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Improvement of Biomass Fuel Properties for Rice Straw Pellets Using Torrefaction and Mixing with Wood Chips

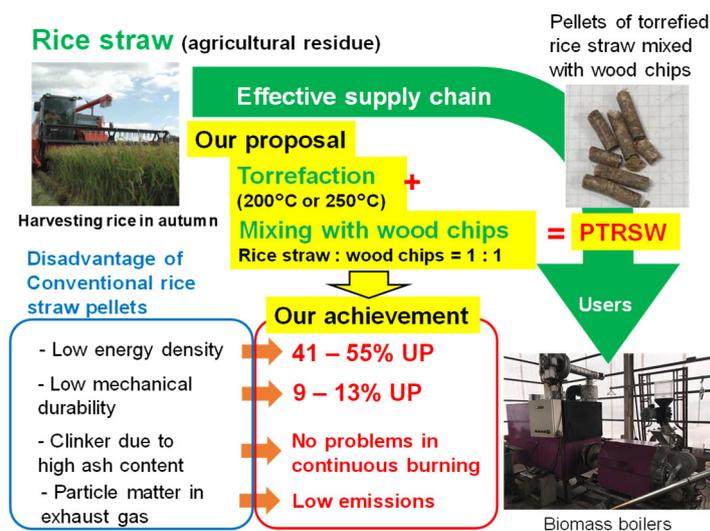
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Abstract

Utilization of rice pellets as biomass fuel has many challenges compared with wood pellets, including low heating value, low bulk density, and high ash content, that cause high logistic costs and clinker formation. To solve these problems, this study focused on upgrading the quality of rice straw pellets to improve logistic efficiency by torrefaction and mixing with wood chips. Torrefaction and mixing with wood chips was effective to improve the energy density, the mechanical durability and the contents of fixed carbon, nitrogen, sulfur and ash, leading to the improvement of both logistic efficiency and combustion behavior. The burning test showed that increases in the fixed carbon content and the mechanical durability contributed to stable increases in the temperature inside the furnace during starting up and reduced the amount of ash in the exhaust gas during stable combustion.

Keywords: rice straw pellets, torrefaction, mixing with wood chips, supply chain, combustion behavior

Graphical abstract



26 **Statement of Novelty**

27 Rice straw has difficulty for biomass fuels because of high supply chain costs caused by
28 low heating value, low bulk density, high moisture content, low grindability, and high
29 ash content. This study attempted to overcome the difficulty by torrefaction and mixing
30 with wood chips to produce rice straw pellets. Pellets of torrefied rice straw mixed with
31 wood chips (PTRSW) improved the energy density and mechanical durability
32 significantly to mitigate the problems on storage and transportation. Since the fixed
33 carbon content and mechanical durability in PTRSW was improved, in the combustion
34 test using a real biomass boiler, PTRSW achieved smooth starting up of the boiler and
35 low emissions of particle matters compared to pellets only from rice straw.

36
37
38

39 **1. Introduction**

40 The promotion of renewable energy utilization is required to reduce greenhouse gas
41 (GHG) emissions and to enhance energy independence within each region. The European
42 Union (EU) determined to reduce GHG emissions and provide secure, affordable, and
43 sustainable energy for its citizens. The ambitious targets for 2030 for GHG emissions
44 reduction and renewable energy share were set to -40% and at least 32%, considering
45 the electricity, heating/cooling, and transportation sectors [1]. According to the 5th
46 Strategic Energy plan in Japan [2], the target for the share of renewable electricity is
47 22–24% by 2030. However, no targets for the heating/cooling or transportation sectors
48 have been set. In Japan, which has low energy independence in the primary energy
49 supply, biomass should be used for heating, particularly in cold regions, such as
50 Hokkaido.

51

52 As the potential of wood biomass for energy production is limited globally [3], higher
53 quantities of alternative agricultural fuels may be used in the near future [4]. In Japan,
54 a number of power generation plants using wood biomass, such as wood chips from forest
55 residue, have been started up, and are operated with a feed-in-tariff benefit. As of the
56 end of March 2017, there were 491 large-scale biomass wood power plants with a certified
57 power generation capacity of 12 million kW [5]. Some plants import palm kernel shell
58 from other countries to obtain cheaper biomass because presently the wood biomass
59 industry in Japan is competitive and the palm kernel shell is 40% cheaper than wood
60 chips in Japan [6]. To increase the share of renewable heat sources, agricultural residue
61 in a region will need to be used in small-scale biomass boilers within the same region,

62 even if the fuel quality is less than that of wood biomass.

63

64 There is an abundance of agricultural residues, such as rice straw in Japan. However,
65 most of the agricultural residue is just returned into the soil as organic matter to enrich
66 the soil [7], which means that the utilization ratio of agricultural residue is only 30% [8].
67 Ishii et al. [9] showed that rice straw pellets could be economically competitive with wood
68 pellets and other fossil fuels when the investment subsidy was 50% and other conditions,
69 such as collection and storage methods, were established. However, rice straw has many
70 shortcomings, such as high moisture content, low bulk density, low heating value, high
71 ash content, hygroscopic nature, low energy density, and poor grindability [10, 11]. These
72 shortcomings make the logistics of using rice straw as biomass fuel uneconomical, such
73 as in the making of rice straw pellets. In addition, high ash content causes a clinker
74 problem that inhibits combustion in boilers.

75

76 Our approach to overcoming this shortcoming is “torrefaction of rice straw” and “mixing
77 with wood chips” to produce composite pellets [12], which are defined as pellets of
78 torrefied rice straw mixed with wood chips (PTRSW) in this study. Torrefaction of rice
79 straw as pretreatment before pelletization, and the production of pellets using both wood
80 and torrefied rice straw would contribute to the wider use of lignocellulosic biomass in
81 other countries.

82

83 The torrefaction process is a thermal treatment process in an inert atmosphere and in
84 the low temperature range of 200–300°C [13]. The torrefied product retains 61–98% of
85 its original energy content, while losing 3–58% of its original mass in case of willow at
86 torrefaction temperature of 210°C to 300°C [14], which is due to a partial loss of the
87 moisture, and volatile matter contained in the biomass. As the temperature increases
88 during the torrefaction process, the initial mass loss occurs after 100°C because of
89 vaporization of the moisture, and then decomposition begins in the order of
90 hemicelluloses, lignin, and cellulose [15]. The removal of oxygen is also the key to weight
91 loss and quality improvement of biomass fuels, such as a decrease in the O/C ratio [16,
92 17], thereby producing a hydrophobic solid product with an increased energy density on
93 a mass basis. This torrefaction temperature of 200–300°C partially decomposes the
94 hemicellulose in the biomass fiber [18], resulting in much less energy required to grind
95 the torrefied biomass [13, 19]. According to IEA Bioenergy [20], torrefaction stands out
96 as a very promising technological option to convert and modify different sources of solid
97 biomass into a bioenergy feedstock similar to coal. Torrefaction requires a lot of energy,

98 but torrefaction gas, including CO, can be used for the torrefaction process. The efficiency
99 was 72–89%, which is defined by the energy content of torrefied wood divided by the sum
100 of the energy content of original wood before torrefaction and supplied energy [21, 22,
101 23].

102

103 According to Chen et al. [24], the number of studies on torrefaction of biomass has
104 increased since 2008. The studies have comprehensively reviewed torrefaction processes
105 and properties of torrefied biomass, such as moisture content, volatile matter, fixed
106 carbon and elemental contents, solid yield, energy density and yield, and grindability for
107 various kinds of biomass (bagasse, bamboo, rice husk, sawdust, spruce, willow, and
108 wheat straw). Tumuluru and Hess [25] summarized the following research findings on
109 the effectiveness of torrefaction: Improved storability, flowability, energy value, reduced
110 logistic and preprocessing costs, variability, and storage off-gas.

