PILOT-SCALE FLUIDIZED BED DRYING SYSTEM FOR COMPLETE DRYING OF PADDY

Reagan J. Pontawe, Nestor T. Asuncion, Roselyn B. Villacorte and Romualdo C. Martinez
PILOT-SCALE FLUIDIZED BED DRYING SYSTEM FOR COMPLETE DRYING OF PADDY

Reagan J. Pontawe, Nestor T. Asuncion, Roselyn B. Villacorte and Romualdo C. Martinez
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>1</td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Objectives</td>
<td>3</td>
</tr>
<tr>
<td>Review of Literature</td>
<td>3</td>
</tr>
<tr>
<td>Conceptual Framework</td>
<td>5</td>
</tr>
<tr>
<td>Methodology</td>
<td>7</td>
</tr>
<tr>
<td>Results and Discussion</td>
<td>13</td>
</tr>
<tr>
<td>The fully-automated pilot-scale fluidized bed dryer</td>
<td>13</td>
</tr>
<tr>
<td>Drying rate if paddy on the fluidized bed drying system</td>
<td>14</td>
</tr>
<tr>
<td>Effects of drying temperature on the drying rate of paddy</td>
<td>15</td>
</tr>
<tr>
<td>Effects of the residence period on the drying rate of paddy</td>
<td>16</td>
</tr>
<tr>
<td>Energy requirement</td>
<td>17</td>
</tr>
<tr>
<td>Drying cost analysis</td>
<td>19</td>
</tr>
<tr>
<td>Head Rice Yield (HRY) of dried paddy</td>
<td>20</td>
</tr>
<tr>
<td>Sensory analysis</td>
<td>21</td>
</tr>
<tr>
<td>Conclusion and Recommendations</td>
<td>22</td>
</tr>
<tr>
<td>References</td>
<td>23</td>
</tr>
</tbody>
</table>
ABSTRACT

Fully-automated pilot-scale fluidized bed drying system with 500kg/hr capacity was evaluated using high moisture paddy. Complete drying of paddy with ≥ 28 % (w.b.) initial moisture content was attained after 2 passes of fluidized-bed drying at 2 min exposure to 70 °C drying temperature and 4.9 m/s superficial air velocity, followed by 60 min ambient air tempering period (30 min without ventilation and 30 min with air ventilation) for a total drying time of 2.07 h. Around 82% of normal mechanical drying time was saved at 70 °C drying temperature. The drying cost was calculated to be P0.63 per kilogram of wet paddy. Specific heat energy consumption was only 2.84 MJ/kg of water removed. The Head Rice Yield recovery of the dried paddy passed the Philippine Agricultural Engineering Standards. Sensory evaluation showed that the color and taste of rice samples dried in the fluidized bed dryer were comparable to air dried paddy. The optimum drying parameters of using fluidized bed dryer is 70 °C drying temperature at 2 min fluidization time, 4.9 m/s superficial air velocity, 10.16 cm grain depth and 60 min ambient air tempering period.

INTRODUCTION

Drying is one way of increasing farmers’ income by reducing quantity and quality losses. It expands farmers’ opportunities, enabling them to store grains and seek better markets without quality deterioration. Drying could be done in several ways, but the most common methods are by directly exposing the grains to sunlight and by using mechanical dryers. In terms of cost, sun drying is cheaper, but it is time-consuming and not feasible during rainy season. Mechanical dryers served the purpose of drying during the wet season. Among the more popular are the flatbed dryers and recirculating batch dryers. These dryers provide good performance though not perfect. The flatbed dryer is simple to operate and maintain, however, it is labor intensive and not manageable when multiple units are operating to attain larger capacity. On the other hand, multiple units of recirculating batch dryers can provide larger drying capacity. Such system is easier to manage compared to multiple units of flatbed dryers. However, drying period is long which takes 8-10 hours per batch and tedious which is not the ideal for handling very high moisture paddy. Wet paddy tends to clump together and clog the dryer (e.g. elevator). This is verified when it contains large amount of impurities. Moreover, high maintenance cost and supervision is needed due to copious moving parts and electric motors using batch-recirculating dryers (Dela Cruz and Pontawe, 2007).

