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

3

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7

8 **Abstract**

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

20

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

23

24 **Graphical abstract**

25
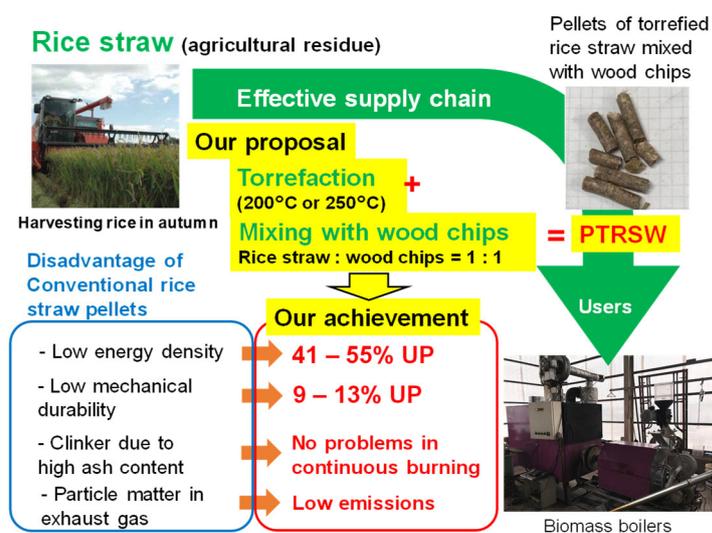
Statement of Novelty

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

1. Introduction

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

As the potential of wood biomass for energy production is limited globally [3], higher quantities of alternative agricultural fuels may be used in the near future [4]. In Japan, a number of power generation plants using wood biomass, such as wood chips from forest residue, have been started up, and are operated with a feed-in-tariff benefit. As of the end of March 2017, there were 491 large-scale biomass wood power plants with a certified power generation capacity of 12 million kW [5]. Some plants import palm kernel shell from other countries to obtain cheaper biomass because presently the wood biomass industry in Japan is competitive and the palm kernel shell is 40% cheaper than wood chips in Japan [6]. To increase the share of renewable heat sources, agricultural residue 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 (Si+P+K)/(Ca+Mg+Al) for the fuel.

132

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

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

Therefore, the objectives of this study were:

1) to clarify the characteristics of PTRSW, such as LHV, bulk density, energy density, mechanical durability, and ash content, which are related to supply chain and combustion behavior, and

2) to clarify the combustion behavior of PTRSW, such as clinker formation and the emission of particle matter, through combustion tests using a small-scale boiler.

2. Materials and methods

2.1 Rice straw and wood samples

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

2.2 Torrefaction method

2.2.1 Torrefaction of rice straw

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

2.2.2 Torrefaction of rice straw pellets

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

2.3 Pelletization

Eight types of pellets were produced to clarify the effectiveness of torrefaction of rice straw, as shown in Table 1. All pellets were produced with an initial water content of 15% just before pelletization. Using another pelletizer (EF-BS-055; Earth Engineering Co., Ltd. in Japan; capacity: 20 kg/h, diameter of die: 6 mm) [12], which is called pelletizer B, five types of pellets were produced. The performances of pelletizers A and B were almost the same in terms of the mechanical durability. Only rice straw was 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 LHVs were calculated from their HHVs and the hydrogen content by using Eq. (1).

239

240 $LHV = HHV - r \times (U + 9H)$,   (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 $$BD = (m1 - m0)/V \times 1000, \qquad (2)$$

254

255 where, BD is the bulk density (kg/m^3), m0 is the weight of empty container (g), m1 is the
256 weight of the container filled with samples (g), and V is the volume of the container (cm^3).

257

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

259

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

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, NOx, and SOx, 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

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

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

3.2 Combustion characteristics

3.2.1 Fuel feeding

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

3.2.2 Temperature

In all conditions, continuous combustion was achieved without clinker problems. Particularly, the combustion was stable for operation times from 1 h to 3 h. Table 5 shows the average temperature at the measurement points during stable combustion. The temperature at the inside of the furnace was 726–818°C. The temperature at the outlet of the burner reached to 855–898°C. As a result, the difference in the temperature of warm current air and outside air was 40.3–43.3°C. Although the feed rate in TP200°C–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

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 SiO_2, K_2O, CaO, Fe_2O_3, and Mn_2O_3, accounting for more than
489   95% of the contents. In particular, SiO_2 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 Na_2O and K_2O for alkali oxide under SiO_2, where the melting point for K_2O was
493   less than 800°C when the SiO_2 content was 80%. As the temperature inside the furnace

494   varied from 726°C to 818°C and the SiO_2 content in the clinker was 75–77%, the melting