111

112 Kizuka et al. [12] torrefied rice straw and revealed that the torrefaction temperature of
113 280°C increased the lower heating value (LHV) from 14.9 MJ/kg to 19.5 MJ/kg with a
114 remaining heat content of 80% and that the torrefaction temperatures of 220°C and
115 250°C increased the LHV to 15.6 MJ/kg and 17.3 MJ/kg with remaining heat contents of
116 96.9% and 92.7%, respectively, suggesting that the torrefaction temperature should be
117 selected depending on priority in making biomass fuels: e.g., when long-distance
118 transportation is needed, 280°C might be selected because of its high energy density.
119 However, for PTRSW, the other fundamental indexes related to supply chain, such as
120 bulk and energy density and mechanical durability have not yet been evaluated to verify
121 our approach.

122

123 In addition, the torrefaction process increases ash content because only the volatile
124 matter is decreased. The clinker problem should be solved by means of other methods.
125 With regard to the ash melting behavior of biomass fuels causing a clinker problem, the
126 main influencing parameters are the mass fractions of calcium (Ca) and magnesium (Mg)
127 in the biomass. Both elements raise the ash melting temperature. The mass fraction of
128 potassium (K) in combination with silicon (Si) lowers the melting temperature, which
129 enhances clinker formation [26]. Mack et al. [4] showed that wheat straw pellets caused
130 a boiler shutdown because of heavy slagging caused by the high degree of sintering
131 indicated by the high molar ratio of $(\text{Si}+\text{P}+\text{K})/(\text{Ca}+\text{Mg}+\text{Al})$ for the fuel.

132

133 Mack et al. [4] pointed out that the combustion behavior of agricultural fuels in boilers

134 might be improved by adapting the combustion unit itself through primary or secondary
135 measures, or by improving fuel properties, and suggested that blending of agricultural
136 fuels with soft wood might be effective. The town of Nanporo in Hokkaido, Japan started
137 a business to use rice straw pellets. To mitigate the clinker problem, Nanporo introduced
138 a co-combustion process of rice straw and wood pellets at a ratio of 1:1 [27]. Actually, the
139 activities in Nanporo town were the starting point of our approach to produce PTRWS.
140 Kizuka et al. [12] showed that an increase in the mixing ratio of torrefied rice straw to
141 wood decreased the basicity, which is one of the indicators of clinker formation, to
142 mitigate the clinker problem. As pointed out by Mack et al. [4], adaptation of the
143 combustion unit itself is needed for low-quality biomass fuels. Particularly, for a small-
144 scale biomass boiler, not only clinker problems, but also emissions of particle matter in
145 flue gas are problems [28]. In order to solve these problems, a combustion test should be
146 conducted using actual boilers and PTRWS to verify continuous burning without clinker
147 and particle matter problems.

148
149 Therefore, the objectives of this study were:

- 150 1) to clarify the characteristics of PTRSW, such as LHV, bulk density, energy density,
151 mechanical durability, and ash content, which are related to supply chain and
152 combustion behavior, and
- 153 2) to clarify the combustion behavior of PTRSW, such as clinker formation and the
154 emission of particle matter, through combustion tests using a small-scale boiler.

155 156 157 **2. Materials and methods**

158 **2.1 Rice straw and wood samples**

159 The rice straw (cut to a length of 15 cm) used in this study was collected in November
160 2016 from Nanporo in Hokkaido, Japan. The wood chip samples (length of 2–3 cm and
161 from the needle-leaved tree, *Abies sachalinensis*) were provided from the wood
162 processing industry that produces wood pellets. The collected rice straw and wood
163 samples were stored at a room temperature of 20–25°C, in the laboratory of Hokkaido
164 University. Our experiments were conducted in 2018. The moisture contents of the rice
165 straw and wood samples were about 10.2% and 7.7%, respectively, and their ash content
166 was about 8.9–12.1% and 0.2–0.4%, respectively. No pretreatment, such as drying, was
167 conducted for rice straw and wood chips.

168 169 **2.2 Torrefaction method**

170 **2.2.1 Torrefaction of rice straw**

171 Next, 3–5 kg of rice straw was put into the stainless reactor (450 mm H × 550 mm W ×
172 470mm L), and the reactor was sealed tightly. The reactor was placed into an electric
173 drying oven (FS-605, Advantec Co., Ltd., in Japan). The reactor was heated up to the
174 designated temperature (200°C or 250°C) in a non-oxygen environment achieved by
175 flowing nitrogen gas into the reactor (about 50 L/min). According to the results in Kizuka
176 et al. [12], when considering setting the torrefaction temperature to 220°C, 250°C, or
177 280°C as described above, 250°C was selected considering that both the LHV and
178 remaining heat content were better compared with the other temperatures. The
179 torrefaction temperature of 200°C was also selected to for comparison with the other
180 torrefaction method, which will be described in the next section. To make the inside
181 atmosphere as homogeneous as possible, the nitrogen flow outlet tube was located into
182 the center of the reactor. The temperature inside the reactor was increased by 1°C /min.
183 After the temperature reached the designated value (i.e., the torrefaction temperature),
184 it was maintained for 1 h. The reactor was then cooled down naturally to room
185 temperature. The only rice straw torrefied homogeneously was used, and another,
186 torrefied heterogeneously, was removed.

187

188 **2.2.2 Torrefaction of rice straw pellets**

189 The rice straw pellets were produced using a pelletizer (EF-BM-370, Earth Engineering
190 Co., Ltd. capacity: 200 kg/h, diameter of die: 6 mm) [27], which is called pelletizer A in
191 this study. The rice straw pellets were torrefied using a screw continuous reactor (Figure
192 1), owned by the Forest Products Research Institute, Hokkaido Research Organization
193 because of the better flowability of rice straw pellets compared with rice straw that is
194 not pelletized. The temperature inside the reactor was set to 200°C and the retention
195 time was about 45 min, which was shorter than the 1 h described in the previous section.
196 As described below, this did not affect the results.

197

198 **2.3 Pelletization**

199 Eight types of pellets were produced to clarify the effectiveness of torrefaction of rice
200 straw, as shown in Table 1. All pellets were produced with an initial water content of
201 15% just before pelletization. Using another pelletizer (EF-BS-055; Earth Engineering
202 Co., Ltd. in Japan; capacity: 20 kg/h, diameter of die: 6 mm) [12], which is called
203 pelletizer B, five types of pellets were produced. The performances of pelletizers A and B
204 were almost the same in terms of the mechanical durability. Only rice straw was
205 pelletized (RSP1). The rice straw torrefied at a temperature of 200°C was pelletized

206 (TP200°C–100%) and PTRSW was produced at a mixture ratio of 1:1 (TP200°C–50%).
207 The rice straw torrefied at a temperature 250°C was pelletized (TP250°C–100%) and
208 PTRSW was produced at a mixture ratio of 1:1 (TP250°C–50%).

209

210 To clarify which step was better to apply the torrefaction process, before or after
211 pelletization, pellets of rice straw were torrefied. Actually, the rice straw pellets (RSP2),
212 which were produced using pelletizer A as described above, were torrefied using the
213 screw continuous reactor (PT200°C). The rice straws used for RSP2 and RSP1 were
214 collected from different fields but the same region. The quality of the rice straw was
215 almost the same. For reference purposes, the wood chips were also pelletized (WP) using
216 pelletizer B.

