or the volume of the tubes (bulk).

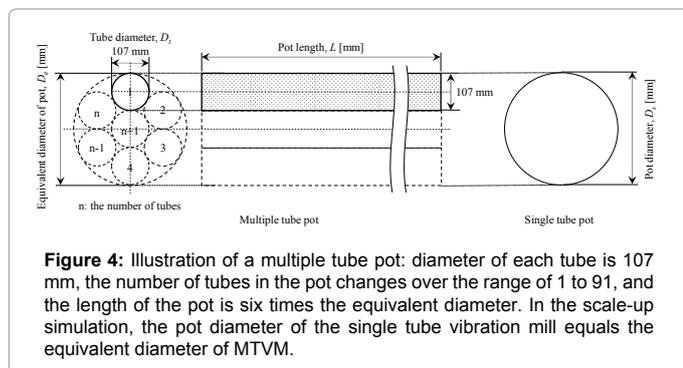
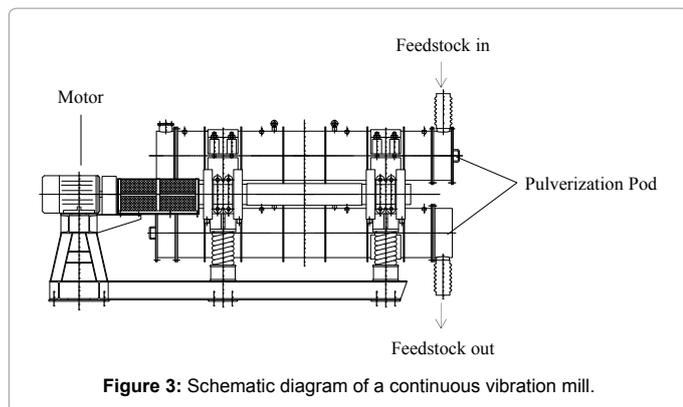
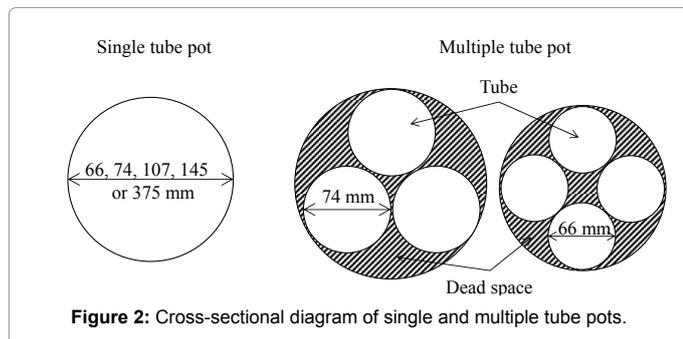
Japanese cider pin-chip was used as the pulverization feedstock, which was pulverized using a cutter mill and wheel mill in series (Steal Plantech Co. Ltd.). Before pulverizing by the vibration mill, the moisture content of the pin-chip was controlled by drying in an oven for 24 h at 353 K. Then, the dried pin-chip was sieved by an electric 1 mm mesh screen. The initial moisture content of the pin-chip was approximately 20%, which was reduced to approximately 3% after drying. The filling weight of the pulverization feedstock was fixed to 1% of the weight of the grinding media. The ratio of pulverization feedstock weight to total grinding media weight was kept constant in all experiments regardless of the pot diameter and/or the number of tubes. The pulverization time varied between 5 and 120 min. The power consumption of the vibration mill was monitored with a power meter during the pulverization experiment.

After pulverization, the wood powder was removed from the pot,

and the particle diameter and cellulose crystallinity were analyzed. The particle size was measured by a laser diffraction/scattering particle diameter analyzer (Horiba, LA-920), and the cellulose crystallinity was analyzed using an X-ray diffractometer (Shimadzu, XRD-6100). A wet method was used for the particle diameter measurements, and the agglomerates were broken down before measurement by two minutes of ultrasonic irradiation. The cellulose crystallinity index was calculated using the Segal method [16] using the X-ray diffraction peaks at $2\theta=18^\circ$ and 22° . The cellulose crystallinity index of the initial feedstock was approximately 50%. To obtain a single value for the particle size and cellulose crystallinity index of the wood powder pulverized by MTVM, we took the mean of the pulverized powder obtained using different tubes. The yield of wood powder in a batch-type mill is the initial filling weight of feedstock when the cellulose crystallinity index of the pulverized wood powder is $<10\%$.