495   of K_2O 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

533

534

References

536   [1] Communication from the Commission to the European Parliament, the Council, the
537   European Economic and Social Committee of the Regions: United in delivering the Energy
538   Union and Climate Action - Setting the foundations for a successful clean energy
539   transition. https://ec.europa.eu/transparency/regdoc/rep/
540   1/2019/EN/com-2019-285-F1-en-main-part-1.pdf (2019). Accessed 24 September 2019
541   [2] The Government of Japan: The 5th Strategic Energy Plan 2018.
542   https://www.meti.go.jp/english/press/2018/pdf/0703_002c.pdf (2019). Accessed 24
543   September 2019
544   [3] Mola-yudego, B., Arevalo, J., Díaz-Yánez, O., Dimitriou, L., Haapala, A., Filho, A.C.F.,
545   Selkimäki, M., Valbuena, R.: Wood Biomass Potentials for Energy in Northern Europe:
546   Forest of Plantations?. Biomass and Bioenergy. 106, 95-103 (2017)
547   [4] Mack, R., Kuptz, D., Schön, C., Hartmann, H.: Combustion Behavior and Slagging
548   Tendencies of Kaolin Additivated Agricultural Pellets and of Wood-straw Pellet Blends in
549   a Small-scale Boiler. Biomass and Bioenergy. 125, 50-62 (2019)
550   [5] Japan Woody Bioenergy Association: Wood Biomass Energy Data Book 2018.
551   https://www.jwba.or.jp/app/download/13159696992/Data+book+2018+%28English+versio
552   n%29.pdf?t=1523342683 (2018). Accessed 24 July 2020
553   [6] Japan Woody Bioenergy Association: Price transition of wood and palm kernel shell
554   https://www.jwba.or.jp/database/price-transition01/ (2020). Accessed 24 July 2020
555   [7] Yagi, K., Minami, K.: Effect of Organic Matter Application on Methane Emission from
556   Some Japanese Paddy Fields. Soil Science and Plant Nutrition. 36, 599-610 (1990)
557   [8] Ministry of Agriculture, Forestry and Fisheries: Fundamental plan for promotion of
558   biomass utilization (In Japanese).
559   http://www.maff.go.jp/j/shokusan/biomass/attach/pdf/index-4.pdf (2016). Accessed 24
560   September 2019
561   [9] Ishii, K., Furuichi, T., Fujiyama, A., Watanabe, S.: Logistics Cost Analysis of Rice Straw
562   Pellets for Feasible Production Capacity and Spatial Scale in Heat Utilization Systems: A
563   Case Study in Nanporo Town, Hokkaido, Japan. Biomass and Bioenergy. 94, 155-166
564   (2016)
565   [10] Werther, J., Saenger, M., Hartge, E.U., Ogada, T., Siagi, Z.: Combustion of Agricultural

566   Residues. Progress in Energy and Combustion Science. 26, 1-27 (2000)

567 [11] Acharya, B., Dutta, A., Minaret, J.: Review on Comparative Study of Dry and Wet
568   Torrefaction. Sustainable Energy Technologies and Assessments. 12, 26-37 (2015)

569 [12] Kizuka, R., Ishii, K., Sato, M., Fujiyama, A.: Characteristics of Wood Pellets Mixed with
570   Torrefied Rice Straw as a Biomass Fuel. International Journal of Energy and
571   Environmental Engineering. 10, 357-365 (2019)

572 [13] van der Stelt, M.J.C., Gerhauser, H., Kiel, J.H.A., Ptasinski, K.J.: Biomass Upgrading
573   by Torrefaction for the Production of Biofuels: A Review. Biomass and Bioenergy. 35,
574   3748-3762 (2011)

575 [14] Acharya, B., Dutta, A.: Characterization of Torrefied Willow for Combustion Application.
576   Journal of Biobased Materials and Bioenergy. 7(6), 667-674 (2013).

577 [15] Zheng, A.Q., Zhao, Z.L., Chang, S., Huang, Z., He, F., Li, H.B.: Effect of Torrefaction
578   Temperature on Product Distribution from Two-staged Pyrolysis of Biomass. Energy
579   Fuels. 26(5), 2968-2974 (2012)

580 [16] Zhang, A.Q., Jiang, L.Q., Zhao, Z.L., Huang Z., Zhao, K. Wei, G.Q, Wang, X.B., He, F., Li,
581   H.B.: Impact of Torrefaction on the Chemical Structure and Catalytic Fast Pyrolysis
582   Behavior of Hemicellulose, Lignin, and Cellulose. Energy Fuels. 29(12), 8027-8034 (2015)

583 [17] Chen, D., Gao, A., Ma, Z., Fei, D., Chang, Y., Shen, C.: In-depth Study of Rice Husk
584   Torrefaction: Characterization of Solid, Liquid and Gaseous Products, Oxygen Migration
585   and Energy Yield. Bioresource Technology. 253, 148-153 (2018)

