Improving energy efficiency and developing an air-cooled grate for the downdraft rice husk furnace

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A B S T R A C T

Paddy drying plays an important role in reducing postharvest losses in rice. This process usually involves using a dryer that requires either fossil fuels or renewable energy to heat the drying air, which removes water from the paddy. This research looked into developing a downdraft rice husk furnace used for paddy drying that resulted in an improved air-cooled grate with optimal operation. This optimal operation was used to generate sufficient heat to increase the drying air temperature by 10–15 °C at an air flow rate of 3.5 m³ s⁻¹, attaining an efficiency of 80%. At optimal combustion, the carbon monoxide (CO) concentration generated in the drying air ranged from 25 to 42 ppm. The furnace’s improved air-cooled grate solved the problem of pipe bending or melting during operation. The pipes in the grate reached a maximum temperature of 650 °C and did not bend or melt during operation. In addition to this, using a grate with the rotatable pipes, which allows for easy changing of the surface area that is directly in contact with the firing zone, can prolong its energy’s lifespan, thus reducing maintenance costs. The ultimate result is a more efficient renewable energy solution for paddy drying.

1. Introduction

As global demand for energy is increasing rapidly, it is estimated that the supplies of major fossil fuel resources, such as coal and oil, will be depleted in about three decades [1,2]. Alternatively, biomass, which can provide a renewable source of energy from plants and animals, is becoming more important as a substitute for fossil fuels while, at the same time, having a lower environmental impact [2–4]. It can be used to generate heat and electricity and can contribute to increased economic development without increasing detrimental greenhouse effects to the atmosphere [3,5]. Biomass currently contributes about 10 and 26% of the total primary energy supply of the world and Southeast Asia, respectively [3].

Rice husks, a crop biomass, are produced after the paddy has been dehusked. There are about 0.28 kg of rice husks generated for every kilogram of milled rice produced [6,7]. With 500 million tons of rice produced worldwide annually [8,9], this results in around 100 million tons of rice husks produced as a byproduct of the milling process. With its calorific value of 11–15.3 MJ kg⁻¹, rice husks can be a cheap and renewable source of energy [10,11].

Mechanical paddy drying is an important process in the rice production cycle to reduce postharvest losses. Paddy is usually harvested at grain moisture content (MC) between 24 and 26% (wet basis) and needs to be dried to at least 14% or less within 24 h after harvesting. Incomplete or uneven drying, or any delay in drying, will result in qualitative and quantitative losses [12,13]. Sun-drying is still the predominant method, but the use of mechanical dryers has increased. For instance, in Vietnam’s Mekong River Delta (MRD), about 45% of 23 million tons of paddy are dried annually by mechanical dryers [14]. Drying is an energy-intensive operation with high energy costs for heating the drying air. Burning rice husks in their loose form is the most efficient way of providing heat for drying paddy in situ in addition to being low in cost [6,7]. Also, using rice husks as renewable energy will result in lower greenhouse gas emissions compared to using fossil fuels because there is no net carbon dioxide (CO₂) emission when rice husks are burned [15].

However, using rice husks is technically difficult because of their ash-related problems. According to Beagle [16] and Rajvir et al. [17], rice husks contain about 20% ash, 15–20% fixed carbon, and 65–70% volatile matter. A high content of ash, alkali, and potassium...
The downdraft rice husk furnace (dRHF) has simplicity similar to the inclined-grate furnace because it does not need fans or cyclone chambers. However, it differs from the inclined-grate furnace, which has updraft burning, because the dRHF works with downdraft burning that creates better combustion and higher efficiency. In research at the International Rice Research Institute (IRRI), the dRHF was designed for a small low-temperature in-bin drying system with a 6-ton paddy capacity for a temperature increase of around 3–6 °C and was aimed only at providing supplementary heat to reduce the relative humidity of the drying air. The second version was adapted and tested for heated air dryers with an increase in air temperature of up to 10–15 °C, targeting a 4–6 ton per batch FBD for paddy. The current version was further improved and applied to dryers with a similar capacity in the Philippines, Cambodia, and Indonesia [25,26].