Estimation of a large-scale MTVM pulverization performance

Using the results of the laboratory-scale experiment, the production rate of wood powder and the corresponding power consumption for a large-scale MTVM was estimated. Figure 3 shows a schematic diagram of a continuous vibration mill. As seen in Figure 4, MTVM has multiple pulverization tubes inside the pot, where a conventional vibration mill has only a single tube. In the case of a single tube pot scale-up, the pulverization pot size (and also the tube diameter and length) simply increases. Conversely, in the case of a multiple tube pot, only the number of tubes increases, but the size stays the same. A number of tubes form a hexagonal structure and the equivalent diameter of the pot-bundled tubes increases with increasing number of tubes. In the MTVM scale-up estimation, many 4.2 inch (107 mm) tubes were considered, but the respective tube diameter and length were kept the same. Table 2 summarizes the relationship between the number of tubes



and equivalent diameter of the multiple tube pot. The thicknesses of the pot and tubes were ignored for calculating equivalent diameter. The pot length also increased in proportion to six times the equivalent diameter. This scale-up ratio was experimentally applied when the conventional single tube vibration mill was scaled up.

1 mm sieved dried pin-chip was assumed as the pulverization feedstock, the same as the laboratory-scale pulverization experiment. It was assumed that the weight of the filled feedstock per tube was 1% of the weight of the grinding media in the tube. The moisture content of the pin-chip was assumed to be approximately 3%, since the pulverization performance of feedstocks with moisture content <3% is almost equal [9]. The crystallinity index of the feedstock was approximately 50%. The grinding media (1 inch (25.4 mm) stainless steel balls) was filled with 80 volume (bulk) % of each tube because a 107 mm diameter tube with 1 inch stainless steel balls showed the best pulverization performance in laboratory-scale experiments [9]. Vibration amplitude and frequency was the same as the laboratory-scale experiments. Since pulverization

Number of tubes, n [-]	1	3	7	19	37	61	91
Equivalent diameter of pot, D_e [mm]	107	230	321	520	722	927	1134
Pot length, L [mm]	642	1380	1926	3120	4334	5560	6805
Initial woody powder weight [kg]	0.2	1.4	4.5	19.6	53.1	112.2	204.9
Total weight [kg]	38.6	244	792	3468	9360	19775	36082

Table 2: Calculation conditions for the large-scale MTVM.

conditions were the same as those of the laboratory-scale experiments (except the number of tubes), it was assumed that the pulverization performance of the large-scale MTVM could be scaled accordingly [15].

In the scale-up estimation, the production rate of wood powder and power consumption per ton of yield was calculated. The production rate was calculated by dividing the filled feedstock weight by the time required for pulverization (TRP). The TRP value from the laboratory-scale experiments was used, which was a function of the tube diameter and inversely proportional to the pulverization rate. Since the power consumption of a vibration mill is proportional to the total weight of the pot [13], the power consumption could be calculated from the total weight including the pot itself, the grinding media, and that of the feedstock. A power usage of 92 W/kg was used for the scale-up estimation. The weight of the pot was calculated by multiplying the surface area of the stainless steel tubes by their “density” of 73.3 kg/m² (assuming a thickness of 1 cm). The weight of the grinding media occupying 80% of the bulk volume of the tubes was estimated using a bulk density of the stainless steel balls of 4600 kg/m³.

Estimation of total power consumption for a stage grinding system

To produce fine wood powder efficiently, stage grinding systems are required. These consist of three different types of woody biomass crushing equipment, including a coarse crusher, middle grinder, and fine pulverizer, as seen in Figure 5. In the first stage of grinding, 5-10 cm pieces of woody chip can be produced with a cutter mill (Ultra chipper, CKS Chuki) from raw wood at a rate of 10 t/h. The wheel-style woody chip mill (KDS Micronex, Steal Plantech) can produce 2 mm-sized pin-chip at a rate of 2 t/h. In the final fine pulverization step, the newly designed MTVM was used. Each grinding stage is a closed system equipped with an electric screen. The power consumptions of the cutter and wheel mills were measured, and these values included the power consumptions of a belt conveyer and electric screen. Power consumption of MTVM was the estimated value. The pot size of MTVM was 1.1 m in equivalent diameter and 6.6 m in length, which allowed 91 tubes of 107 mm diameter. The assumed feedstock was thinned wood of Japanese cedar from Gifu Prefecture, Japan. The moisture content of the 2 mm chip after the coarse and middle grinding was assumed to be 10%–15%. Pin-chip was dried to the moisture content of 3% for fine pulverization. The energy consumption for drying was not considered in this estimation. A cellulose crystallinity index <10% was considered as the metric of quality of the fine powder product (suitable for direct use in bio-ethanol production).