586 [18] Koppejan, J., Sokhansanj, S., Melin, S., Madrali, S.: IEA Bioenergy Task 32 report. Final
587   report, status overview of torrefaction technologies. http://www.ieabcc.nl/publications/
588   IEA_Bioenergy_T32_Torrefaction_review.pdf (2012). Accessed 24 September 2019

589 [19] Bridgeman, T.G., Jones, J.M., Shield, I., Williams, P.T.: Torrefaction of Reed Canary
590   Grass, Wheat Straw and Willow to Enhance Solid Fuel Qualities and Combustion
591   Properties. Fuel. 87, 844-856 (2008)

592 [20] IEA Bioenergy, Task 40: Possible Effects of Torrefaction on Biomass Trade.
593   https://www.ieabioenergy.com/wp-content/uploads/2016/09/Two-page_Summary_
594   Torrefaction-biomass- trade.pdf (2015). Accessed 24 September 2019

595 [21] Cardona, S., Gallego, L.J., Valencia, V., Martínez, E., Rios, L.A.: Torrefaction of
596   Eucalyptus-tree Residues: A New Method for Energy and Mass Balances of the Process
597   with the Best Torrefaction Conditions, Sustainable Energy Technologies and
598   Assessments, 31, 17-24 (2019)

599 [22] Nanou, P., Carbo, M.C., Kiel, J.H.A.: Detailed Mapping of the Mass and Energy Balance
600   of a Continuous Biomass Torrefaction Plant. Biomass and Bioenergy. 89, 67-77 (2016)

601 [23] Bass, R., Garcia-Perez, M., Horneck, D., Lewis, M., Pan, B., Peters, T., Stevens, B.,

602   Wysocki, D.: Carbon Implications of Converting a Coal-fired Power Plant to Combustion
603   of Torrefied Arundo Donax. Applied Bioenergy. 1,30-43 (2014).

604 [24] Chen, W.H., Peng, J., Xiaotao, T.B.: A State-of-the-art Review of Biomass Torrefaction,
605   Densification and Applications. Renewable and Sustainable Energy Reviews. 44, 847-
606   866 (2015)

607 [25] Tumuluru, J.S., Hess, R.: New Market Potential: Torrefaction of Woody Biomass.
608   Materials World. 6 (2015)

609 [26] Öhman, M., Boman, C., Hedman, H., Nordin, A., Böstrom, D.: Slagging Tendencies of
610   Wood Pellet Ash During Combustion in Residential Pellet Burners. Biomass and
611   Bioenergy. 27, 585-596 (2004)

612 [27] Ishii, K., Furuichi, T.: Influence of Moisture Content, Particle Size and Forming
613   Temperature on Productivity and Quality of Rice Straw Pellets. Waste Management. 34,
614   2621-2626 (2014)

615 [28] Feldmeier, S., Wopienka, E., Schwarz, M., Schön, C., Pfeifer, C.: Applicability of Fuel
616   Indexes for Small-scale Biomass Combustion Technologies, Part 1: Slag Formation.
617   Energy Fuels. 33, 10969-10977 (2019)

618 [29] Japanese Industrial Standards: Coal and Coke—Methods for Proximate Analysis. JIS M
619   8812. (2004)

620 [30] Japanese Industrial Standards: Coal and Coke—Mechanical Methods for Ultimate
621   Analysis. JIS M 8819. (1997)

622 [31] Japanese Industrial Standards: Coal and Coke-Determination of Gross Calorific Value
623   by the Bomb Calorimetric Method, and Calculation of Net Calorific Value. JIS M 8814.
624   (1993)

625 [32] Japan Wood Pellet Association: Quality Standard for Wood Pellets (in Japanese). (2011)

626 [33] Chen, W.H., Kuo, P.C.: Torrefaction and Co-torrefacction Characterization of
627   Hemicellulose, Cellulose and Lignin As Well As Torrfaction of Some Basic Constituents
628   in Biomass. Energy. 36, 803-811 (2011)

629 [34] Chen, D., Zhou, J., Zhang, Q., Zhu, X., Lu, Q.: Upgrading of Rice Husk by Torrefaction
630   and Its Influence on the Fuel Properties, Bioresources. 9(4), 5893-5905 (2014)

631 [35] Wannapeera, J. Fungtammasan, B., Worasuwannarak, N.: Effects of Temperature and
632   Holding Time during Torrefaction on the Pyrolysis Behaviors of Woody Biomass. Journal
633   of Analytical and Applied Pyrolysis. 92, 99-105 (2011)

634 [36] Ma, Z., Zhang, Y., Shen, Y., Wang, J., Yang, Y., Zhang, W., Wang, S.: Oxygen Migration
635   Characteristics during Bamboo Torrefaction Process Based on the Properties of Torrefied
636   Solid, Gaseous, and Liquid Products. Biomass and Bioenergy. 128, 105300 (2019)

