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Case Study: Technical Considerations to Optimize Rice Husk Burning in a Boiler to Retain a High Solubility of the Silica in Rice Husk Ash

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Authors' contributions

This work was carried out in collaboration between all authors. Author MT designed the study, wrote the protocol and wrote the first draft of the manuscript. Authors MY and AY managed the literature searches and analyses of the study data. Author RS managed the experimental process. All authors read and approved the final manuscript.

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ABSTRACT

Aims: Optimal conditions were investigated for the operation of a boiler using rice husks as fuel. Superior operation resulted in the production of high quality ash as well as heat recovery. Good quality ash is a useful resource that can bring profits to a local community.
Study Design: Rice husks were burned in a boiler and the boiler operation was evaluated by measuring the ash solubility in an alkali solution. The operational factors influencing the performance were determined.
Location and Duration of Study: The study was located at the local Imizuno Agricultural Association (IAA) in Imizu, Japan, the location of Toyama Prefectural University. Data were collected from June 2011 to March 2016.

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Methodology: The quality of ash was evaluated by examining its solubility. The NaOH method and Testing Method 4.4.1.c were employed to measure solubility. The operational factors of temperature control, maximum temperature setting, air flow capacity, and fire grate movement pattern were chosen to determine the optimal boiler performance.

Results: The following was determined for temperature control: Do not use the AUTO setting at the beginning of the process but engage the AUTO setting once the boiler has finished idling. The optimal maximum temperature was found to be 500ºC; the air flow capacity was 30 Hz; and the fire grate moving pattern was 5-5-6.

Conclusion: For boiler burning or an exothermal reaction, two phases were needed to produce a better quality of ash: An exothermal reaction for the first phase and an endothermic reaction for the second phase. Also, there may be additional factors that contribute to a superior operation.

Keywords: Rice husk; boiler; solubility; high quality of ash; operational condition; optimal operation.

1. INTRODUCTION

Rice husks have been gaining much attention for their amorphous silica property, which has been referred to as "bio-ore of silica" [1]. Recently, not only the agricultural field but many other fields such as medicine have been focusing on the silica in rice husks [2]. However, rice husks are still generally viewed as a waste product that needs to be disposed of. As a result, an abundant amount of rice husks has been disposed of as a valueless material in many parts of the world. For a practical use of rice husks, the best method is to burn the husks and use the concentrated silica as an agricultural fertilizer. The carbohydrates that occupy a large proportion of rice husks by weight can be an effective biomass fuel to produce heat and the remaining silica in the rice husk ash can be used as an essential element for rice growth in healthy agricultural conditions [3,4]. Several Southeast Asian countries have been producing energy for a long time by burning rice husks [5]. Tateda (2016b) reported on the establishment of a local energy system using rice husks to save on management costs of drying rice husks and running greenhouses during winter, and concluded that the system was practically sustainable [6]. Burning rice husks is not a difficult task and individuals can obtain heat from the process. However, the silica would crystallize and no longer be a valuable resource if the rice husks are burned carelessly and without the proper consideration. There was a previous incident in Japan, in which a boiler blasted free because its stack was clogged with crystallized silica due to careless operation. Silica in the rice husk ash after burning must be amorphous; otherwise, crystalline silica is dangerous in operation, even to human health, and becomes useless as a resource.

Silica deposited in the cell walls [7] of the rice husk, called "opal" [8,9], is amorphous; thus, an important consideration when burning rice husks is how high the solubility of silica in the rice husk ash can become as a result of burning. Amorphous silica can be dissolved in an alkali solution. The degree of amorphous silica can be evaluated by determining its solubility. The higher the solubility, the better the amorphous state of the silica in the rice husk ash; in other words, the better the quality of the ash, and vice versa.

An electric furnace is usually used to burn rice husks to extract precious silica from the husks [10-12], which is referred to as "sintering" or "calcination," and it is generally accepted that a high quality of silica could be produced by the furnace, yet the costs to run the electric furnace are too high to burn a large amount of rice husks. Direct combustion of rice husks was introduced by several researchers [5,13], but very limited information, such as "combustion should be less than 800ºC for getting amorphous silica" [13], has been made available; the research did not mention the quality of the silica in the rice husk ash after combustion. In this study, detailed steps to achieve the optimal operation of a boiler were described for stakeholders in this field. The best quality of silica, based on a solubility evaluation, in rice husk ash and heat could be obtained simultaneously through the optimal operation. Since the boiler used in this study was very simple and inexpensive, the best practices reported here can be transferred and applied to using rice husks as a resource in many parts of world, especially in Southeast Asian countries. This is the consecutive report of Tateda, et al. [1].