Results and Discussion

Pulverization performance of laboratory-scale MTVM

Figure 6 shows the 50% particle size of pulverized woody biomass pulverized using a batch-type single-pot vibration mill. The pulverization pot diameter was varied between 66 and 375 mm. As was

shown in a previous study [14], the effect of pot length on pulverization performance (particle size and cellulose crystallinity index) could be ignored. Since the size of the grinding media was the same for all experiments, the 50% particle size of the pulverized powder became <math><40\ \mu\text{m}</math> (minimum particle size) after sufficient pulverization time. However, the pot diameter significantly influenced the pulverization rate, which increased with a smaller size pot for the same filling ratio of feedstock. In general, the grinding media rotates inside the pot, and the rotational velocity of the media is inversely proportional to the square of the pot diameter, as seen in Figure 7. The rotational velocity (related to the impact frequency between the grinding media and feedstock) decreases with increasing pot diameter, hence an increase in pot diameter leads to poorer fine grinding of woody biomass. The rate of decrease in particle diameter was not constant over time but much faster at the beginning of pulverization (when the particle size was larger). Eventually, the particle size reached a constant minimum value over time regardless of the pot diameter, as long as the same size grinding media were used. However, the particle diameter slightly increased after reaching the minimum particle size when using a small pulverization pot, indicating compaction and agglomeration of the fine powder with excess pulverization.

Figure 8 depicts the cellulose crystallinity index of pulverized woody biomass. The cellulose crystallinity index of pulverized wood powder decreased with pulverization time, since the cellulose crystal in the woody biomass is broken by the impact of the grinding media.

Similar to the particle size, the crystallinity index also decreased faster when a smaller pot was used. The fracture rate of cellulose crystals, defined as the decreasing rate of the cellulose crystallinity index, increased with decreasing pot size, and the values remained constant over time until the cellulose structure became amorphous. The fracture rate is the inherent property determined by the pot size, media size, and other pulverization conditions. In particular, the pot size influences the fracture rate significantly because the feedstock amount per cross-sectional area of the pot increases. However, the fracture rate is not always in proportion to the pot size.

Figure 9 illustrates the relationship between the fracture rate and pot diameter. The fracture rate for particles over the size of d107 is proportional to a part of the square of the pot diameter, which could be related to the number of impacts (i.e., the rotational velocity) affecting the fracture rate of the cellulose crystal. However, the pulverization rate slightly decreased under the size of d107 pot when the 1 inch balls were used for the fine pulverization. Perhaps this is due to the pulverization conditions not being optimum. The best grinding media size depends on the pulverization pot size, and the 1 inch balls could be optimum for the d107 pot only when the vibration frequency is 60 Hz and amplitude is 9 mm. It was shown in a previous study that 1/2 inch (12.25 mm) balls provided the best pulverization performance for a d74 pot, and 1/4 inch (6.35 mm) shows a best performance for a d66 pot [9]. It is well known that pulverization performance decreases with smaller diameter

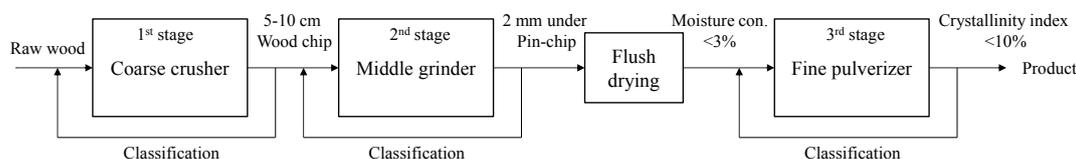


Figure 5: Flow chart of the stage grinding system.

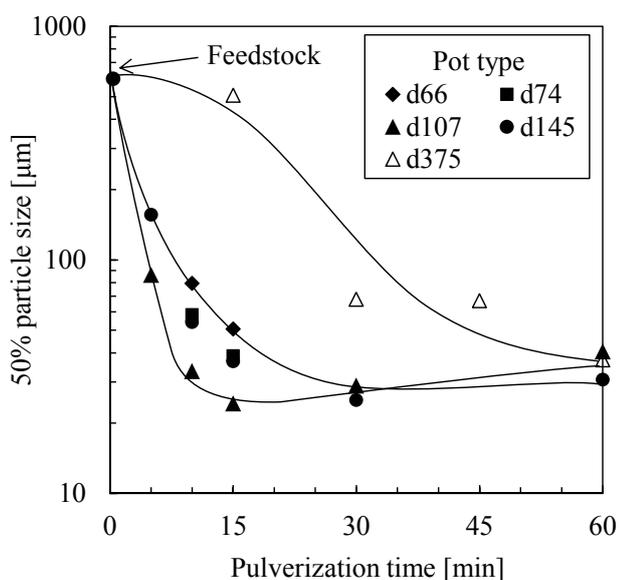


Figure 6: 50% particle size of pulverized wood powder vs. pulverization time for different pots. Experiment conducted in a batch-type vibration mill.