217

218 **2.4 Analysis of pellets**

219 **2.4.1 Proximate and ultimate analysis**

220 All analytical methods were conducted in accordance with standard methods in Japan.
221 Three samples were chosen to determine the water content, ash content, volatile portion
222 and fixed carbon content. The volatile portion was measured by loss on ignition at 600°C
223 and the ash content was measured by heating at 815°C, according to Japanese Industrial
224 Standards, and in particular, standard JIS M 8812 [29]. The fixed carbon content was
225 calculated by subtracting the moisture content, the ash content, and the volatile portion
226 from the weight of the sample.

227

228 In accordance with JIS M 8819 [30], an automatic elemental analyzer (vario EL cube:
229 Elementar Analysensysteme GmbH, Germany) was used to analyze the content of
230 carbon, nitrogen, hydrogen and sulfur. Four samples were analyzed. It is noted that the
231 content of oxygen was calculated by subtracting the water, ash, carbon, nitrogen,
232 hydrogen, and sulfur contents from the weight of the sample.

233

234 **2.4.2 Lower heating values (LVHs)**

235 In accordance with JIS M 8814 [31], the higher heating values (HHVs) of the samples
236 were measured using a bomb calorimeter (C7000: IKA, Germany). One mass of
237 approximately 0.5 g of shredded samples was analyzed; this was repeated four times.
238 The LVHs were calculated from their HHVs and the hydrogen content by using Eq. (1).

239

$$240 \text{LHV} = \text{HHV} - r \times (\text{U} + 9\text{H}), \quad (1)$$

241

242 where, LHV and HHV are the lower and higher heating values (MJ/kg), respectively, r
243 is the evaporative latent heat (2512 kJ/kg), U is the moisture content (kg/kg) and H is
244 the hydrogen content (kg/kg).

245

246 **2.4.3 Bulk density and energy density**

247 After drying a container with known volume, it was filled with samples, and then
248 dropped naturally three times from a height of 15 cm to densify the samples. The adding
249 of more samples to the container and natural dropping were repeated to fill the container
250 with samples. The weights of the empty container and container with samples were
251 measured, and the bulk density of the samples was calculated by using Eq. (2).

252

$$253 \quad BD = (m_1 - m_0)/V \times 1000, \quad (2)$$

254

255 where, BD is the bulk density (kg/m³), m_0 is the weight of empty container (g), m_1 is the
256 weight of the container filled with samples (g), and V is the volume of the container (cm³).

257

258 The energy density (ED) was calculated by using Eq. (3).

259

$$260 \quad ED = LHV \times BD \quad (3)$$

261

262 **2.4.4 Mechanical durability**

263 Mechanical durability is an important criterion for the storage and transportation of
264 pellets. The mechanical durability was measured by the following procedure in
265 accordance with quality standards for wood pellets [32]. Pellets were sieved to remove
266 loose residues using a 3.15 mm sieve. To test the mechanical durability, a rotary box (300
267 mm L × 125 mm W × 300 mm H), in which a baffle plate (230 mm L × 50 mm W) was
268 fixed, was used [27]. The rotary box was operated at 50 rpm for 10 min to make the
269 pellets collide together after sieving to break them up. Afterwards, the broken samples
270 from the rotary box were sieved again and the weight of pellets remaining on the sieve
271 was measured. The mechanical durability was defined as the ratio of the weight of pellets
272 after collisions to the weight of pellets before collisions.

273

274 **2.4.5 Thermogravimetry and differential thermal analysis (TG–DTA)**

275 TG–DTA was conducted for the rice straw, rice straw torrefied at the temperatures of
276 200°C and 250°C, and wood chips by using TG–DTA equipment (STA7300; Hitachi High-
277 Tech Science Corporation Corp.). All samples were heated to 605°C at the increase rate

278 of 10°C/min.

279

280 **2.5 Combustion test**

281 **2.5.1 Small-scale rotary kiln biomass pellet boiler**

282 This study applied a commercially available small-scale rotary kiln biomass boiler (TKD-
283 SBU02; Takeda Tekko-Sho Co., Ltd.), as shown in Figure 2. It was developed for heating
284 greenhouses in agriculture. The specifications of the boiler are given in Table 2. This
285 boiler was developed for heating greenhouses in agriculture. Even when a biomass with
286 high ash content is burned, a rotary kiln performs smooth ash removal. Intermittent
287 rotation of the kiln prevents ash or clinker from stagnating inside the furnace to mitigate
288 clinker growth. Two air injection systems, such as direct aeration to biomass and
289 aeration for rotational flow, ensure stable combustion, even if agricultural residues with
290 heating values lower than woody biomass are used as fuels.

291

292 **2.5.2 Procedure**

293 Three kinds of pellets were used in this combustion test: TP200°C–50%, PT200°C, and
294 RSP2. The period of the combustion test was 3 h for each pellet type.

295

296 The boiler was started automatically, according to the procedure shown in Figure 3. The
297 electric heater ignited the pellets 1 min after the feeding of the pellets started. The
298 feeding of pellets was stopped at 3.5 min. The air flow was started at 4 min to grow
299 flaming. At 7.5 min, the feeding of pellets was restarted, and at 10 min, the rotation of
300 kiln was started. At 13 min, the electric heater ignited again and the rotational flow was
301 started for stable operation.

302

303 The rotary valve intermittently fed the pellets to the furnace. The valve was opened for
304 3 s and closed. The period of the valve closing was adjusted so that the feed rate of pellets
305 would be adjusted to 360–400 MJ/h. The rotary kiln was turned by about 14.4° after
306 every seven feeding times at furnace temperatures less than 300°C, and every three
307 feeding times at furnace temperatures more than 300°C.

308

309 **2.5.3 Measurement**

310 The amounts of supplied pellets and ash were measured, from which the ash in the
311 exhaust gas was estimated based on mass balance. The points for the measurement of
312 temperature and flow rate are shown in Figure 3. The temperatures at the inside of the
313 furnace, the outlet of the furnace, the outside air, the warm current air, and the exhaust

314 gas were measured. The flow rate of the warm current air and the exhaust gas were also
315 measured. Analyzing the exhaust gas, such as particle matter, CO, NO_x, and SO_x, is
316 important, but this was not measured in this study.

317

318

319 **3. Results and Discussion**

320 **3.1 Effectiveness of torrefaction in logistics**

321 **3.1.1 Proximate and ultimate analysis**

322 Table 3 shows the result of the proximate analysis for each pellet type. Since all pellets
323 were produced after adjusting the water content to about 15%, the water contents were
324 8–10% except for PT200°C, which was torrefied after pelletization. Mixing with wood
325 chips and rice straw (TP200°C–50% and TP250°C–50%) decreased the ash content in
326 rice straw from 9.16–9.74% to 4.70–5.12%, which can mitigate clinker problems.
327 Torrefaction increased the fixed carbon contents in TP200°C–100% and TP250°C–100%
328 to 15.93% and 16.80%, respectively, which were higher than that for RSP1 (15.67%).
329 Comparing RSP2 with PT200°C, the fixed carbon content, as well as the water content,
330 were improved by torrefaction after pelletization.