2. MATERIALS AND METHODS

2.1 Rice Husks

The rice husks from Koshihikari (*Oryza sativa L.*) used in this study were obtained from the local Imizuno Agricultural Association (IAA) in Imizu, Japan, where the Toyama Prefectural University is located. The rice harvested in the area is transferred to the large rice storage yard at the IAA before the rice is processed. This processing entails milling and cleaning the rice to produce a product suitable for sale. Most of the rice husks generated in this community are accumulated and stocked at the IAA, amounting to 600 tons of rice husks annually. Half of the stocked rice husks are used as flooring material for the housing of domestic animals and as water drainage systems in the paddy fields. However, such usage of rice husks is neither stable nor sustainable, and the entire amount of 600 tons/year will eventually reach the end of its useful life and have to be treated as waste. The density of rice husks is very low, at 0.1–0.2 ton/m^3, meaning that extremely large storage spaces would be necessary for disposal unless recycling methods are developed. Generation of rice husk does not directly connect to disposal, so waste rice husk is stored anyway somewhere before disposal. The husk is currently considered merely as waste and is therefore a burden on the rice producers in the area.

2.2 Boiler Used in This Study

In this study, the boiler shown in Fig. 1 was used to combust the rice husks. The boiler has an air blower system and the rice husks fed from the inlet is combusted in an oxygen-rich condition on moving fire grates, which are shown as a sloped surface in the figure. By the movement of the grates, rice husks could be moved forward during combustion. The combustion capacity of the boiler is 100 kg/h of rice husk, with a water content of approximately 10–13%. Table 1 shows sampling ports for temperature measurement inside the boiler furnace, which correspond to the numbers in Fig. 1.

Fig. 2 shows the ash deposit sink used to keep ash at a high temperature. The sink was made by removing two lines of fire grates that were originally located there.

2.3 Ash Sample Collection and Temperature Measurement

Ash was sampled by discharging ash from the outlet by loosening with a screw (Figs. 1 and 2) at an early stage in the experiment. After installation of the sink, ash sampling was performed manually with a shovel by an operator. Ash sampling was conducted immediately after combustion was stopped (Time 0), one day after combustion was stopped (Time 1), two days after

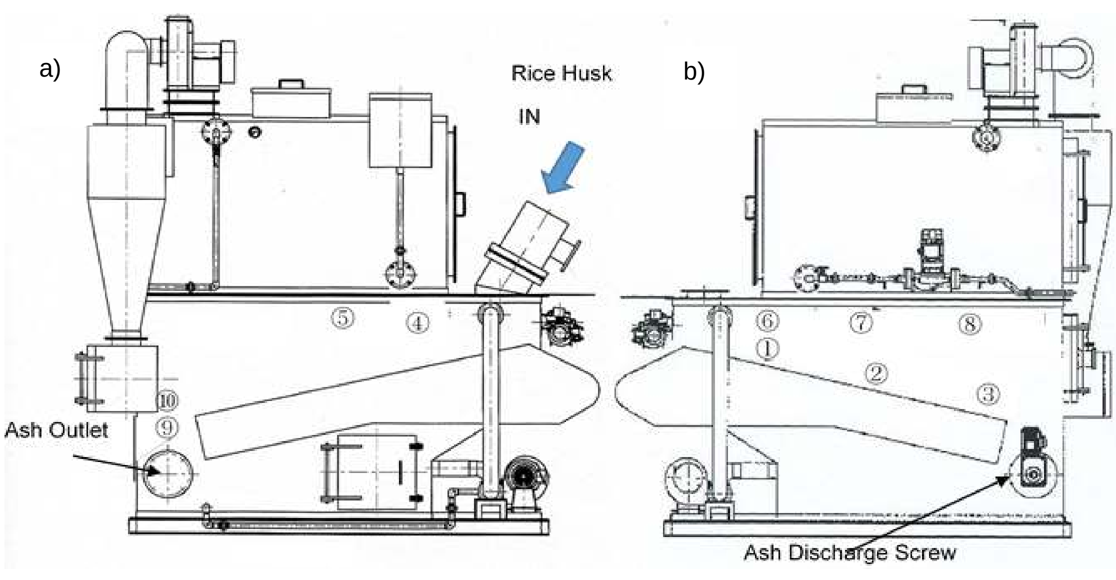

Fig. 1. Diagram of the Boiler from a) the left side view and b) the right side view. The numbers indicate sampling ports for temperature measurement