Fluidized bed drying system offers better and faster solution when drying high moisture paddy. Paddy is subjected for short duration to a very high air flow resulting to fluidization of the grain bed. The grains are semi-suspended in air and experience vigorous mixing. This eliminates the problem of grain clumping and results to faster and more uniform drying. The grain bed acquires fluid-like character when fluidized and thus flows more readily (Soponronnarit, 1994, 1995, 1996a, 1996b, 2003).

To this date, there is no commercial paddy drying system that entirely uses fluidized bed dryers for both first and second stage drying. Such system could potentially result to a more compact design. The concept has been initially explored by Siebenmorgen...
(2006) but the study was limited to a laboratory scale set-up. In the 1990s, the group of Dr. Soponronnarit investigated this concept and arrived at a conclusion that such system is not technically feasible from the view point of heating efficiency and grain quality, particularly in terms of head rice yield (HRY). For this reason, their works concentrated on high temperature first stage drying above 100 °C where they reported more efficient performance of fluidized bed system. A number of more recent experimental research works gave indications that too high drying temperature could result to some physico-chemical changes in rice which may not be acceptable (Siebenmorgen, 2006).

Based on the studies cited above, complete drying of high moisture paddy using fluidized bed drying system is feasible. Thus, in 2013 the development of fluidized bed drying system for complete drying of paddy was explored at PHilMech through a laboratory-scale set up with 5 kg/batch capacity (Pontawe et.al., 2013). Primarily the concept of multi-stage batch drying of paddy under fluidized bed conditions was explored. The project team evaluated the laboratory-scale model and established the drying parameters that best suit the operation of a fluidized bed drying system for complete drying of high moisture paddy.

The results suggested that 70oC drying temperatures with 2 minutes fluidization time were suited for the fluidized bed dryer in drying high moisture paddy. Meanwhile, the drying also involves some technical parameters like static pressure (6 in H2O), grain depth (10.16 cm), superficial air velocity (4.9 m/s) and 1 hour ambient air tempering period (30 min without air ventilation and 30 min with air ventilation). The quality of the dried product passed the Philippine Agricultural Engineering Standards for Head Rice Yield recovery. Moreover, sensory evaluation showed that the color and taste of rice dried in fluidized bed dryer were acceptable to consumers.

Therefore, there is an incentive of validating the results to a bigger-scale fluidized bed drying system. Thus, prior to the development of a commercial-scale fluidized bed dryer, a pilot-scale fully-automated dryer was developed to validate the viability of drying wet paddy using fluidized bed dryer system.
OBJECTIVES

General:
To develop a pilot-scale model fluidized bed dryer for high moisture paddy with full-automatic control system.

Specific:
1. To design and fabricate a pilot-scale (500 kg/h capacity) fully automated fluidized bed dryer for drying high moisture paddy;
2. To validate the technical operating conditions for full drying of high moisture paddy;
3. To evaluate the Head Rice Yield recovery and energy consumption of the developed pilot-scale model fluidized bed dryer system; and
4. To determine the drying cost per kilogram of wet paddy dried at fluidized bed drying system.

REVIEW OF LITERATURE

Fluidized bed drying enables rapid paddy drying by utilizing high temperatures (90 to 200 °C) and uniform drying across the drying bed by using high air velocities (2.3 to 4.4 m/s) (Soponronnarit, 1996; Soponronnarit, 1994). Fluidization techniques have been reported to produce increased head rice yields (HRYs) compared to conventional drying methods (Tirawanichakul, 1999).

In the University of Arkansas, the center of excellence in rice research in the United States, Cnossen (2000) and Schluterman (2007) have investigated the role of the glass transition temperature (Tg) during rice drying. Tg is the temperature at which material properties change from a glassy to a rubbery state. They have proposed a hypothesis that incorporates material behavior in these states to explain fissure formation. It was shown that drying at 60°C (above Tg) could occur without reducing HRYs if rice was adequately tempered at the GT before cooling.