331

332 To clarify the effectiveness of torrefaction, the content of volatile, fixed carbon, and ash
333 were recalculated without the water content. The increase in the torrefaction
334 temperature from 200°C to 250°C decreased the volatile portion from 72.66% (TP200°C-
335 100%) to 71.33% (TP250°C-100%) and from 78.14% (TP200°C-50%) to 77.41% (TP250°C-
336 50%). The thermal stability of the major biomass constituents during torrefaction is
337 cellulose > lignin > hemicelluloses [15]. Chen and Kuo [33] conducted torrefaction of
338 hemicelluloses, cellulose, and lignin individually at torrefaction temperature of 230°C,
339 260°C, and 290°C, and found that hemicelluloses were decomposed, but cellulose and
340 lignin were only slightly decomposed at 230°C. In this experiment, hemicelluloses
341 contributed to decrease in the volatile portion. Comparing RSP1 and TP200°C-100%, the
342 torrefaction temperature of 200°C did not change the volatile portion, but comparing
343 RSP2 with PT200°C, the volatile portion decreased. Chen et al. [34] also suggested that
344 the volatile portion changed little at temperatures of 200°C and 230°C. The torrefaction
345 temperature in the screw continuous reactor might be higher than our setting of 200°C,
346 even if the retention time was shorter than 1 h (45 min). This result was reflected by the
347 sensitive temperature range for the decomposition of hemicellulose.

348

349 As shown in Table 3, the ultimate analysis showed that increases in the torrefaction

350 temperature removed oxygen from 40.77% (TP200°C-100%) to 36.99% (TP250°C-100%)
351 and 42.98% (TP200°C-50%) to 40.8% (TP250°C-50%). This result is supported by existing
352 studies [17, 35, 36]. In addition, the nitrogen content was increased by torrefaction from
353 0.560% (RSP1) to 0.753% (TP200°C–100%) and 0.766% (TP250°C–100%), but that the
354 sulfur content was decreased from 0.08% (RSP1) to 0.063% (TP200°C–100%) and
355 0.0057% (TP250°C-100%). Knudsen et al. [37] and Saleh et al. [38] reported that
356 torrefaction removed sulfur from wheat straw. In addition, PTRSW decreased both
357 nitrogen and sulfur content in the pellets by mixing with wood chips. These properties
358 can mitigate emissions of nitrogen oxides and sulfur oxides during burning of the pellets.
359

360

361 **3.1.2 Lower heating value (LHV)**

362 In general, the LHV of rice straw is lower than that of wood. This study produced the
363 same tendency, as shown in Table 3: 14.80 MJ/kg and 15.42 MJ/kg for RSP1 and RSP2,
364 respectively, and 17.6 MJ/kg for WP. Torrefaction increased the LHV of pellets with rice
365 straw, to 15.56 MJ/kg, 16.09 MJ/kg, and 15.74 MJ/kg in TP200°C–100%, TP250°C–100%,
366 and PT200°C, respectively, leading to improvements of 2% to 9% in the LHV. The
367 increase in the LHV of rice straw during torrefaction was comparable with that reported
368 in other studies for agricultural residues [17, 34, 35]. In addition, mixing with wood chips
369 improved the LHV further to 16.56 MJ/kg and 16.80 MJ/kg in TP200°C–50% and
370 TP250°C–50%, respectively.

371

372 **3.1.3 Bulk density and energy density**

373 Table 3 also shows that torrefaction increased the bulk density to 1.2–1.4 times that for
374 RSP1. Particularly, the torrefaction temperature of 250°C increased to more than that
375 in WP. Torrefaction improves grindability to decrease particle size [12, 39], resulting in
376 an increase in bulk density during the pelletization process. However, torrefaction of the
377 rice straw pellets (PT200°C) did not change the bulk density compared with normal rice
378 straw pellets (RSP2) because rice straw pellets themselves were just torrefied (PT200°C).
379 The small portion of volatiles seemed to be decomposed without any change in the
380 structure of the pellets, which decreased the bulk density.

381

382 Finally, the energy density was calculated using the LHV and bulk density to evaluate
383 the effectiveness of torrefaction on the transportation of pellets, as shown in Table 3.
384 Torrefaction increased the energy density to 1.3–1.5 times that for RSP1. In addition,
385 PTRSW increased 1.4–1.5 times that for RSP1. However, torrefaction of rice straw pellets

386 (PT200°C) did not change the energy density compared with that for RSP2. Torrefaction
387 after pelletization had no advantages in terms of energy density. Thus, torrefaction of
388 rice straw before pelletization mixing with wood chips was effective to improve the
389 energy density of rice straw pellets.

390

391 **3.1.4 Mechanical durability**

392 Figure 4 shows the relationship between mechanical durability and bulk density. The
393 mechanical durability of rice straw pellets (RSP1 and RSP2) was about 86%, meaning
394 the pelletizers A and B performed similarly in regard to mechanical durability. Although
395 torrefaction of rice straw pellets at the torrefaction temperature of 200°C (PT200°C) did
396 not change the mechanical durability, the pelletization of torrefied rice straw (TP200°C-
397 100% and TP200°C-50%) increased it to the same level as that for WP. As described above,
398 this is because torrefaction improved grindability, and the small particles were pelletized
399 effectively with high density. Torrefaction at the temperature of 250°C did not increase
400 the mechanical durability compared with that of 200°C because the high torrefaction
401 temperature was assumed to have changed the chemical properties of the rice straw,
402 leading to changes in the pelletizing properties. Stelte et al. [40] also pointed out that
403 torrefaction increased the friction in the press channel while pellet strength decreased
404 with an increase in torrefaction temperature. However, PTRSW improved the
405 mechanical durability (TP250°C–50%). Wood chips play the role of binder for torrefied
406 rice straw. Although mechanical durability is an important indicator for the
407 transportation of pellets, high mechanical durability can help good combustion of pellets,
408 such as reduction of fly ash in the exhaust gas [41].

409

410 **3.1.5 TG/DTA**

411 Figure 5 shows the results for TG, derivative TG (DTG), and DTA for rice straw, wood
412 chips, and rice straw torrefied at the temperatures of 200°C and 250°C, respectively, in
413 which peak time, temperature and DTG/DTA values are also shown.

414

415 Since all samples were dried up before the TG/DTA analysis, no changes in TG for water
416 evaporation were seen. The order in the residual mass was torrefied rice straw (250°C),
417 torrefied rice straw (200°C), and rice straw, because the volatile portion, mainly
418 hemicelluloses, was already removed during the torrefaction process. A higher
419 torrefaction temperature resulted in a higher residual mass [42].

420

421 In DTG and DTA, there were two peaks except for the rice straw. As described above, the

422 thermal stability of major biomass constituents during torrefaction is cellulose > lignin
423 > hemicelluloses [15]. Hemicellulose in each sample were thermally decomposed and
424 volatilized around the first peak, and then cellulose and lignin were decomposed until
425 the second peak. Around the second peak, char combustion was also observed. The first
426 peak in the rice straw that was torrefied at the temperature of 250°C was lower than the
427 others because portions of hemicellulose were already decomposed by torrefaction [42].
428 The fact that there was smaller second peak in raw rice straw compared with the others
429 indicates that the volatile portion was mainly burned during the broad first peak.

430

431 In the wood chips, both first and second peaks were observed, but the second peak
432 showed a continuous exothermal reaction. There were sharp second peaks in both the
433 torrefied rice straw samples because torrefaction increased the fixed carbon content.
434 During the char combustion around the second peak, the torrefied rice straw samples
435 showed longer tails than that of wood chips in DTA. Although the materials and
436 conditions were different from those in this study, Ma et al. [42] showed that bamboo
437 torrefied at 300°C had longer tails than raw samples and samples torrefied at 200 and
438 250°C.