Table 1. Temperature sampling ports for thermocouples

Port number	Location details
1	Surface of upper part of fire grates
2	Surface of middle part of fire grates
3	Surface of lower part of fire grates. After installation of the sink, the ash accumulated in the front part of the sink.
4	Head space on the left side where the rice husks are fed in
5	Head space on the left side on the middle position of fire grates
6	Head space on the right side where rice husks are fed in
7	Head space on the right side on the middle position of fire grates
8	Head space on the right side on the lower position of fire grates
9	The lower position of ash deposition sink
10	The upper position of ash deposition sink

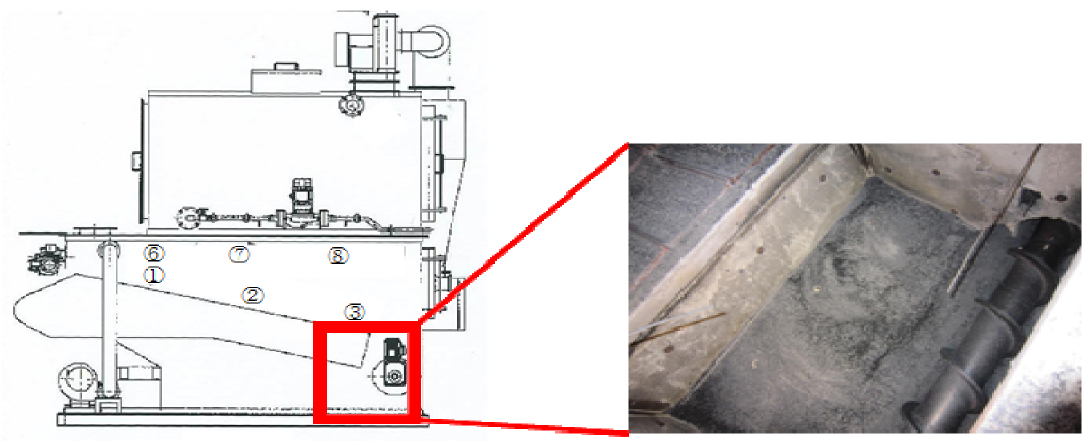

Fig. 2. Ash deposit sink in the furnace of the boiler

(Time 2), and three days after (Time 3). The temperature distribution in the furnace was measured with 10 thermocouples (Type K) and recorded for analysis by a data logger (Paperless Recorder GP10, Yokokawa).

2.4 Quantitative Measurement of Solubility

In this study, the sodium hydroxide (NaOH) method at an early stage and the Testing Method 4.4.1.c [14,15] were employed to measure the solubility of the silica in the rice husk ash. The NaOH method is a simple method and the Testing Method 4.4.1.c is a more official method (not authorized by Japanese Government, however), and the former showed mostly higher values than the latter (Fig. 3).

The NaOH method can be described as follows: The ash sample (1 g) was placed in a 250 ml Erlenmeyer flask, and 150 ml of 0.5 M NaOH (Kanto Kagaku), heated at 60℃, was poured into the flask, which was placed in a water bath at 60℃. After one hour of stirring, the NaOH solution was quickly cooled to room temperature and purified water was added to a level of 250 ml. Subsequently, the 250 ml solution was filtered with one micro glass-fiber filter, after which an aliquot of the filtered sample was placed in a white porcelain dish and dried on the water bath. A few milliliters of hydrochloric acid (HCl, 1+1 [conc. HCl: purified water = 1:1 in volume]) was added to the white porcelain dish and it was dried in the water bath. The process of HCl addition and drying was repeated several times. Subsequently, the dish was placed in a drier and was dried completely at 110℃. After cooling, 50 ml of HCl (1+4) was poured into the dish and the dish was heated to 90℃. After the dissolution of the residue on the bottom of the dish was complete, the solution was filtered with one micro filter. The material on the filter was dissolved with HCl (1+10) and the procedure was repeated.