2.2. Experimental set-up

To evaluate the performance factors, including flue gas quality and efficiency, the furnace was installed with a fan and test apparatus (Fig. 2a and 2b) based on the protocol outlined in the Japanese Industrial Standard JIS B 8330-1962 [27]. In this setup, the air flow rate and static pressure could be controlled to simulate that of a target drying system. Fly ash formed during combustion could be mixed with the drying air by the blower causing adverse effects on the drying paddy. This performance was measured through the amount of fly ash collected by the net assembled at the end of the test apparatus (Fig. 2c).

The furnace was designed to match a FBD that has a capacity of 3–4 Mg of paddy per batch. This FBD requires drying air at a static pressure of 20–50 mmHg and air flow rate of 1–1.5 m³ s⁻¹ Mg⁻¹ based on our experiences on paddy drying and also on other citations [13,28].

Fig. 3 shows the characteristics of the fan measured in accordance with the Standard JIS B 8330-1962 [27]. Based on these requirements for the air provided by a small-scale FBD for paddy drying, static pressure and air flow rate were chosen at the point 3.5 m³ s⁻¹ corresponding to a static pressure of 20 mm H₂O. At this point, the static and mechanical efficiencies of the fan were 61 and 75%, respectively.

2.3. Measurement and calculation methods

The dRHF was studied based on its energy capacity, efficiency, and the quality of flue gas. Energy capacity corresponding to air
The efficiency of the dRHF was determined through the drying air efficiency \( \text{Eff}_{\text{dry}} \) using Equation (1) (Eq. (1)), based on the energy balance between the heat generated and the energy or calorific value of the husks burned in the furnace during its operation.

\[
\text{Eff}_{\text{dry}} = \frac{M_{\text{air}} \times Cp \times (T_d - T_a)}{M_f \times LHV}
\]

where \( M_{\text{air}} \) is the air flow rate measured in \( \text{m}^3 \text{s}^{-1} \); \( Cp \) is the specific

![Fig. 2. a). Installation scheme for the dRHF, blower, and test duct for the experiment. b). dRHF experiment set-up at IRRI.](image)

![Fig. 3. Characteristics of the dryer fan used in the research.](image)
Heat of the dry air measured in kcal kg\(^{-1}\) C\(_0\); \(T_d\) is the temperature of the heated air in the test duct (representing the drying air temperature), \(°C\); \(T_a\) is the ambient air temperature, \(°C\); \(M_f\) is the rice husk consumption rate, kg s\(^{-1}\); and \(LHV\) is the low heat value of the rice husks, kcal kg\(^{-1}\), which was converted from high-heat values, expressed by Eq. (2) [29]:

\[
LHV = HHV - 0.221 \times H - 0.0245 \times M - 0.008 \times Y,
\]

where \(HHV\) is the higher heating value measured by a calorimeter Parr 6100; \(H\) is the percent hydrogen; \(M\) is the percent moisture; and \(Y\) is the percent oxygen.

The quality of flue gas generated from the dRHF was evaluated by measuring the fly ash and carbon monoxide (CO) concentration in the drying air, which consists of a mix of flue gas and ambient air. These parameters of fly ash and CO were measured in the drying air instead of the flue gas because the actual end-product generated by the furnace and the blower is the drying air, which directly affects the paddy, thereby potentially endangering human health. Furthermore, the CO amount is an indicator of combustion performance such that the higher the CO generated, the lower the furnace efficiency because CO is a result of incomplete combustion.

The CO concentration in the drying air was measured using the gas analyzer EUIK RASI 700 – KIT02 [30].

2.4. Setting up the parameters and statistical methodology

The performance of the dRHF is affected by the drying air flow rate generated by the fan against the counter pressure of the test duct, rice husk material (moisture content) and its feeding rate, and the secondary air for combustion. For this study, the air flow rate for drying was controlled and set to 3.5 m\(^3\) s\(^{-1}\) and at 20 mmH\(_2\)O as already mentioned. The research variables were HFR, which is measured by its mass and controlled by the feeding frequency, and SAR. Secondary air for combustion was provided through a tube connecting the drying fan outlet to the combustion chamber, which supplies a small portion of hot air (Fig. 4a). This hot air turns back into the furnace and burns the CO generated during the main combustion process. The flow rate was controlled by a valve to adjust the amount of secondary air recycled from the fan (Fig. 4b).