439

440

441 **3.2 Combustion characteristics**

442 **3.2.1 Fuel feeding**

443 Table 4 summarizes the feed rate for each pellet. The feed rate in RSP2 was the highest
444 on the basis of energy, followed by PT200°C and TP200°C–50%. The feed rate in volume
445 is an important indicator because it determines the capacity of storage for pellets. The
446 feed rate required for the same feed rate in energy base as RSP2 was calculated. The
447 feed rate in TP200°C–50% was the smallest among the three pellets, meaning about 30%
448 can be saved in the capacity of a storage tank compared with that for RSP2.

449

450 **3.2.2 Temperature**

451 In all conditions, continuous combustion was achieved without clinker problems.
452 Particularly, the combustion was stable for operation times from 1 h to 3 h. Table 5 shows
453 the average temperature at the measurement points during stable combustion. The
454 temperature at the inside of the furnace was 726–818°C. The temperature at the outlet
455 of the burner reached to 855–898°C. As a result, the difference in the temperature of
456 warm current air and outside air was 40.3–43.3°C. Although the feed rate in TP200°C–
457 50% was the smallest among the three pellets, as shown in Table 4, the temperature at

458 the outlet of the burner was 897°C which was almost the same as that for RSP2 because
459 the temperature at the inside of the furnace in TP200°C–50% was relatively higher than
460 that in RSP2, with no char combustion.

461

462 There were differences in temperature change until 1 h (during starting up) among the
463 three pellets. Figures 6 and 7 show the temperature changes inside the furnace and at
464 the outlet of the burner, respectively. All pellets were ignited 3 min after the initial
465 ignition, and the temperature inside the furnace increased to 300°C. In the case of
466 TP200°C–50%, the temperature continued to rise up to 800°C. For PT200°C and RSP2,
467 the temperatures decreased once, and in particular, the temperature in RSP2 dropped
468 significantly. Rice straw pellets (RSP2) fed from 0 min to 3.5 min were burned completely
469 around 300°C because rice straw does not have char combustion, as described above.
470 However, in the case of TP200°C–50%, the temperature rose continuously because char
471 combustion of torrefied rice straw and wood chip occurred.

472

473 **3.2.3 Clinker formation**

474 Clinkers were collected from the furnace after the combustion test. As shown in Table 6,
475 the total weight of clinker varied from 104 to 123 g, where it was the smallest in the case
476 of PT200°C. The maximum size of clinker varied from 8 × 8 cm to 8 × 15 cm. In all pellets,
477 there was no combustion inhibition by clinker formation for the combustion test period
478 of 3 h. Further continuous combustion seems to be possible without clinker problems.
479 This is because the ratio of clinker to fuel was only from 0.19% to 0.21%. Although direct
480 comparison of this result is impossible, in the combustion tests conducted by Regueiro et
481 al. [43], using a small-scale combustor with underfeed fixed bed and grass-based types
482 of pellets with ash content of about 6%, the ratio of clinker to fuel was 3.67 to 5.78%. The
483 rotary kiln biomass boiler used in this study was effective for smooth discharge of ash
484 from the furnace.

485

486 Clinker formation depends on the elemental composition of the ash and the temperature
487 inside the furnace. Table 6 shows the elemental composition of the ash and the clinker.
488 The main components were SiO₂, K₂O, CaO, Fe₂O₃, and Mn₂O₃, accounting for more than
489 95% of the contents. In particular, SiO₂ accounted for 60–70% for the ash, and for 75–
490 77% for the clinker. Na and K decrease the melting point [44], which encourages clinker
491 formation during combustion. Jenkins et al. [45] made the binary phase diagram
492 between Na₂O and K₂O for alkali oxide under SiO₂, where the melting point for K₂O was
493 less than 800°C when the SiO₂ content was 80%. As the temperature inside the furnace

494 varied from 726°C to 818°C and the SiO₂ content in the clinker was 75–77%, the melting
495 of K₂O contributed to the clinker formation. It was expected that the clinker formation
496 would be significant in PT200°C and RSP2 because of their higher ash content than that
497 of TP200°C–50%. However, the tendency in clinker formation was the same among the
498 three pellets. This was because the rotary kiln was effective in its smooth ash removal
499 to prevent clinker growth.

500

501 **3.2.4 Ash in the exhaust gas**

502 Mass balance was calculated during stable combustion, as is shown in Figure 8, to
503 evaluate the amount of ash in the exhaust gas. The amount of ash in the exhaust gas
504 was estimated by subtraction of the volatile matter and moisture and the ash discharged
505 from the furnace from the amount of pellet input. The amount of ash in the exhaust gas
506 in TP200°C–50% was the lowest, at less than 1.0%. This was because the ash content for
507 TP200°C–50% was the lowest and its mechanical durability was the highest of the three
508 pellet types. Regueiro et al. [46] pointed out that emissions of particle matter are affected
509 by mechanical and physical properties as well as primary air flow. In this study, the air
510 flow was constant in all cases. In utilizing rice straw as a biomass fuel, PTRSW was also
511 effective to reduce the ash in the exhaust gas.

512

513 **4. Conclusion**

514 This study attempted to improve the quality of rice straw pellets using torrefaction and
515 mixing with wood chips. The following conclusions were drawn:

- 516 1) Torrefaction and mixing with wood chips is effective to improve the quality of rice
517 straw pellets. In particular, the energy density, mechanical durability, and ash content
518 were significantly improved, which can solve logistical problems of rice straw pellets
519 as biomass fuel and the clinker problems during combustion.
- 520 2) Torrefaction also increases the fixed carbon content, depending on the torrefaction
521 temperature. The combustion tests showed torrefaction contributed to high
522 temperatures inside the furnace during starting up, because of char combustion.
- 523 3) Pellets of torrefied rice straw mixed with wood chips (PTRSW) reduced the pellet
524 feeding rate, contributing to less storage volume compared with only rice straw pellets.
525 In particular, the amount of ash in the exhaust gas was reduced. This might be because
526 the ash content and mechanical durability was improved.

527

528

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533

534

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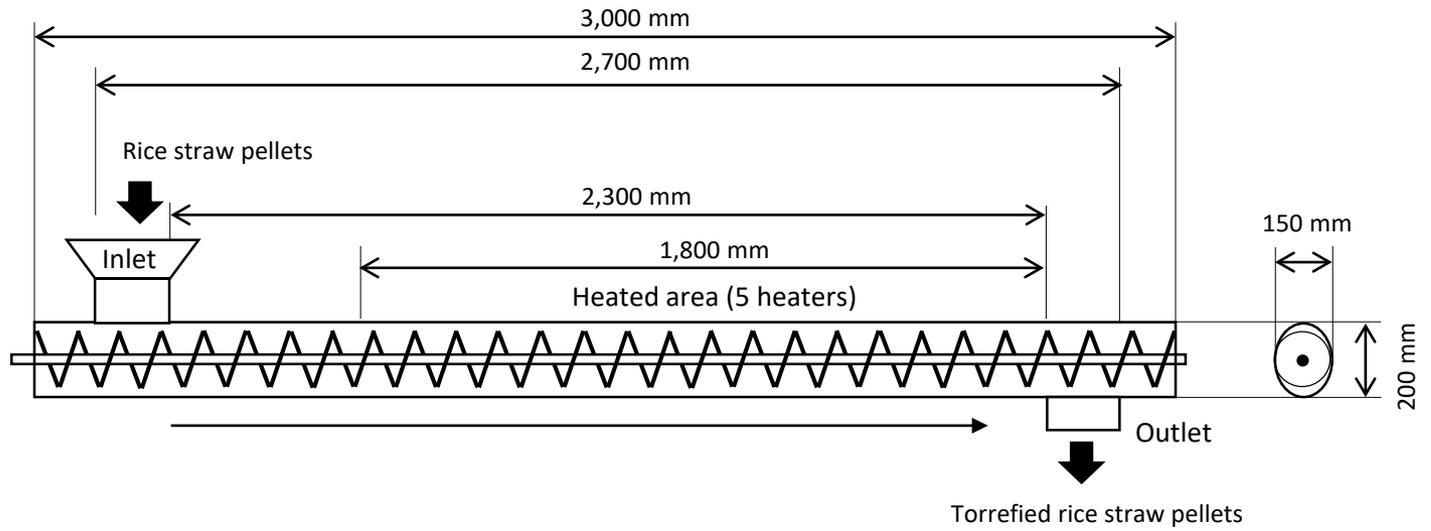