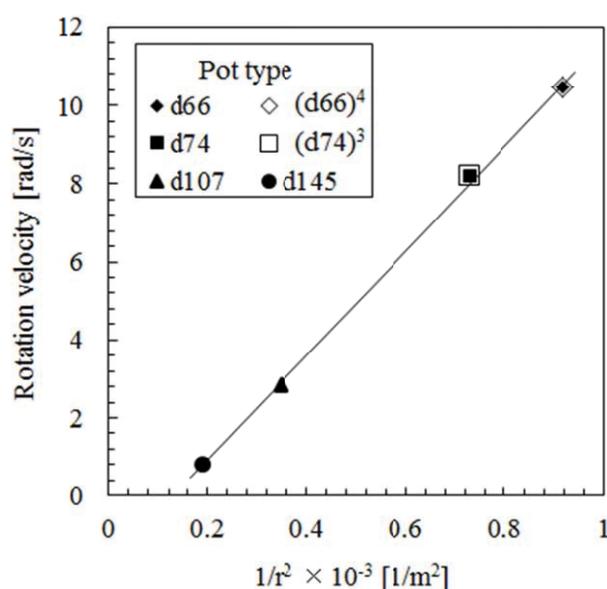


Figure 7: Rotational velocity of the grinding media in different pots (Batch-type vibration mill).

balls because the weight of the balls decreases even though the impact frequency increases.

Figures 10 and 11 illustrate the effect of the number of tubes on pulverization. Figure 10 shows the pulverized particle size, and Figure 11 shows the crystallinity index of cellulose when the single or multiple tube pots were used. The pulverized particle size depends slightly on the tube size, but the particle size was almost the same regardless of the number of tubes. The crystallinity index of cellulose shows the same pulverization performance regardless of the number of tubes when the same size tube was used. Hence, the pulverization performance was affected by the tube size but not the number of tubes.

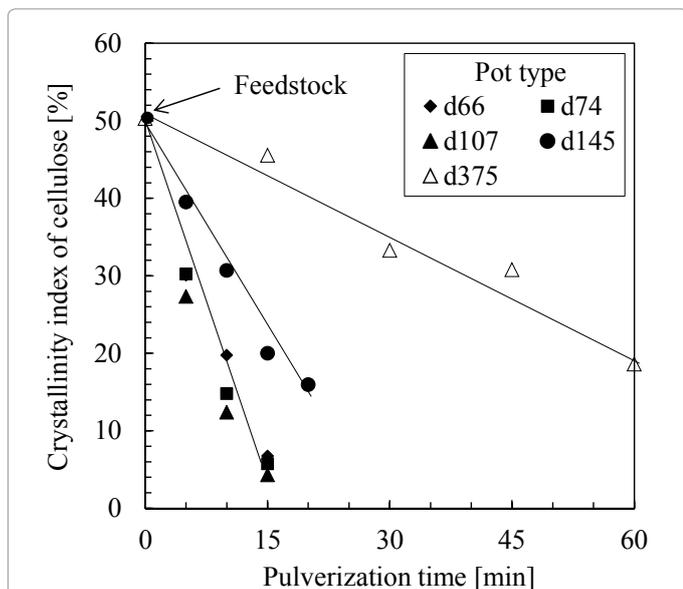


Figure 8: Crystallinity index of cellulose of pulverized wood powder vs. pulverization time for different pots.

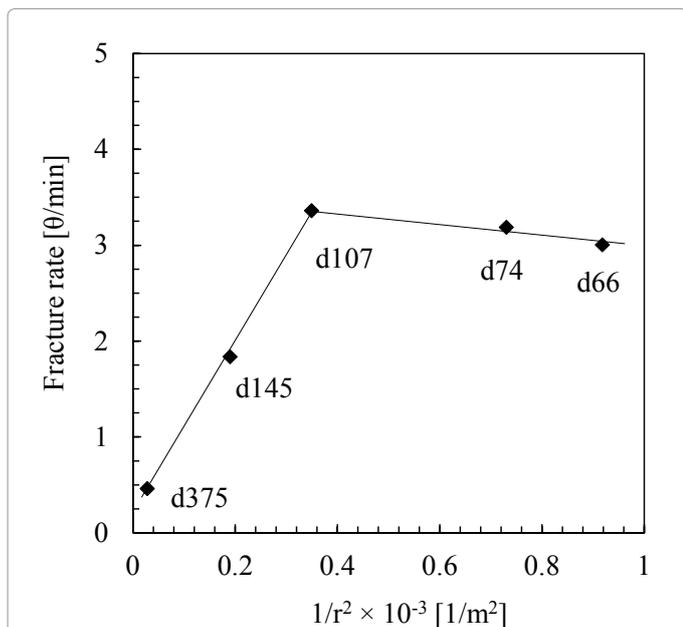


Figure 9: Relationship between fracture rate of cellulose crystal and pulverization pot diameter.