Table 1 shows the ranges of variables or input parameters. The central level (0) was identified based on the specifications of the original furnace design and was extended to two sides (+1 and –1) with the gradients of 3 and 0.025 for HFR and SAR, respectively, to investigate the corresponding changes in the performance of the dRHF.

The rice husks used in the experiments came from the same batch sourced from the IRRI rice mill. Rice husk and drying air parameters, which were measured in test duct assumed as drying chamber, were obtained using the measurements or calculations in Table 2. It also used the measurements and conversion factors reported in Seveda et al. [2] and The Engineering Toolbox [31].

### Table 1

Ranges of researched variables.

<table>
<thead>
<tr>
<th>Level</th>
<th>HFR (kg h(^{-1}))</th>
<th>SAR (m(^3) s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1</td>
<td>20</td>
<td>0.05</td>
</tr>
<tr>
<td>0</td>
<td>17</td>
<td>0.025</td>
</tr>
<tr>
<td>–1</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>Gradient</td>
<td>±3</td>
<td>±0.025</td>
</tr>
</tbody>
</table>

### Table 2

Parameters of rice husk and drying air.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drying air flow rate</td>
<td>m(^3) s(^{-1})</td>
<td>3.5 (0.05)</td>
<td>Measured in the test duct assumed as drying chamber</td>
</tr>
<tr>
<td>Specific volume of air</td>
<td>m(^3) kg(^{-1})</td>
<td>0.89</td>
<td>Calculated based on Psychometry</td>
</tr>
<tr>
<td>Specific heat</td>
<td>Kcal kg(^{-1}) °C(^{-1})</td>
<td>0.24</td>
<td>Calculated based on Engineering Toolbox</td>
</tr>
<tr>
<td>HHV of rice husk</td>
<td>MJ kg(^{-1})</td>
<td>14.8 (0.52)</td>
<td>Measured by calorimeter Parr 6100</td>
</tr>
<tr>
<td>LHV of rice husk</td>
<td>Kcal kg(^{-1})</td>
<td>13.3 (0.52)</td>
<td>Calculated based on Eq. (2)</td>
</tr>
</tbody>
</table>

Value in parenthesis is standard deviation.
Table 3

Effdry at different rice HFR and SAR.

<table>
<thead>
<tr>
<th>SAR m³ s⁻¹</th>
<th>HFR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14 kg h⁻¹</td>
</tr>
<tr>
<td>0</td>
<td>70.3 (2.19)</td>
</tr>
<tr>
<td>0.025</td>
<td>75.4 (2.10)</td>
</tr>
<tr>
<td>0.05</td>
<td>77.1 (3.82)</td>
</tr>
</tbody>
</table>

Value in parenthesis is standard deviation.

The experiments were conducted with three replications for each treatment. Data were analysed using two-factor Analysis of Variance (ANOVA) in Excel software. Multiple correlations of the researched factors were analysed using MATLAB software.

3. Results

3.1. Performance of the dRHF

The increase in drying air temperature by the heat generated from the dRHF reflects its energy capacity corresponding to the identified air flow rate (3.5 m³ s⁻¹). Fig. 5a, b, and c show the ambient and drying air temperatures at different HFRs of 14, 17, and 20 kg h⁻¹, respectively. Drying air temperature increased on the average by 10, 15, and 18 °C corresponding to the HFR from lower to higher values. HFR at 17 kg h⁻¹ resulted in a husk layer thickness of 95 (±3) mm on the grate. This setting generated a more stable drying temperature than the other HFRs as it generated proper combustion in the dRHF.

Effdry reflects the energy efficiency of the dRHF. Table 3 shows that Effdry ranged from 58 to 82.8% resulting from the tests at different HFR and SAR. These data were analysed using two-factor ANOVA in Excel software (Table 4).