Figure 1 Screw continuous reactor for torrefaction of rice straw pellets

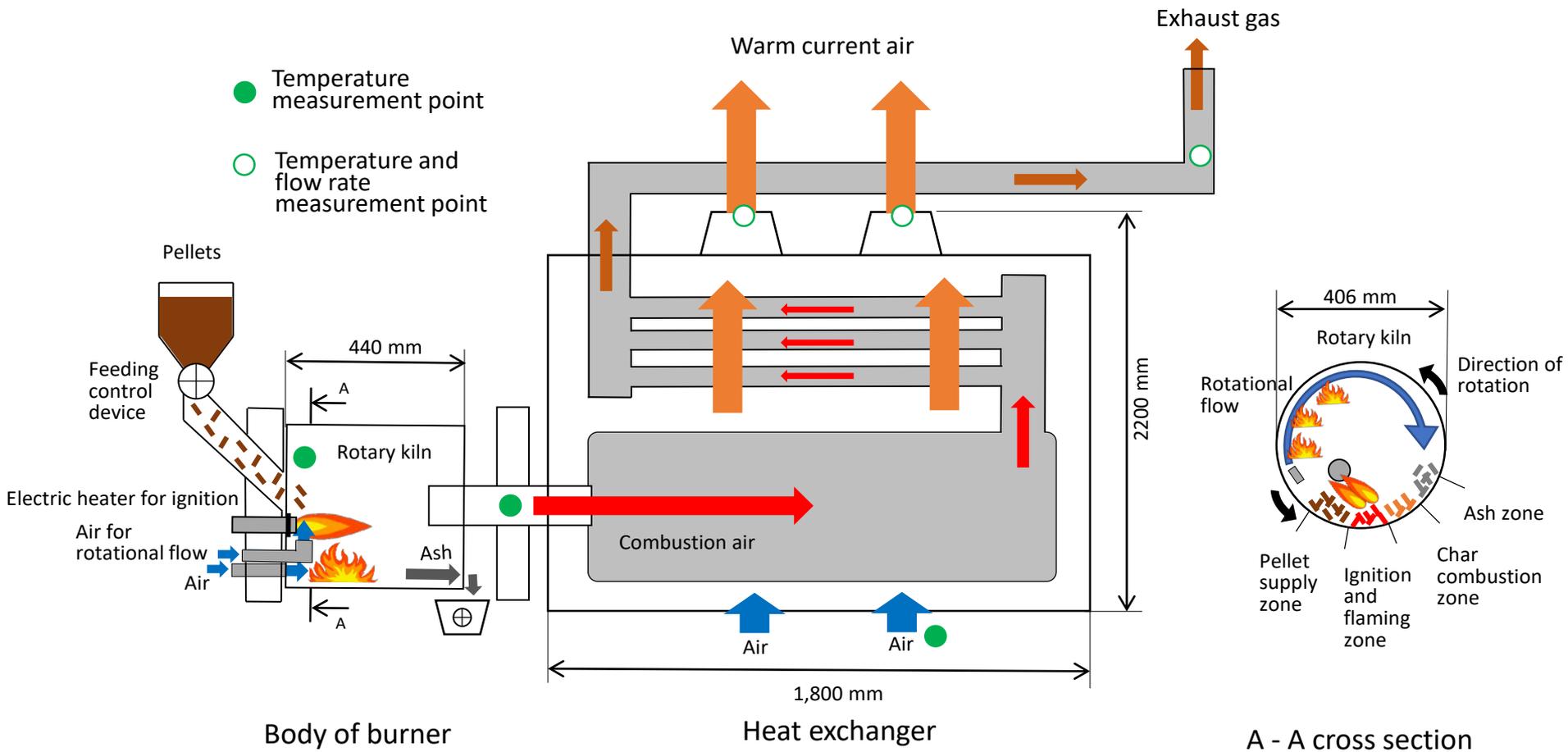


Figure2 Small-scale rotary kiln biomass pellet boiler

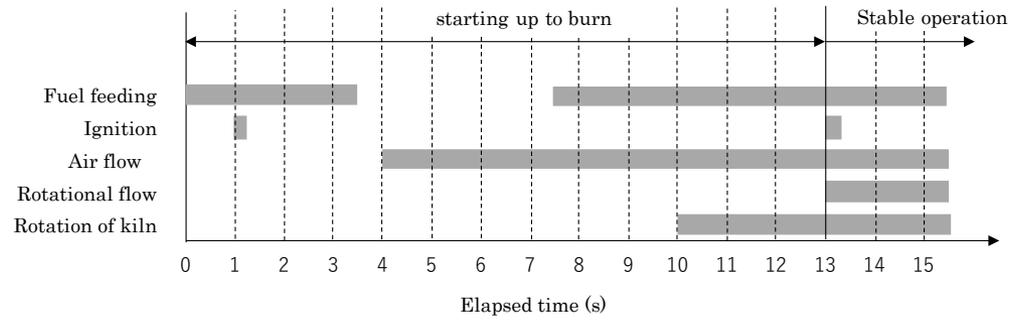


Figure 3 Procedure of combustion test

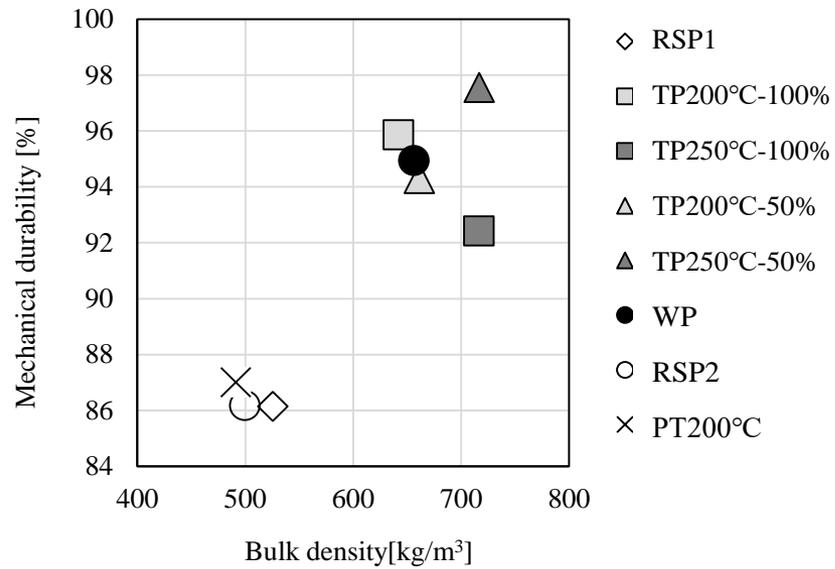


Figure 4 Relationship between mechanical durability and bulk density

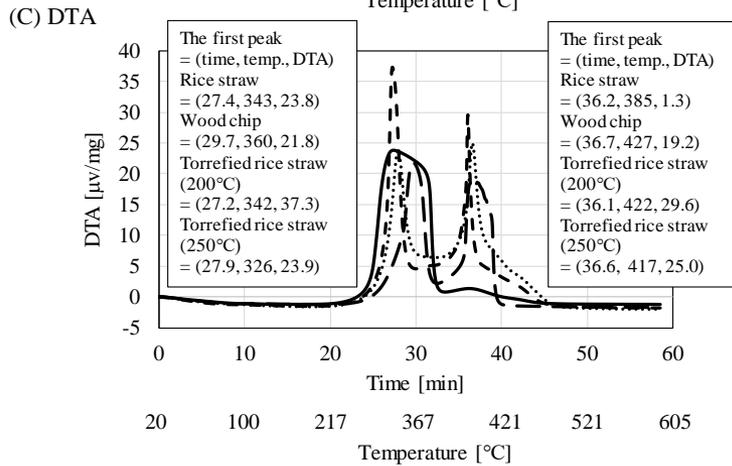
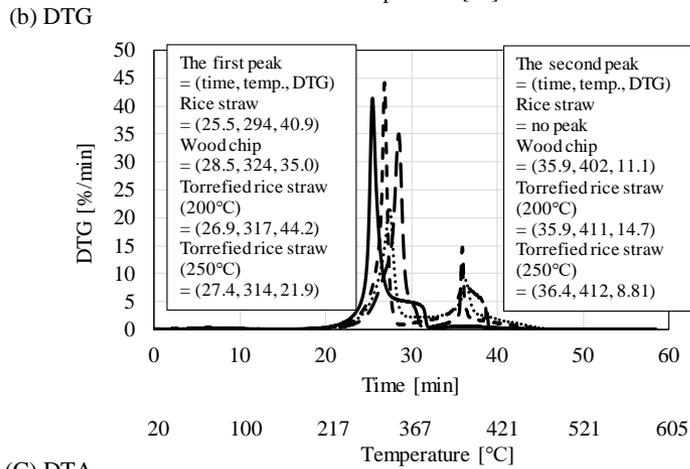
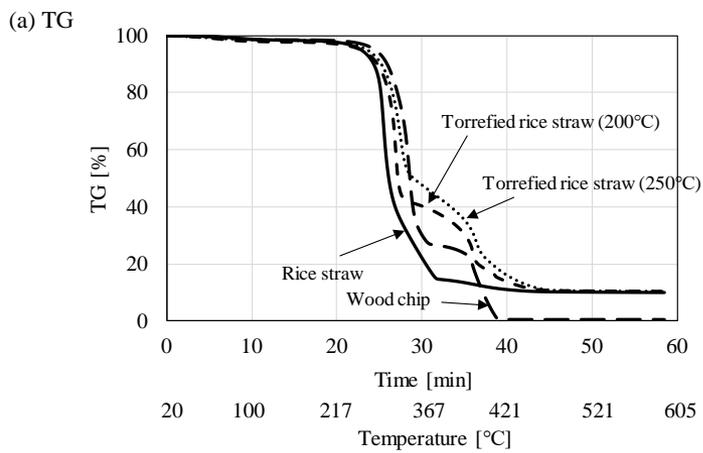