637 [37] Knudsen, J.N., Jensen, P.A., Lin, W., Frandsen, F.J., Dam-Johansen, K.: Sulfur

638   Transformations during Thermal Conversion of Herbaceous Biomass. Energy and Fuels.
639   18, 810–819 (2004)

640 [38] Saleh, S.B., Flensborg, J.P., Shoulaifar, T.K., Sárossy, Z., Hansen, B.B., Egsgaard, H.,
641   sDeMartini, N., Jensen, P.A., Glarborg, P., Dam-Johansen, K.: Release of Chlorine and
642   Sulfur during Biomass Torrefaction and Pyrolysis. Energy and Fuels. 28, 3738–3746
643   (2014)

644 [39] Phanphanich, M., Mani, S.: Impact of Torrefaction on the Grindability and Fuel
645   Characteristics of Forest Biomass. Bioresource Technology. 102(2), 1246–1253 (2011)

646 [40] Stelte, W., Nielsen, N.K., Hansen, H.O., Dahl, J., Shang, L., Sanadi, A.R.: Pelletizing
647   Properties of Torrefied Wheat Straw. Biomass and Bioenergy. 49, 214-221 (2013)

648 [41] Temmerman, M., Rabier, F., Jensen, P.D., Hartmann, H., Böhm, T.: Comparative
649   Study of Durability Test Methods for Pellets and Briquettes. Biomass and Bioenergy.
650   3, 964-972 (2006)

651 [42] Ma, Z., Zhang, Y., Li, C., Yang, Y., Zhang, W., Zhao, C.: N-doping of Biomass by
652   Ammonia (NH_3) Torrefaction Pretreatment for the Production of Renewable N-
653   containing Chemicals by Fast Pyrolysis. Bioresource Technology. 292,122034 (2019)

654 [43] Regueiro, A, Jezerská, L., Pérez-Orozco, R., Patiño,D., Zegzulka, J., Nečas,J:
655   Viability Evaluation of Three Grass Biofuels: Experimental Study in a Small-scale
656   Combustor. Energies. 12, 1352 (2019)

657 [44] Demirbas, A.: Potential Applications of Renewable Energy Sources, Biomass Combustion
658   Problems in Boiler Power Systems and Combustion Related Environmental Issues.
659   Progress in Energy and Combustion Science. 31, 171-192 (2005)

660 [45] Jenkins, B.M., Baxter, L., Miles Jr.c, T.R., Miles, T.R.: Combustion Properties of Biomass.
661   Fuel Processing Technology. 54, 17-46 (1998)

662 [46] Regueiro, A., Jezerská, L., Patiño,D., Pérez-Orozco, R., Nečas,J, Žídek, M:
663   Experimental Study of the Viability of Low-grade Biofuels in Small-cale Appliances.
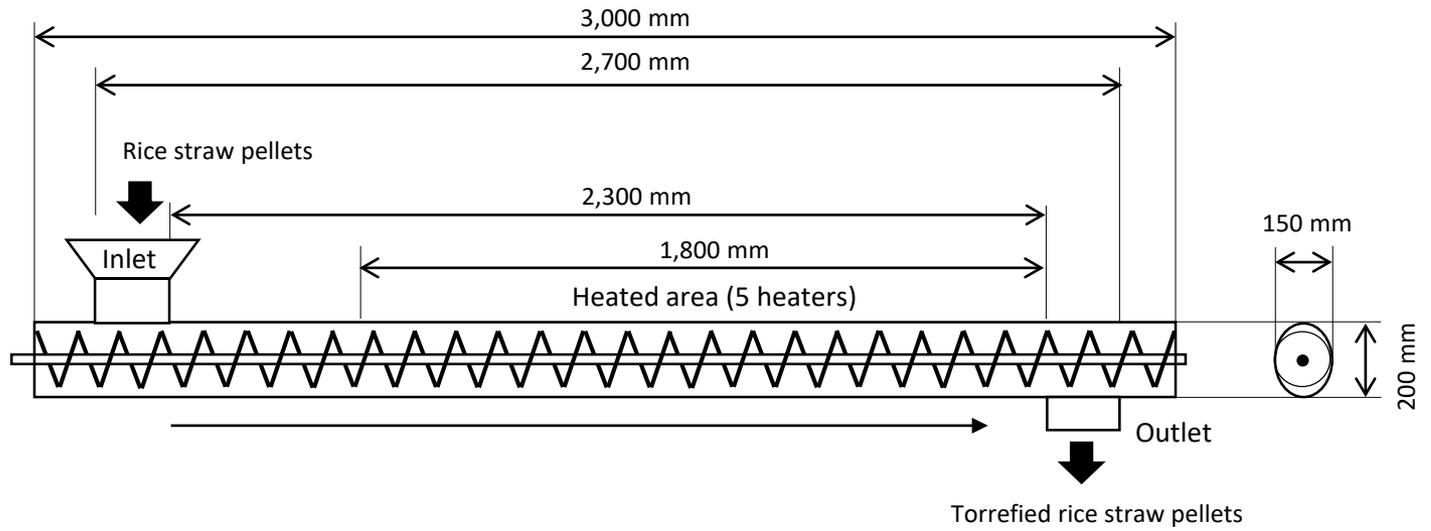664   Sustainability. 9, 1823 (2017)