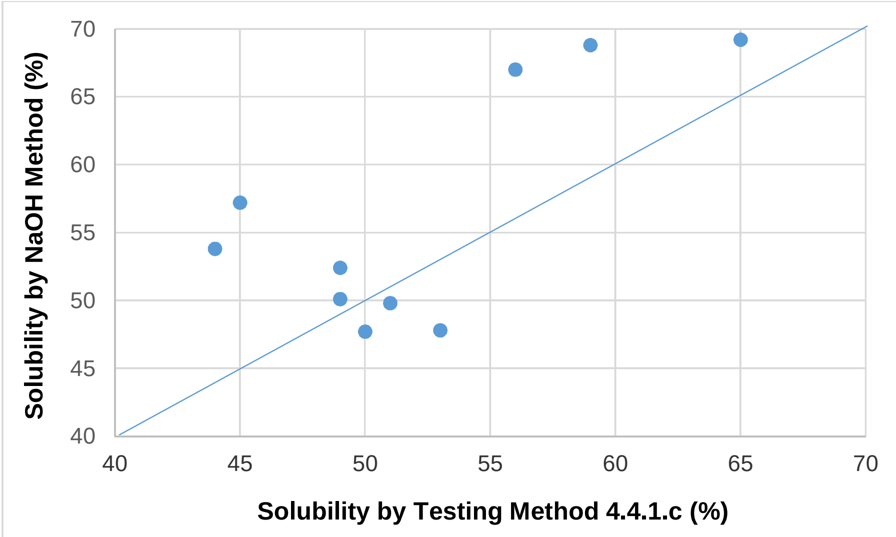

Fig. 3. Solubility data comparison between the NaOH method and testing method 4.4.1.c

3. RESULTS AND DISCUSSION

3.1 Burning with and without a Set Maximum Temperature

Operation of the boiler was performed without setting a maximum temperature at the early stage of this experiment. Samples at only Time 0 were taken for a solubility measurement of this operation. Solubility during this period was measured by the NaOH method and the mean, median, and standard deviation were 49.4%, 50.1%, and 6.4%, respectively. Next, the maximum temperature was set at 600℃ (port No. 8 in Fig. 1) and burning was conducted. It was found that some measuring ports detected temperatures exceeding 1,000℃, which will make silica in rice husks crystallize, even when 600˚C was selected as the setting. Fig. 4 shows the representative temperature profile data of the boiler when the maximum temperature was set at 600℃. The symbol "CH" in the figure corresponds to the temperature sampling ports in Fig. 1 and Table 1. Temperatures at sampling port Nos. 4 to 7 (CHs 4 to 7) exceeded 1,000℃ according to Fig. 4. Next, the maximum burning temperature was set at 500℃. Measured temperatures almost never reached 1,000℃. Solubility measured by Testing Method 4.4.1.c was 57.3%, 59.0%, and 5.3% for the mean, median, and standard deviation, respectively. Comparing values of the operation without a set maximum temperature, it can be said that higher values (quality) of ash would be produced when the burning of rice husks was conducted under a controlled operation. Since the values of the NaOH method were always higher than those of the Testing Method 4.4.1.c, in the case of Fig. 2, the solubility values of burning without the temperature setting would be lower than the values shown in the case of Testing Method 4.4.1.c. Thus, a controlled operation is very important to improve the quality of ash. Rice husks have been used for energy recovery, especially in Southeast Asia [16]; however, the improvement of ash quality in the operation as discussed here has not yet been considered.

3.2 Establishing the Importance of Curing Time after Burning

After discovering that the solubility of the ash increased after a curing phase under a high temperature, the sink was installed in the boiler (Fig. 2). By taking out two lines of fire grates, approximately 200 L of free space was created to hold ash stock. It is similar to a composting process. For compost, the first phase is the degradation of organic material and the second is the curing phase. During the curing phase, the quality of the compost increases [17]. To increase the quality of rice husk ash, two phases are required if an exothermal reaction, such as burning in a boiler, is taking place (Fig. 5). The first phase is for burning flammable materials such as cellulose, hemi-cellulose, and lignin, and the second phase is for burning nonflammable material, which is carbon. Energy recovery occurs in the first phase.