As shown in Table 4, the P-value of rows is 0.03, lower than 0.05, meaning that there is a significant difference in average Effdry between different SARs. The P-value of columns is 0.71 > 0.05, so the average Effdry is not significantly different between the different HFRs. On the other hand, at the furnace’s feeding rate of 14 kg h⁻¹ with different SARs, the Effdry was almost the same. The reason for this is that, for a lower feeding rate while using the same furnace and fan at an air flow rate of 3.5 m³ s⁻¹, there is enough air to burn the CO in the flue gas effectively even without secondary air. For the higher feeding rates of 17 and 20 kg h⁻¹, Effdry was significantly different with and without secondary air at 60 and 80%, respectively (Table 4). The correlation of HFR and SAR to Effdry resulted in a regression model with a regression coefficient of 95.5% Eq. (3):

\[
\text{Effdry} = 1.79 - 240.4 \times \text{SAR} + 9.48 \times \text{HFR} + 60 \times \text{SAR} \times \text{HFR} - 8926 \times \text{SAR}^2 - 0.337 \times \text{HFR}^2,
\]

where Effdry is the drying air efficiency; SAR is the secondary air ratio; and HFR is the husk feeding rate. This correlation is illustrated in Fig. 6. The optimised Effdry was 80% at the feeding rate of 15–20 kg h⁻¹ and SAR of 0.035–0.05 m³ s⁻¹.

Fly ash and CO were measured in the drying air consisting of a mix of flue gas and ambient air corresponding to the optimised set of HFR and SAR at 17 kg h⁻¹ and 0.04 m³ s⁻¹, respectively. There was no significant fly ash detected during the 9-h operation of the dRHF.

Table 4

ANOVA of Effdry with different rice HFR and SAR.

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P-value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rows (secondary airflow rates)</td>
<td>456.4</td>
<td>2</td>
<td>228</td>
<td>9.01</td>
<td>0.032*</td>
</tr>
<tr>
<td>Columns (feeding rates)</td>
<td>18.79</td>
<td>2</td>
<td>9.39</td>
<td>0.371</td>
<td>0.711мм</td>
</tr>
<tr>
<td>Error</td>
<td>101.3</td>
<td>4</td>
<td>25.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>578.6</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*significant at 5% level and мм not significant at 5% level.
3.2. Development of air-cooled grate for dRHF

Based on our assessments in the Philippines in 2014, there were more than 50 IRRI-dRHF units being used for paddy drying, which illustrates a good market potential for commercialising this furnace as a clean bioenergy solution. The only constraint to commercialisation, so far, has been the low durability of its grate. Based on the downdraft principle, the dRHF grate is exposed to extremely high temperatures and is prone to bending (Fig. 8) after a relatively short operation time of less than 200 h.

Based on the principle of cooling down the grate to prevent it from bending and melting, we developed a solution called “air-cooled fire grate” for the dRHF. Fig. 9a shows the schematic principle of the operation of the dRHF with the air-cooled grate while Fig. 9b shows this improved grate after a 200-h operation. The air-cooled fire grate includes 19 separate pipes that are rotatable inside the holes of the supporting furnace walls. Each pipe has rows of holes inside the combustion chamber to allow the cool ambient air from outside of the furnace to be sucked in by the under pressure created by the dryer’s blower. This outside air cools the pipes, which are in contact with the burning husks. The air sucked in through the pipes serves as a secondary air required for clean combustion, which also contains the thermal energy transferred from the grate’s pipes.

The temperatures of the 19 pipes measured during combustion are shown in Fig. 10. Only three pipes had the maximum temperature of 650 °C while the other pipes were less than 500 °C. At these temperature thresholds, the rotatable pipes of the grate did not bend or melt during operation (Fig. 9b), which resulted in the dRHF’s increased life span. The older version of the grate had a temperature ranging from 800 to 1000 °C, which caused it to bend down during operation, hence a short life span of only about 200 h. While total life span has not yet been evaluated, the air-cooled grate can work beyond 300 h.