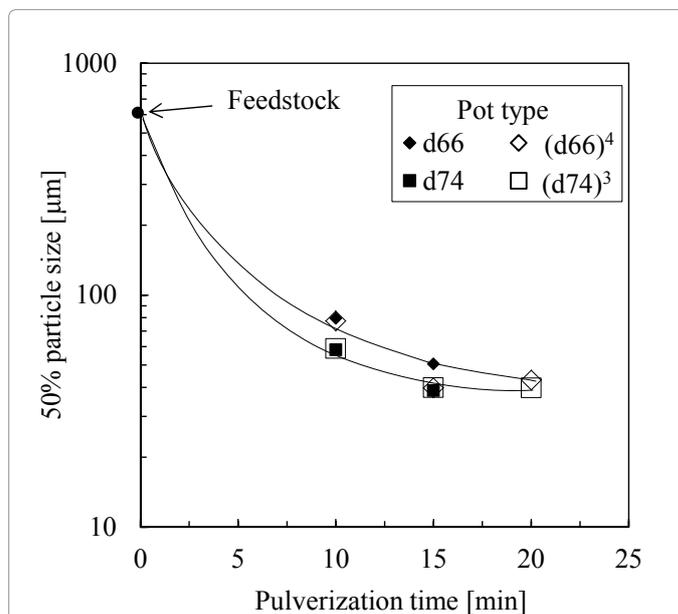


Figure 10: 50% particle size of pulverized wood powder vs. pulverization time for the single and multiple tube pots.

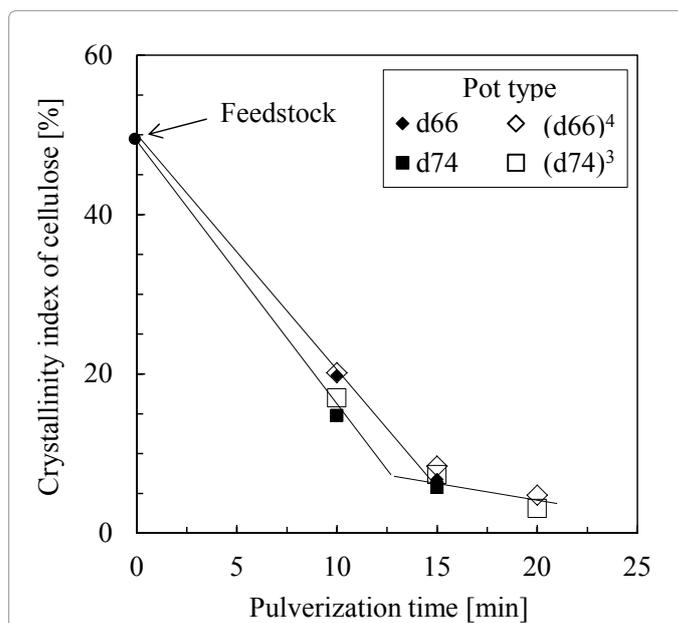


Figure 11: Crystallinity index of cellulose of pulverized wood powder vs. pulverization time with the single and multiple tube pots.

Table 3 summarizes the production rate and consumed energy per ton of wood powder. Note that the energy consumption in this table is the measured value, but the length and weight of the pot varies depending on the pot used. Obviously, the production rate significantly increased when a bigger pot was used. However, the production rate per unit pot volume was the worst when the d375 pot was used. Although wood powder production can increase easily by scaling up the pot size, the respective energy consumption increases drastically with the total pot weight. The pulverization performance deteriorated when using larger pots, and there is a trade-off between production and energy consumption for the scale-up of a single tube vibration mill. However,

the energy consumption per unit production can decrease using the multiple tube pot, since the yield increases with the number of tubes. The powder production of (d74)3 is three times that of d74 and that of (d66)4 is four times that of d66, but the consumed electricity are 1.65 and 1.84 times, respectively. Hence, scaling up a vibration mill by increasing the number of small pulverization tubes but not the pot size has big advantages for both wood powder production and energy savings.