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Figure 1 Screw continuous reactor for torrefaction of rice straw pellets
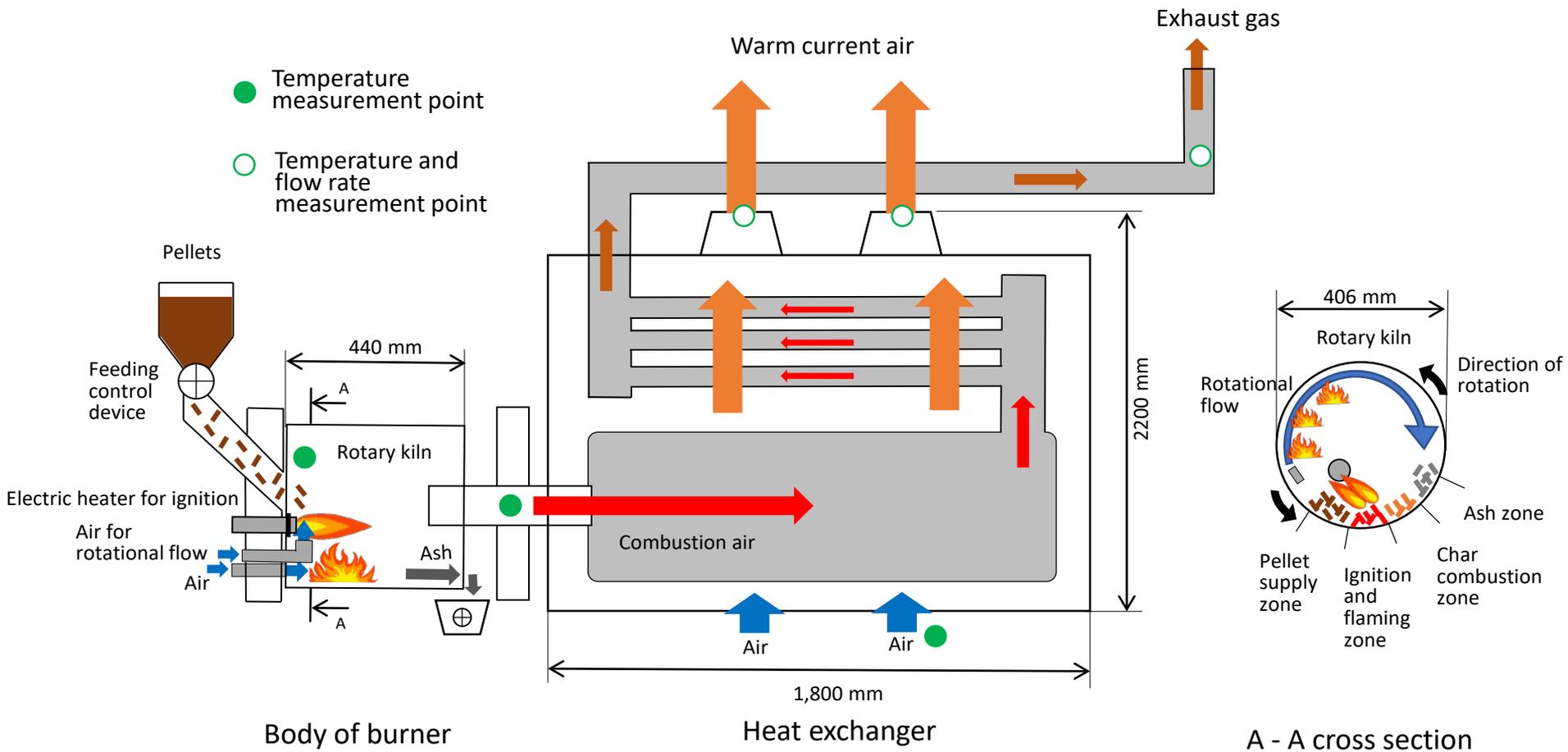
Figure2 Small-scale rotary kiln biomass pellet boiler