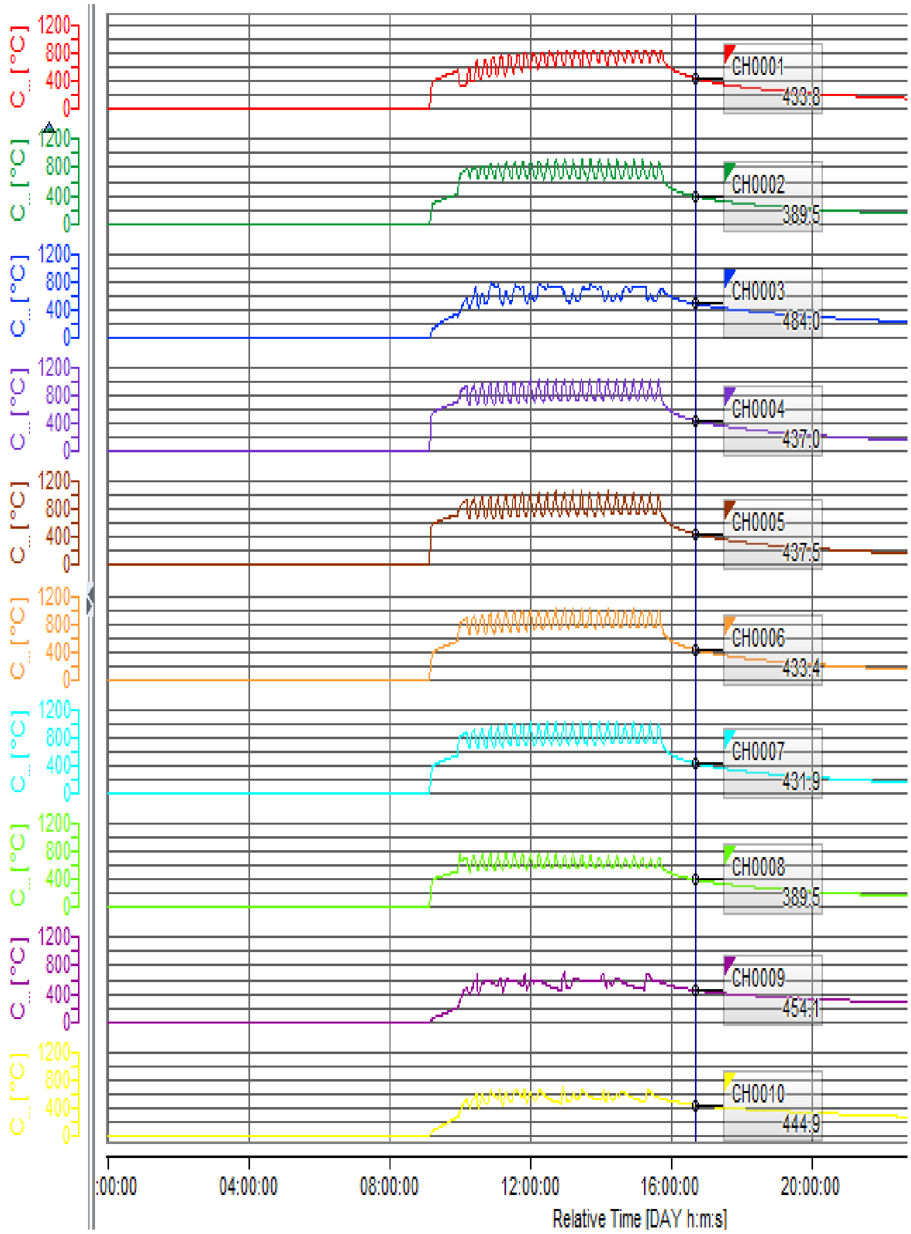

Fig. 4. Temperature distribution of boiler operation set at 600ºC for the maximum temperature

If ash is created only in the first phase, the color of the ash is black and its solubility is low, which means the quality of the ash is not good. In the second phase, akin to the curing phase in composting, the remaining unburned carbon on the surface of ash particles is burned and volatizes into air as CO_2. The ash becomes white at this point. The carbon on the surface of the ash particles can be burned if the carbon is in the proper environment, which would provide an endothermic reaction to the ash. Burning the remaining carbon on the surface of ash particles requires calories, so heat must be provided exogenously. When burning rice husks in an electric furnace, it is quite easy to obtain high solubility (high quality) ash because burning in an electric furnace is an endothermic reaction and ash receives a continuous energy supply. As seen in our study, a temperature of at least 400℃ is required for the second phase. Below 400℃, the remaining carbon on the ash surface could not be volatized as CO_2. For an easy and inexpensive modification of the boiler and a minimal heat loss from ash, the sink was installed in the boiler to provide the second phase for the ash. Ash after the first phase falls into the sink, losing a minimal amount of heat, and automatically proceeds to the second phase. Fig. 6 shows the representative solubility data for 10 consecutive operations. Solubility was measured with the Testing Method 4.4.1.c and the operation conditions were as outlined in Table 2.

The fluctuation of solubility in the graph might be caused mainly by unreliability of the manual sampling method. The samplings at Times 0 to 3 were performed by an operator with a hand shovel by manually digging into the ash pile at the point near temperature measuring port No. 9, as seen in Fig. 1. Samples were taken by digging into the ash pile from the surface, which was at an extremely high temperature; thus, it was difficult to take a sample from the exact same spot each time. Moreover, ash in the sink is a solid, so its qualities are heterogeneously distributed in the pile and only a tiny amount (1 g) is used for the solubility measurement. Although such limitations existed, notable remarks on solubility trends were found. Solubility at Time 3 mostly increased as compared to Time 0. Solubility at Time 0 was higher than the values recorded in the uncontrolled operation. This result was due to the maximum temperature being set and the ash being in the curing phase in the sink. According to the study results, it can be seen that the second phase plays a very important role in improving the quality of the ash. However, other data showed that an extended curing time (the second phase) up to Time 5 did not improve the quality of the ash (Fig. 7).