Estimation of large-scale MTVM pulverization performance

Figure 12 shows the estimated production rate of wood powder and the consumed energy per unit production when a conventional vibration mill and MTVM are scaled up. For the estimation of a conventional single tube vibration mill, the production rate was calculated from the fracture rate of woody biomass (assuming that it was proportional to the pot size, as seen in Figure 9). For both systems, the consumed energy per unit production was calculated assuming the consumed electricity was proportional to the total pot weight divided by the yield [15]. Conversely, the fracture rate of each tube in MTVM was assumed to be constant as long as the tube size was the same, as shown in Figure 11. The d107 tube was used in this estimation, and the fracture rate of woody biomass was fixed to 0.056 h^{-1} . The production of wood powder simply scaled with the number of tubes. The production rate with a conventional vibration mill increased only slightly with increasing pot diameter. When the single tube vibration mill was scaled up, the production rate was not increased significantly but energy consumption increased drastically. Therefore, the consumed energy per production increased with increasing pot size in the single

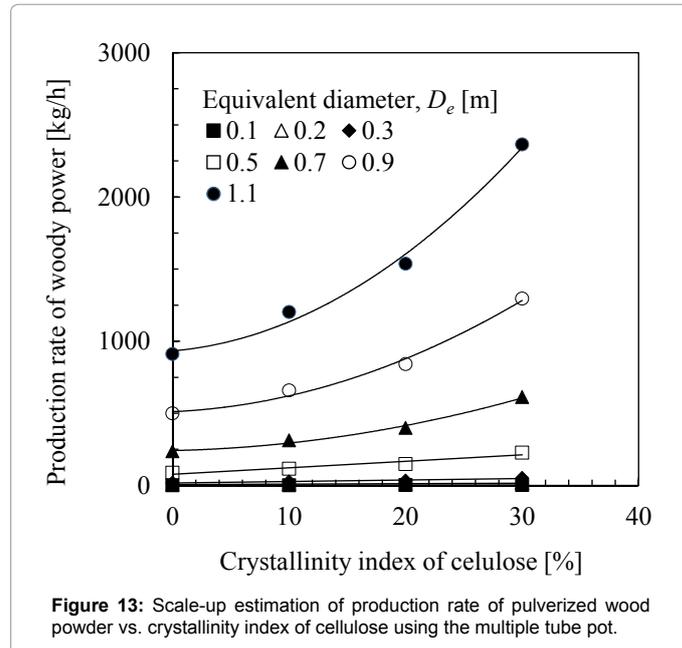
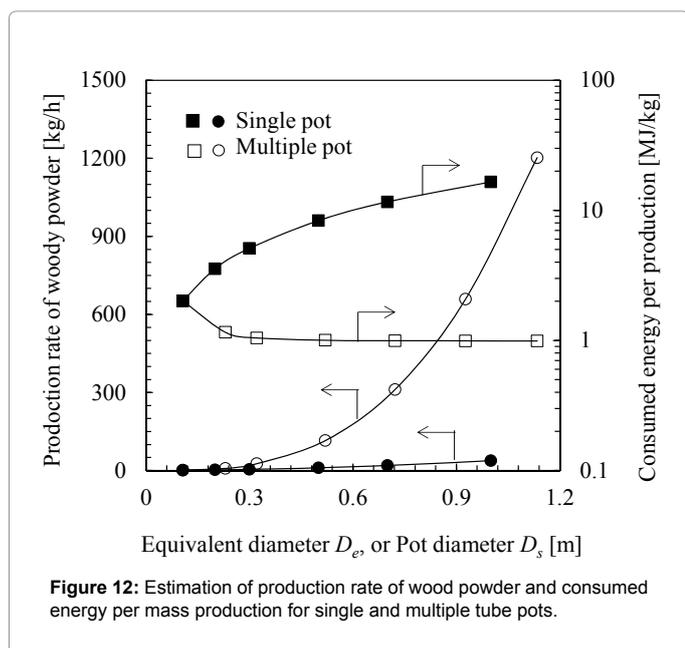
tube vibration mill. Conversely, the production rate for the scaled-up MTVM increased with increasing pot diameter (i.e., number of tubes). Since the production rate exponentially increased with increasing number of tubes, the consumed energy per unit yield decreased for small pots (below seven tubes). However, it became almost constant (0.98 MJ/kg) for larger pots (above seven tubes) because the total weight of the pot also increased exponentially. The scaled-up MTVM had a clear advantage over a single tube system with respect to the production rate and energy consumption and can be recommended for fine pulverization scale-up.