Temperature measurement point

Temperature and flow rate measurement point

Pellets

Feeding control device

Electric heater for ignition

Air for rotational flow

Air

440 mm

A

A

Rotary kiln

Ash

Body of burner

Warm current air

Exhaust gas

Combustion air

Air

Air

2200 mm

1,800 mm

Heat exchanger

406 mm

Rotary kiln

Rotational flow

Direction of rotation

Ash zone

Pellet supply zone

Ignition and flaming zone
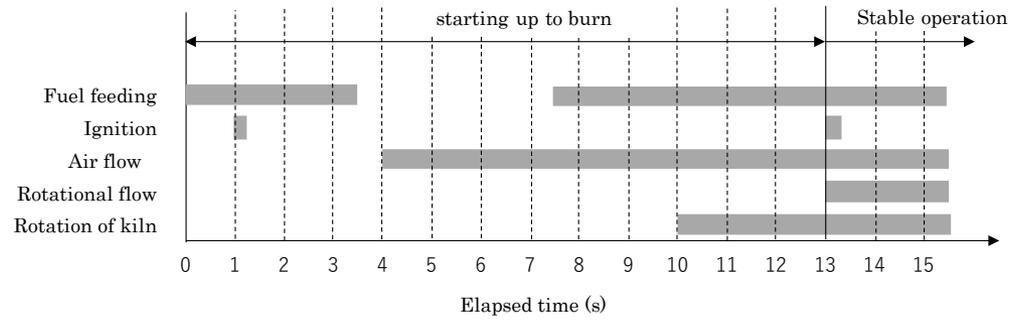
Char combustion zone

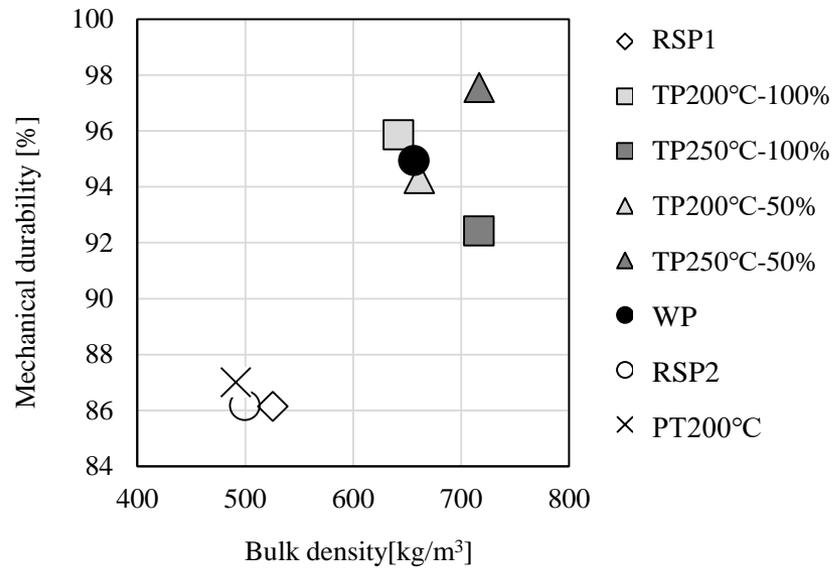A - A cross section

Figure 3 Procedure of combustion test

Figure 4 Relationship between mechanical durability and bulk density

(a) TG

TG [%]

Torrefied rice straw (200°C)

Torrefied rice straw (250°C)

Rice straw

Wood chip

Time [min]

Temperature [°C]

(b) DTG

DTG [%/min]

The first peak
= (time, temp., DTG)
Rice straw
= (25.5, 294, 40.9)
Wood chip
= (28.5, 324, 35.0)
Torrefied rice straw
(200°C)
= (26.9, 317, 44.2)
Torrefied rice straw
(250°C)
= (27.4, 314, 21.9)

The second peak
= (time, temp., DTG)
Rice straw
= no peak
Wood chip
= (35.9, 402, 11.1)
Torrefied rice straw
(200°C)
= (35.9, 411, 14.7)
Torrefied rice straw
(250°C)
= (36.4, 412, 8.81)

Time [min]

Temperature [°C]

(C) DTA

DTA [μv/mg]

The first peak
= (time, temp., DTA)
Rice straw
= (27.4, 343, 23.8)
Wood chip
= (29.7, 360, 21.8)
Torrefied rice straw
(200°C)
= (27.2, 342, 37.3)
Torrefied rice straw
(250°C)
= (27.9, 326, 23.9)

The first peak
= (time, temp., DTA)
Rice straw
= (36.2, 385, 1.3)
Wood chip
= (36.7, 427, 19.2)
Torrefied rice straw
(200°C)
= (36.1, 422, 29.6)
Torrefied rice straw
(250°C)
= (36.6, 417, 25.0)

Time [min]