4. Discussion

Basically, a suitable rice husk furnace is chosen for a drying system based on its efficiency, quality of flue gas (free of fly ash, low CO content), heat capacity, nature of operation (manual or automatic), investment costs, labor requirements, and energy costs. Small-scale rice husk furnaces that are widely used for paddy drying typically have inclined grates with updraft firing, which have a drying-air efficiency of 50 to 60% according to Nguyen-Van-Xuan et al. [22] and also based on our assessments in the Philippines. The improved dRHF studied here can attain a much higher efficiency of 60–80%, depending on the HFR and SAR values. The baffles (Fig. 2a) filter the fly ash formed during combustion mixed in the drying air. Therefore, a negligible amount of fly ash was detected during the experiment. Given this advantage, clean flue gas of this combustion system can be used directly to heat up airflow for drying paddy that still needs to be dehusked at milling stage. Direct heating obviously has lower operation costs and generates higher efficiency than indirect heating with heat exchangers.

The dRHF under study can attain a temperature increase of 10–15 °C above the ambient air temperature at the air flow rate of 3.5 m³ s⁻¹ required for a flatbed dryer with 3–3.5 Mg capacity. For instance, in the tropical countries with ambient air ranging from 25 to 35 °C depending on the season (wet or dry), the dRHF can provide the required heat to increase the ambient air temperature to more than 40 °C, meeting the requirement for paddy drying. To avoid the danger of overheating the dried product (higher than 44 °C drying air temperature), the temperature can be controlled and kept constant by adjusting the HFR. This is another advantage of the dRHF because its feeding rate is controlled automatically by an electronically-controlled ram.

Secondary air affects combustion efficiency and cleanliness. This research showed that the optimised secondary air for combustion ranged from 0.035 to 0.05 m³ s⁻¹ corresponding to the husk feeding and drying air flow rates. The excess air coefficient at this optimised point was 2.7 (±0.18), in agreement with those mentioned by Braunbeck [23] and also close to the range of excess air ratio revealed in other research [17,22,32].

CO is an important component in flue gas not only reflecting the combustion performance but also adversely affecting human health [33]. On average, exposures at 100 ppm of CO or higher are considered dangerous to human health [34]. In the United States, the CO limits long-term workplace exposure levels to less than 50 ppm averaged over an 8–h period [35]. At optimal combustion using the dRHF in this research, the amount of CO generated ranged from 25 to 42 ppm, lower than the threshold of the US standard.

Rice husks used for energy production through combustion usually cause major problems such as agglomeration, fouling, and bending of the furnace’s components at a low temperature of about 800 °C [6,20]. The improved grate with air-cooled firing solution...
overcame this barrier. The temperature of the pipes constituting the grate reached a maximum of 650 °C compared to the 800–1000 °C of uncooled grates. In addition to this advantage, the grate consisting of the rotatable pipes allows adjustment of the surface area in contact with the firing zone. In case these pipes are damaged during long-term use, they can easily be replaced individually with much lower cost than when replacing the whole grate in older furnace models.

Fig. 9. a). Principle of dRHF’s grate with air cooling. b). Improved grate after 100 h of operation with no bending and limited wear.
5. Conclusions

The downdraft furnace principle has good potential to overcome the problems of existing small-scale rice husk furnaces, i.e., high labor requirements, uneven temperatures, low energy efficiency, and high levels of pollution. Here, researchers developed a downdraft rice husk furnace for paddy drying and then made recommendations for its optimal operation. An improved grate was also developed. Optimal operation with husk feeding and secondary air flow rates of 15–20 kg h⁻¹ and 0.035–0.05 m³ s⁻¹, respectively, corresponding to the excess air ratio of 2.7 (±0.18), generated the required temperature increase of 10–15 °C for the 3.5 m³ s⁻¹ of the drying air with an efficiency of 80%. At optimal combustion, the CO concentration generated in the drying air ranged from 25 to 50 ppm, way below the U.S. limits. The improved air-cooled grate of the dRHF solved the problem of grate bending. The pipes constituting the dRHF’s grate reached a maximum temperature of 650 °C compared to the 800–1000 °C temperature of uncooled grates, thus, they did not melt during operation. In addition to this advantage, the new grate, consisting of rotatable pipes, allowed easy changing of the surface area that comes into contact with firing zone to prolong its life span and reduce maintenance costs. Thus, an improved and efficient renewable energy solution for paddy drying was created.

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