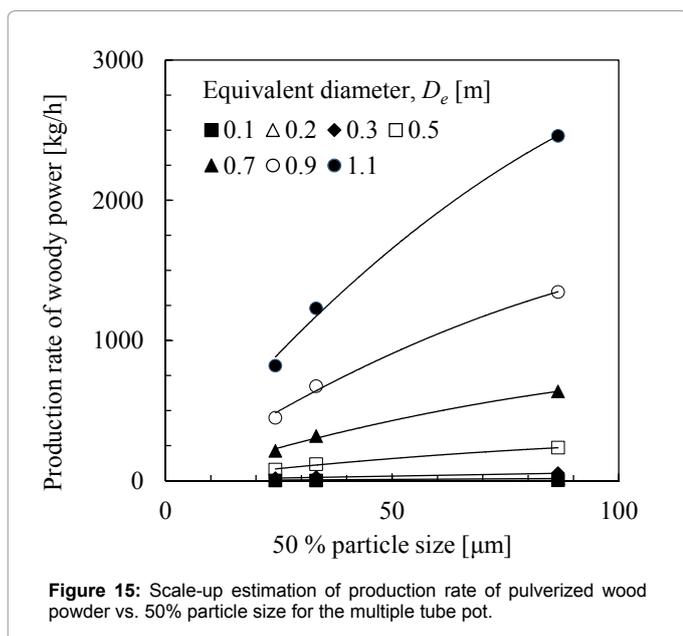
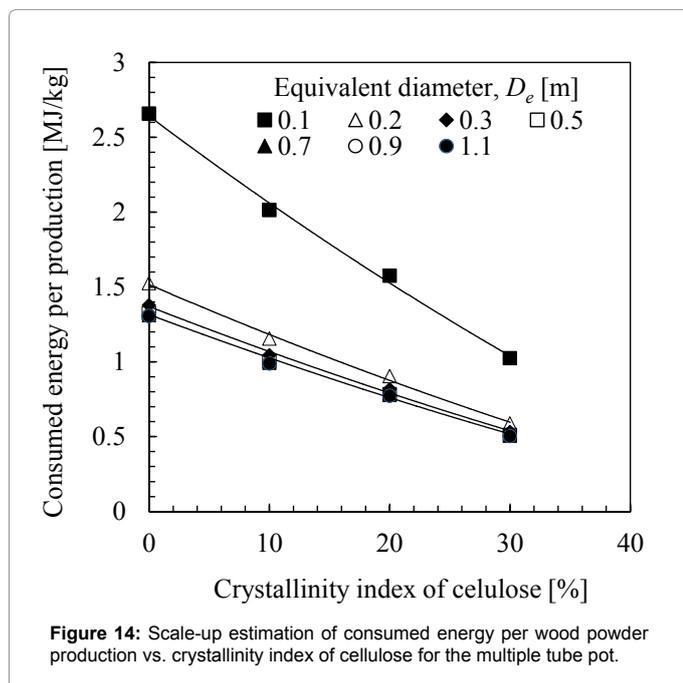
The fine pulverization and breaking of the cellulose crystal are necessary when the fine powder is used for direct enzyme saccharification, but it is not always necessary to produce amorphous cellulose for woody biomass refineries. Figures 13 and 14 summarize the production rate and energy consumption per unit yield for MTVM scale-up as functions of the crystallinity index of cellulose. Breaking the cellulose crystals needs enormous pulverization energy, but the production rate can be increased and energy consumption decreased if the crystallinity index of the product stays above 10%. The production rate significantly increased with increasing equivalent diameter, and energy consumption showed almost the same trend when the equivalent diameter was over 0.3 m.

The same estimation was conducted for particle size. Figures 15 and 16 show the production rate and consumed energy per unit yield as a function of the 50% particle size of the product. Unlike the case of cellulose crystal destruction, the particle size resulting from pulverization with a vibration mill is not proportional to the

Pot type	d66	d74	d107	d145	(d74)3	(d66)4	d375
Fracture rate [min^{-1}]	3.00	3.19	3.36	1.84	3.03	2.86	0.46
Production rate of woody powder [kg/h]	0.12	0.16	0.21	0.38	0.46	0.46	1.65
Production rate per volume [$\text{kg}/(\text{h} \cdot \text{m}^3)$]	158	167	172	99	159	151	25
Consumed electricity [kW]	0.32	0.34	0.42	0.53	0.56	0.59	3.00
Consumed energy per production [MJ/kg]	9.47	7.53	7.31	5.33	4.35	4.58	6.53

Table 3: Pulverization performances with different pots.





pulverization time, and size reduction becomes difficult when the pulverized particle size becomes smaller. But the trend of particle size reduction is assumed to be the same as long as the woody biomass is pulverized in the same size tube. Hence, these values were calculated from the pulverization result of the single tube of d107. The production rate can easily be improved by scaling up MTVM, and 2500 kg/h of 100 μm wood powder can be achieved with a 1.1 m diameter MTVM. Moreover, the energy consumption per unit yield can be reduced to 0.5 MJ/kg-product.