3.3 Determining the Optimal Operation of the Boiler

By changing factors outlined in Table 2, the best combination for the optimal operation was investigated.

3.3.1 Air flow capacity

The best air flow capacity was investigated by changing the capacity from 10 to 50 Hz, as seen in Table 2, and the solubility at each Hz was evaluated. The results are shown in Fig. 8. The data were representative and showed clearly significant differences.

According to Fig. 8, the 30 Hz air flow capacity was best; thus, 30 Hz was selected for the optimal air flow capacity.

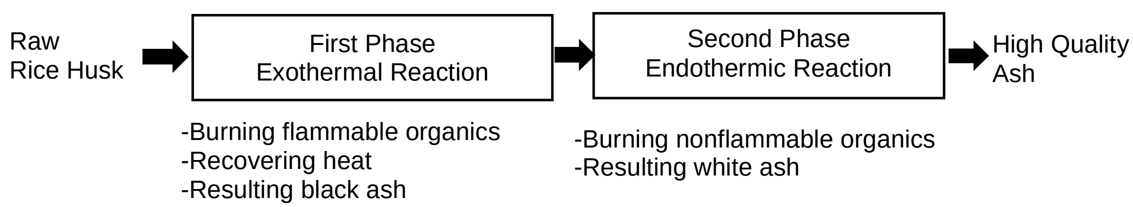

Fig. 5. Two phases for improving quality of ash during boiler burning

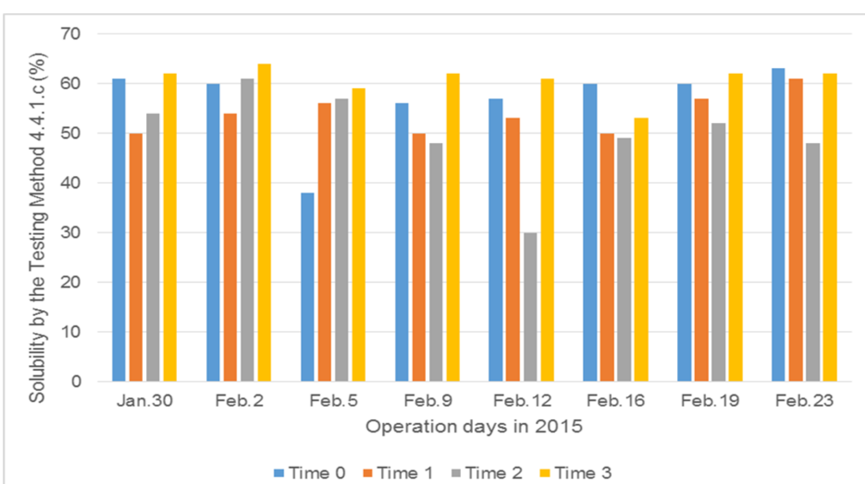

Fig. 6. Ten consecutive operations after installation of the sink

3.3.2 Fire grate operation

Rice husks were fed from the inlet and moved down through the surface of No. 1, 2, and 3 in Fig. 1 by the back and forth movement of the grates. Fire grates were basically operated continuously; however, their movement could be controlled. The grates were operated using a stop mode (intermittent operation) to determine the optimal operational conditions. For this experiment, the fire grate operation detailed in Table 2 was changed in a series of continuous and intermittent (3-3-6, 3-6-8, and 5-5-6) modes. "3-3-6," for example, means that the fire grates moved for 3 s and stopped for 3 s, and the rice husks were retained on the grates for 6 min. The results are included in Table 3. All data of Times 0 to 3 were used to obtain the mean, median, and standard deviations.

According to the table, it can be seen that the 5-5-6 operation was best and the most stable quality (high solubility) can be achieved with this combination.

3.3.3 Temperature control

The factor of temperature control, as seen in Fig. 2, was changed in this experiment. The maximum temperature was not changed but remained at 500℃. Under the AUTO operational condition, the temperature in the inside of the furnace gradually increased to reach the maximum temperature of 500℃ at temperature sampling port No. 8, as seen in Fig. 1 and Table 1. It took time to reach 500℃ under the AUTO condition because the automatic feeder of rice husks often limited the feeding to prevent the temperature from exceeding 500℃. Therefore, the boiler in this experiment was operated without using the AUTO control; rather, the manual setting was used from the starting period until the temperature at No. 8 reached 700ºC. At that point, the temperature control was switched to AUTO. Solubility data were 69%, 70%, and 3.9% for the mean, median, and standard deviation, respectively. According to the results, operation without the AUTO setting at the beginning showed better data than the operation on full AUTO control. The representative temperature profile data of the boiler is shown in Fig. 9. Compared to Fig. 2, it is clear that the temperature distribution inside the furnace should be below 800˚C to produce high quality ash. This conclusion corresponds to the results of Sun, et al. [13]. The representative solubility data is shown in Fig. 10. Solubility consistently increased from Time 0 to Time 3.