Temperature [°C]
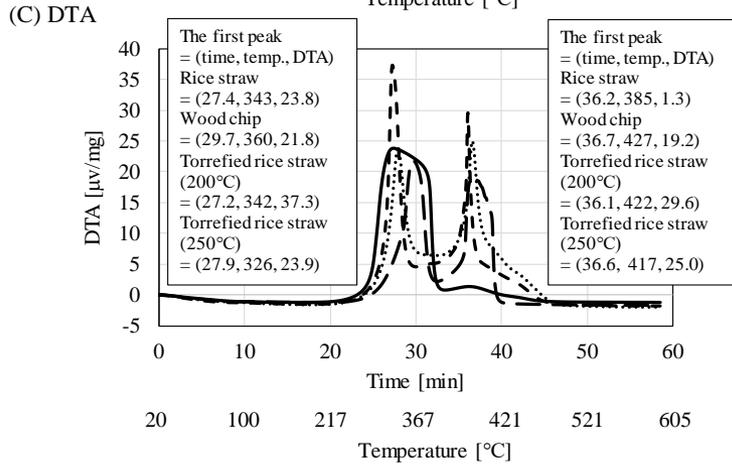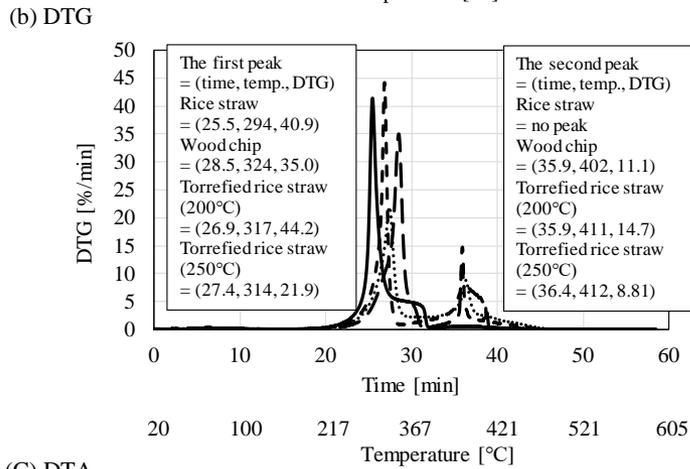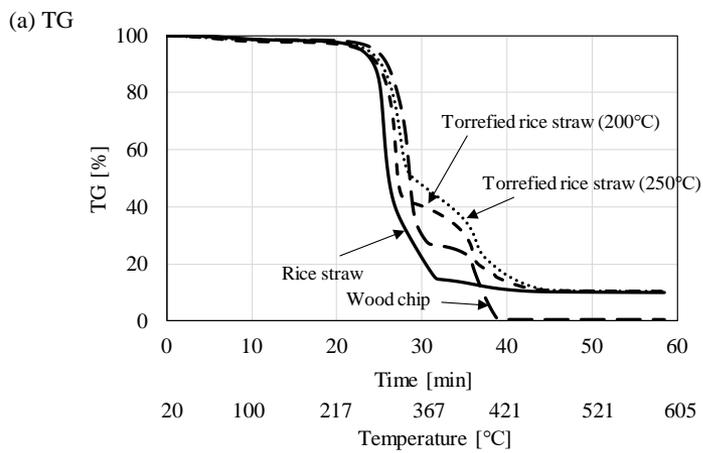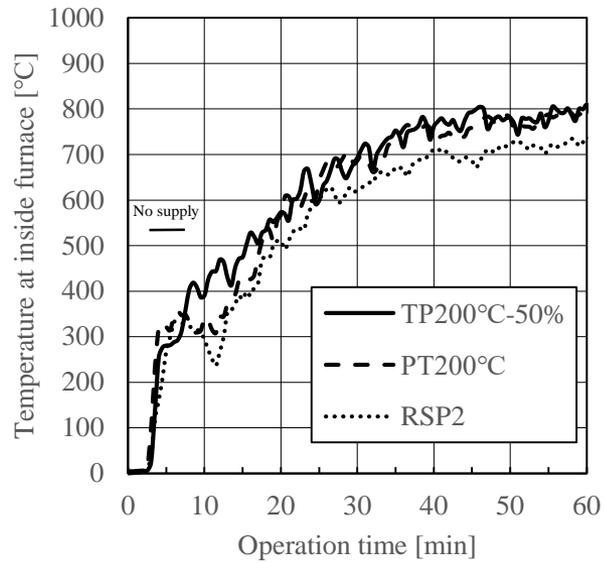
Figure 5 Results of TG, DTG and DTA