Figure 5 Results of TG, DTG and DTA

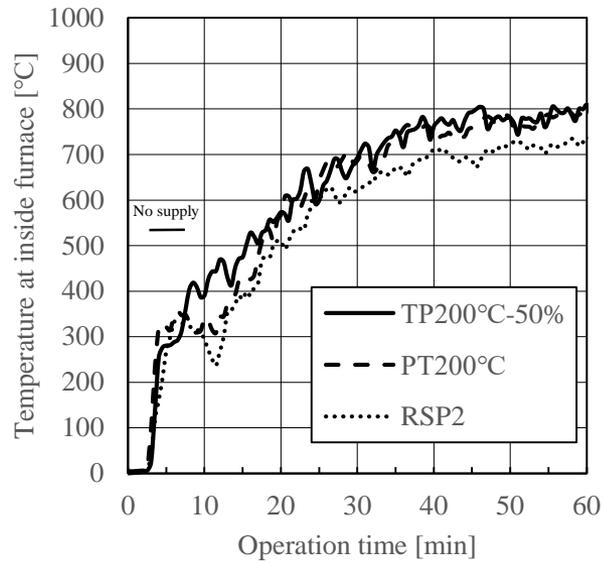


Figure 6 Temperature at the inside of furnace

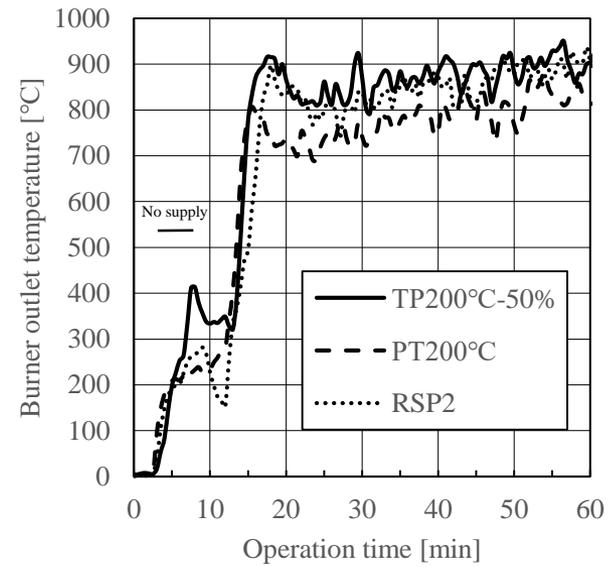


Figure 7 Temperature at the outlet of burner

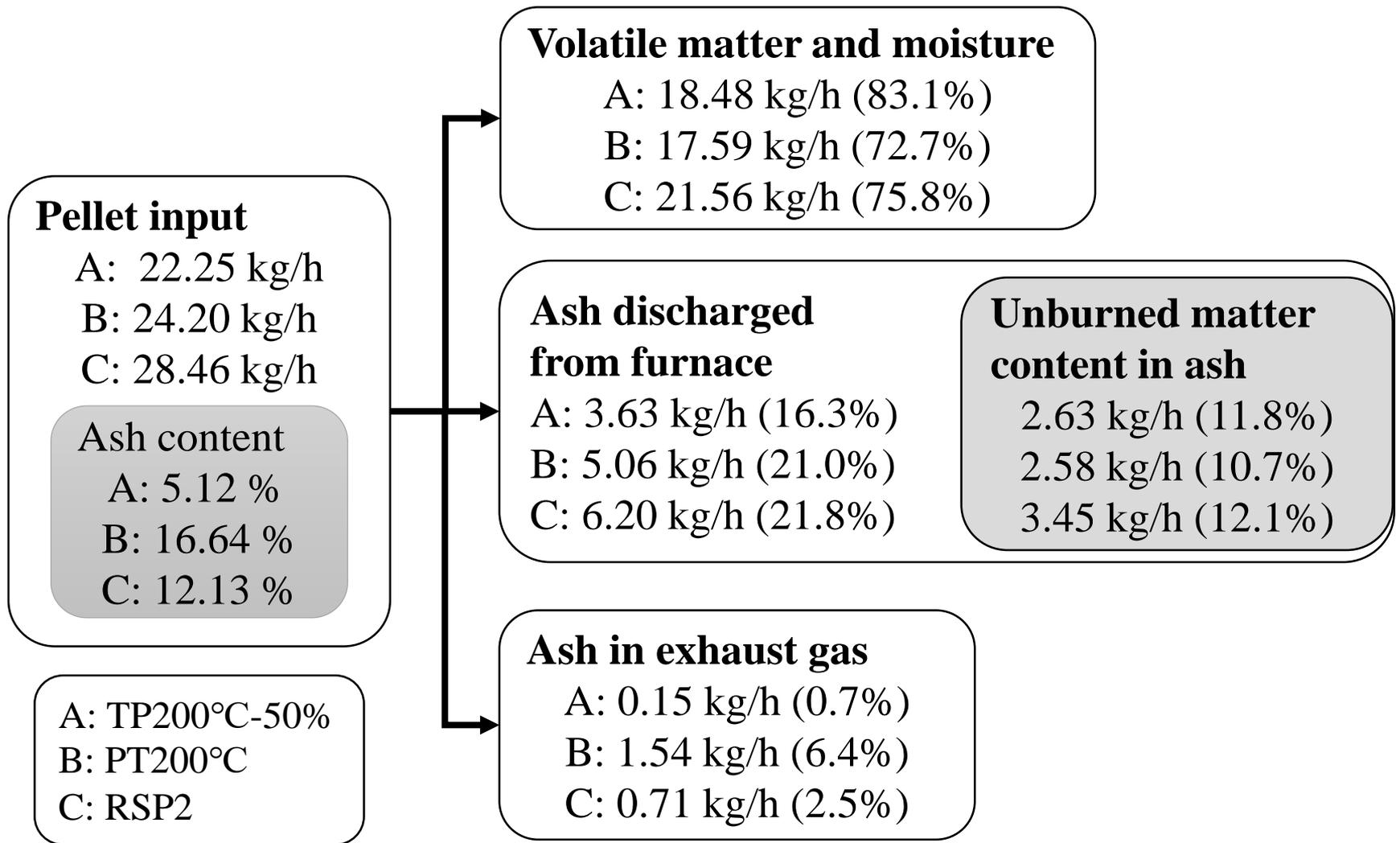


Figure 8 Mass balance in the combustion test

Table 1 Pellet production conditions

Sample name	Explanation	Torrefaction reactor	Torrefaction temperature	Pelletizer	Mixing ratio of wood chips
RSP1	Pellets of rice straw	-	-	B	-
TP200°C-100%	Pellets of torrefied rice straw	Stainless reactor	200°C	B	0%
TP200°C-50%	Pellets of torrefied rice straw mixed with wood chips (PTRSW)		200°C	B	50%
TP250°C-100%	Pellets of torrefied rice straw		250°C	B	0%
TP250°C-50%	Pellets of torrefied rice straw mixed with wood chips (PTRSW)		250°C	B	50%
RSP2	Pellets of rice straw		-	-	A
PT200°C	Torrefaction of RSP2	Screw continuous reactor	200°C	A	-
WP	Pellets of wood chips	-	-	B	-

Table 2 Specification of small-scale rotary kiln biomass pellet boiler

Type	TKD-SBU02
Fuels	Wood pellets, agricultural residue pellets, rice husk, etc.
Output	10 to 60 Mcal/h (12 to 70 kW) depending on fuels
Temperature inside the furnace	800 to 900°C
Fuel supply	2.5 to 15 kg/h
Ignition method	Electric heater
Air flow	66 m ³ /min (50 Hz), 76 m ³ /min (60 Hz)
Power	AC 100 V (50/60 Hz)
Power consumption	17 A (Ignition 28A) (50 Hz), 21 A (Ignition 31 A)(60 Hz)
Outside dimension	L 3.2 m, W 0.3 m, H 2.2 m
Weight	700 kg
Features	Rotary kiln type furnace Fuel feeding equipment with rotary valve Automatic ash removal

Table 3 Results of analysis

Sample		Proximate analysis (wt. %)				Proximate analysis (wt. %) without water			Ultimate analysis (wt. %)					LHV (MJ/kg)	Bulk density (kg/m ³)	Energy density (GJ/m ³)
		Volatile	Fixed carbon	Water	Ash	Volatile	Fixed carbon	Ash	[C]	[O]	[H]	[N]	[S]			
Rice straw pellets	RSP1*	65.52	15.67	9.63	9.16	72.52	17.34	10.14	41.19	42.3	5.730	0.560	0.080	14.80	525.67	7.78
Reice straw pellets	TP200°C-100%	65.68	15.93	9.61	8.78	72.66	17.62	9.71	43.14	40.77	5.560	0.753	0.063	15.56	642.05	9.99