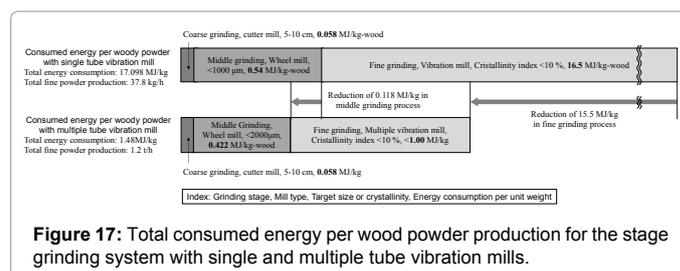
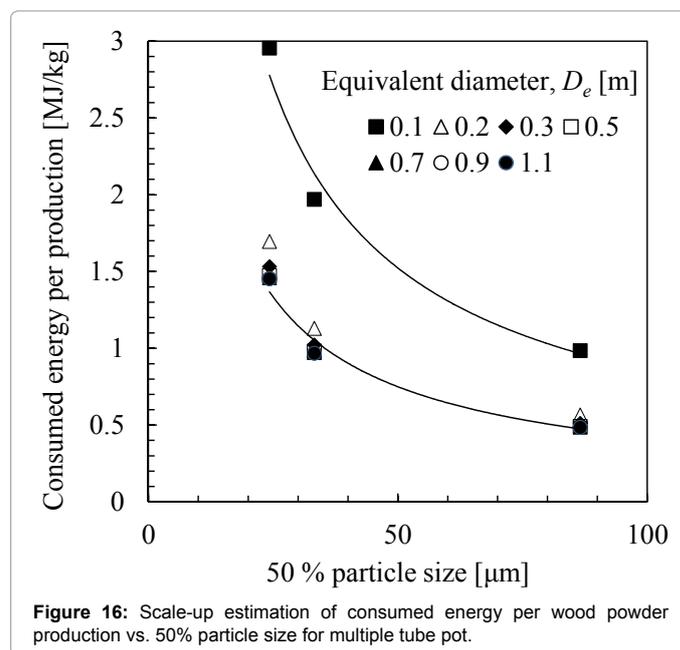
Prediction of total power consumption in a stage grading system

From the estimation results of MTVM, the total energy consumption

for a stage grinding system was calculated. Figure 17 shows the comparison between the energy consumption values of a conventional vibration mill and newly developed MTVM. The pulverized powder with a crystallinity index of cellulose <10% is considered a quality product. The energy consumption in coarse grinding with a cutter mill and middle grinding with a wheel mill were measured, while the value for fine grinding with MTVM was estimated from the laboratory-scale measurements. Woody biomass chips with a size of 5-10 cm were produced by coarse grinding with a very small energy consumption of 0.058 MJ/kg. The middle grinding with a wheel mill consumed 0.54 MJ/kg to make chips less than 1 mm in size, and making wood chips less than 2 mm in this second stage can save approximately 0.12 MJ/kg of energy. If wood powder with a crystallinity index <10% is required for the final product, 16.5 MJ/kg of energy needs to be consumed with a conventional vibration mill. However, the energy consumption using MTVM is <1.00 MJ/kg even if the <2 mm chips are used as the fine grinding feedstock. The total energy consumption using MTVM is 1.48 MJ/kg, and approximately 70% of the total energy consumption is used for fine pulverization (3rd stage). However, this energy consumption for fine pulverization could be reasonable for bio-ethanol production. The total production of wood powder is also much larger using MTVM than the conventional mill. The largest MTVM (1.1 m equivalent diameter pot) can produce 1200 kg/h of wood powder compared to only 37.8 kg/h in a conventional vibration mill.

Conclusions

Laboratory-scale MTVM experiments were performed and the



results were used to predict the fine powder production and energy consumption per unit yield for an up-scaled MTVM system. Since the fracture rate of woody biomass in a small pot is much faster than in bigger pots, MTVM limited the pot size and used numerous small pulverization tubes. Such a system showed high pulverization performance for fine powder production and reduced energy consumption per unit yield. The overall production of wood powder significantly increased in the scaled-up MTVM, and approximately 1.2 t/h of fine powder can be produced with a 1.1 m size pot. Since production rate increased with a scaled-up MTVM, the relative energy consumption for fine powder production could be reduced to 1 GJ/t-product. In a stage grinding system for fine wood powder production, the total energy consumption was 1.48 GJ/t where 70% of this value was consumed for fine grinding using MTVM. This energy consumption was much lower than the conventional single tube pulverizer.

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