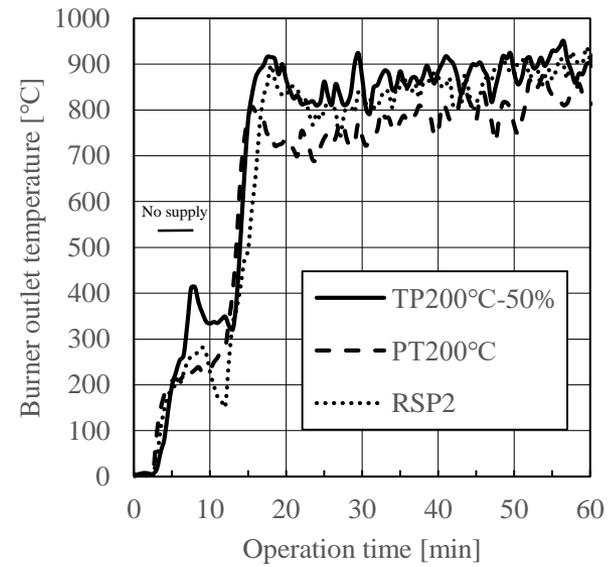Figure 6 Temperature at the inside of furnace
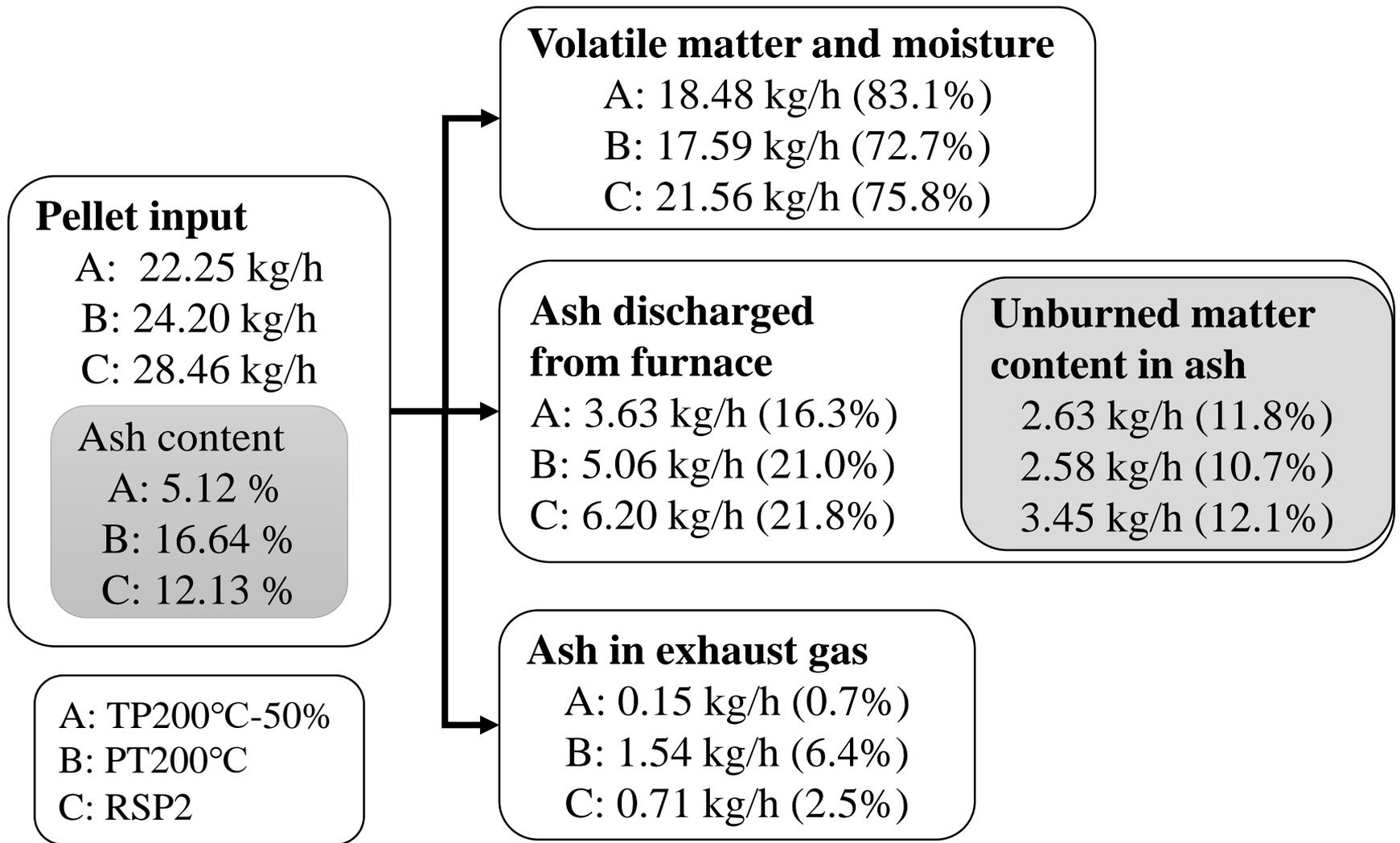

Figure 7 Temperature at the outlet of burner

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		200°C	B	0%
TP200°C-50%	Pellets of torrefied rice straw mixed with wood chips (PTRSW)	Stainless reactor	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/m³)	Energy density (GJ/m³)
		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 temeprature 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 - temeprature 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	
Maxmum 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_2O	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_2O_3	2.71	1.95	1.86	1.75	1.73	1.35
Mn_2O_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