Table 2. Boiler operation conditions

Factor	Condition	Explanation
Temperature control	AUTO	Automatic and manual control options are available.
Maximum temperature setting	500˚C	According to result in section 3.1.
Fire grates operation	Continuous	Normal operation. Rice husks are carried forward by the movement of fire grates.
Air flow capacity	30 Hz	It connects directly to the air flow amount sent into the furnace. Values of 10, 20, 30, 40, and 50 Hz can be chosen. The middle of 30 Hz was chosen.

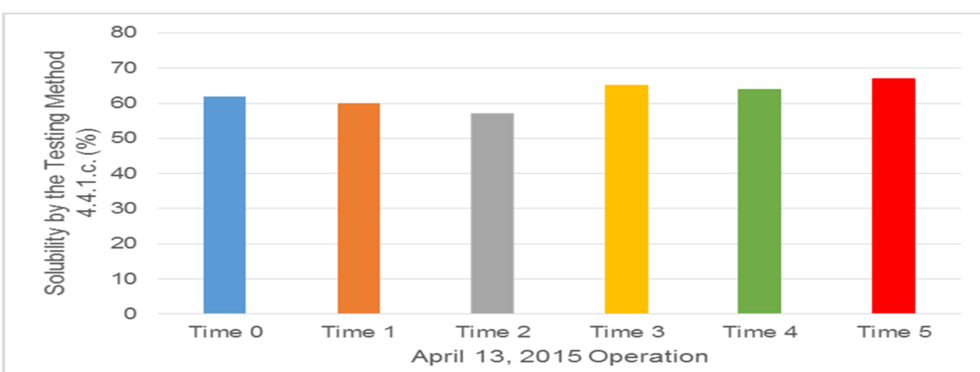

Fig. 7. Five consecutive data for solubility

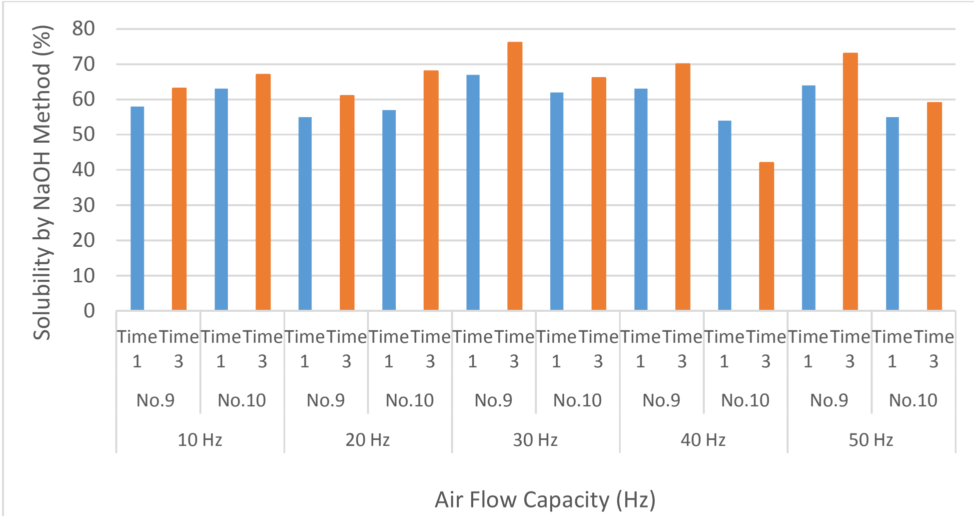

Fig. 8. Solubility measurements based on differences in air flow capacity (Hz)