(Torrefaction - Pelletization)	TP250°C-100%	66.02	16.80	7.44	9.74	71.33	18.15	10.52	46.24	36.99	5.430	0.766	0.057	16.09	716.50	11.53
PTRSW	TP200°C-50%	71.00	14.74	9.14	5.12	78.14	16.22	5.64	45.63	42.98	5.840	0.420	0.028	16.56	661.40	10.95
	TP250°C-50%	70.49	15.87	8.94	4.70	77.41	17.43	5.16	47.18	40.8	6.250	0.073	0.000	16.80	716.78	12.04
Wood chip	WP	77.71	14.64	7.24	0.41	83.78	15.78	0.44	48.12	45.31	5.730	0.720	0.130	17.60	656.40	11.55
Rice straw pellets	RSP2**	64.89	14.62	8.36	12.13	70.81	15.95	13.24	40.88	39.3	5.560	0.730	0.090	15.42	499.70	7.71
Torrefied rice straw pellets (Pelletization - Torrefaction)	PT200°C**	67.06	16.64	3.63	12.66	69.59	17.27	13.14	41.09	39.39	5.370	0.810	0.070	15.74	491.20	7.73

* The same rice straw was used for pelletization.

** The rice straw in RSP2 and PT200°C was different from that used in RSP1.

Table 4 Summary of fuel feeding

Pellets	Feed rate [MJ/h]	Feed rate in weight [kg/h]	Feed rate in volume [L/h]	Feed rate in volume* [L/h]	Ratio to RSP2 [%]
TP200°C-50%	366.5	22.1	33.5	38	70.4
PT200°C	370.7	23.6	47.9	54	99.7
RSP2	414.6	26.9	53.8		

* Feed rate in volume required for the same feed rate as RSP2

Table 5 Average temperature at the measurement points

Pellets	Average temperature from 1 to 3 h [°C]			
	Inside of furnace	Outlet of burner	Exhaust gas	ΔT
TP200°C-50%	818	897	194	41.3
PT200°C	793	855	186	40.3
RSP2	726	898	196	43.3

ΔT = Temperature of warm current air - temperature of outside air

Temperature of outside air = 4 - 5°C

Table 6 Result of component analysis for ash and clinker

	TP200°C-50%		TP200°C		RSP2		
Clinker remained inside of furnace							
Total weight [g]	104		113		123		
Ratio of clinker to fuel[%]	0.19		0.21		0.19		
Maximum size [cm]	8 × 15		8 × 10		8 × 8		
Composition [wt%]	Ash	Clinker	Ash	Clinker	Ash	Clinker	
SiO ₂	60.21	77.03	67.16	75.44	70.01	76.27	
K ₂ O	23.77	10.34	18.70	13.61	16.61	13.51	
CaO	9.66	6.93	5.16	4.18	5.39	4.12	
Fe ₂ O ₃	2.71	1.95	1.86	1.75	1.73	1.35	
Mn ₂ O ₃	2.69	1.87	3.33	2.42	3.75	2.50	
Others	0.97	1.89	3.81	2.61	2.51	2.45	