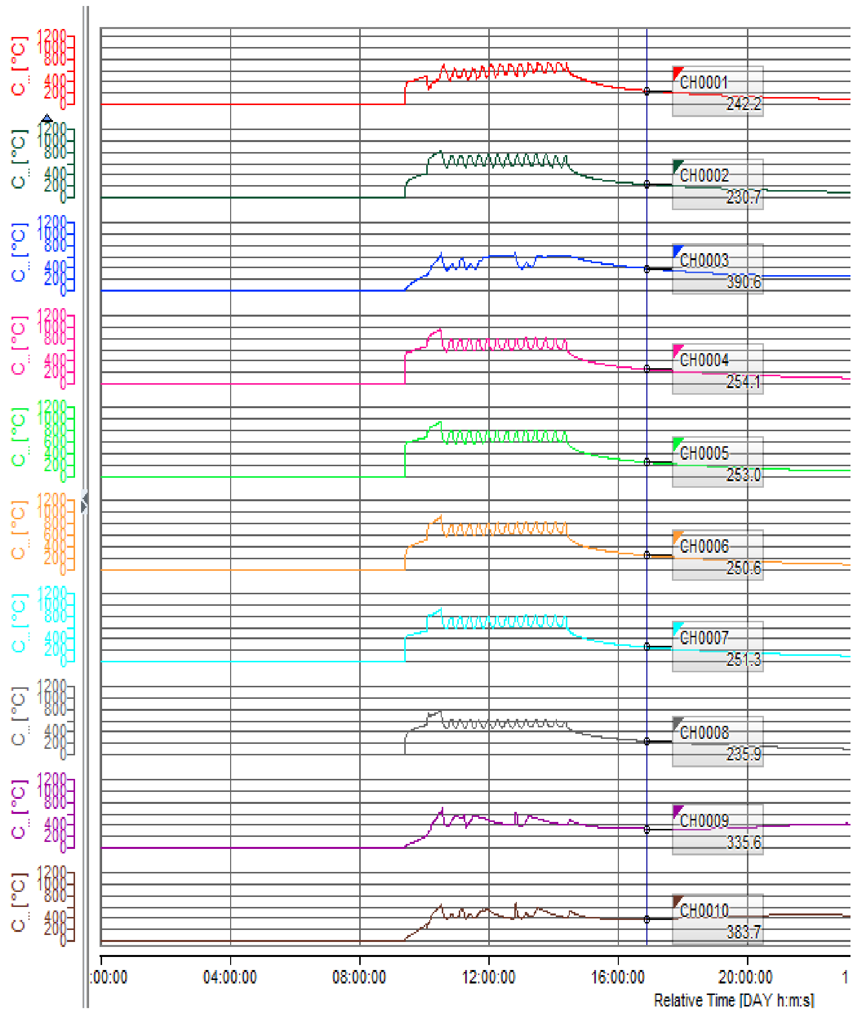

Fig. 9. Temperature distribution of boiler operation without AUTO setting at the beginning

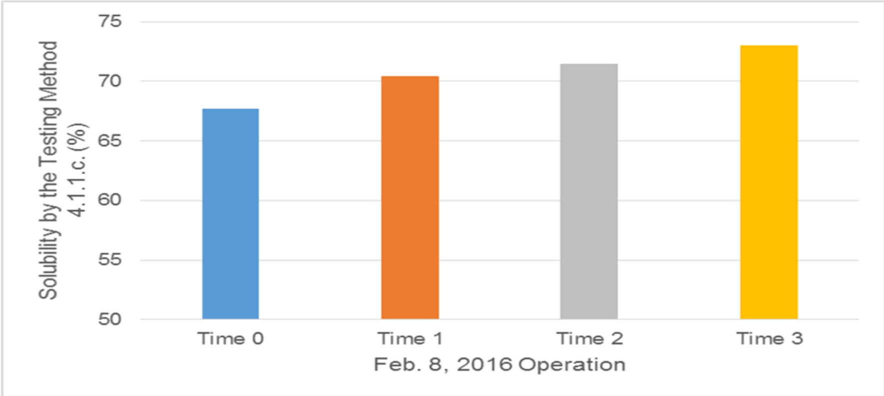

Fig. 10. Operation without AUTO control at the beginning

Table 3. Influence on quality of different fire grate operation settings

Fire grate operation	Solubility by the testing method 4.4.1.c (%)		
	Mean	Median	Standard deviation
Continuous	54	56	7.8
3-3-6	61	60	3.3
3-6-8	56	56	5.0
5-5-6	60	60	2.3

4. CONCLUSIONS

The optimal operation of a boiler to produce high quality or high solubility ash was investigated. From the results, the following conclusions were extracted:

- For boiler burning, or an exothermal reaction, two phases were needed: the exothermal reaction for the first phase and the endothermic reaction for the second phase;
- A maximum temperature setting was necessary; and
- The following specific settings were determined: No AUTO setting at the beginning and AUTO setting engaged after the boiler idling finished, 500ºC as the maximum temperature, 30 Hz for air flow capacity, and 5-5-6 for fire grate movement.

There could be additional factors that influence the operation, resulting in a better performance. Besides just generating heat by burning rice husks, the boiler operation should be more carefully considered to produce better quality ash. Then, the ash would be more valuable and bring larger profits to the local community.

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COMPETING INTERESTS

The authors declare that there is no actual or potential conflict of interest.

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