Fluidized bed drying studies have shown that with sufficient tempering, HRYs could be maintained or increased using temperatures of 90 to 150 °C to dry 30% initial moisture content (MC) rice to around 18% final MC (Soponronnarit, 1999; Taweerattanapanish, 1999; Wiset, 2001). Other research has cited the effects of fluidized bed drying on pasting properties (Wiset, 2001) and starch gelatinization (Inprasit, 2001), but changes in these functional properties warrant more study. Furthermore, little research has been done on the effects of high-temperature drying on rice with IMCs less than 20%.

In the University of Arkansas, Siebenmorgen (2006) used a pilot-scale air-impingement oven to simulate fluidized bed conditions. The oven was capable of maintaining temperatures up to 260°C. An air velocity of around 3 to 4 m/s was used, which fully fluidized rice within enclosed-screen drying trays. Paddy with initial moisture content of 22% were dried in the air-impingement oven to 15% and 13% MC using air at 60, 90, 120
and 150 °C. After drying samples were tempered at either the GT or 60°C for durations ranging from 0 to 120 min.

Results showed that tempering for 60 min was typically necessary to attain the maximum HRY for each drying treatment. The HRY values for 60- and 120-min tempering durations were generally not significantly different. The HRYs were greater when drying to 15% MC than to 13% MC. Tempering at the GT also produced greater HRYs than tempering at 60 °C. The highest HRYs, with no functionality degradation, were achieved by drying to 15 % MC using 120 to 150°C air and tempering at the GT. It was possible to dry to 13 % MC in one drying pass using 150°C air with tempering at the GT for 120 min with no significant HRYR, but some starch modification occurred.

Significant changes in rice quality, including decreased peak and final viscosity, occurred when drying at 120 to 150 °C and tempering at the GT. All quality parameters were maintained when drying air temperatures did not exceed 90 °C, MC after one drying pass was not less than 15 %, and rice was tempered at the GT for at least 60 min. Tempering at temperatures lower than GT, however, may risk HRY reduction, as explained by glass transition hypothesis.

A follow up study by Siebenmorgen (2016) used a pilot-scale, fluidized bed drier to investigate the effects of various drying air temperatures and incoming rice MCs on various rice quality parameters, including the amount of MC reduction per pass, grain tempering and milling quality. Milling quality data from these tests were also plotted onto the state diagram in an attempt to understand the limits of high temperature drying on the various rice quality parameters. Results of the study showed that high temperature fluidized bed drying of up to 150 °C at harvest moisture contents below 22% is feasible without substantial reductions in milling quality as long as the MC reduction does not exceed 4 to 5 percentage points.

In the University of New South Wales in Australia, Wiset (2004) studied the effects of high temperature drying using fluidized bed dryer on physico-chemical properties of rice. Three varieties were dried from high initial moisture content of about 27 % down to 13 to 14 % using a two stage drying system. A fluidized bed dryer reduced the moisture content down to 18 %. Drying experiments were carried out at 100, 125 and 150 °C. Further moisture content reduction down to 14 % was achieved by shade drying. As a result of these treatments, head rice yield increased proportionally with the drying temperature. In contrast to that, the yellowness, measured by colorimeter in terms of b-value, showed an opposite trend. Starch characteristics were studied by Rapid Visco Analyzer (RVA), x-ray diffraction and differential scanning calorimetry (DSC).

Results showed that pasting properties were affected by the drying temperature. The peak viscosity and break down were decreasing with the increase of drying temperature in all varieties while the set back values were increasing in Langi and Amaroo only. All starch samples displayed the typical A type x-ray diffraction pattern. The apparent crystallinity determined by x-ray diffraction was reduced with increasing drying temperature. The gelatinization peak shifted to higher temperature while the endothermic enthalpy of gelatinization decreased with increasing drying temperature.
Also in the University of New South Wales, Sunthonvit (2004) studied the effects of high temperature drying on the flavor components in Thai jasmine rice variety. Paddy samples were dried using a two-stage drying process, involving a fluidized bed at high temperature, followed by ambient air drying. Three drying temperatures; 100 °C, 125 °C, and 150 °C were studied. Volatile compounds were extracted and analysed.

A total of 94 volatile compounds were identified. These include 21 alcohols, 19 aldehydes, 17 acids, 14 ketones, 9 heterocyclic compounds, 8 hydrocarbons, and 6 miscellaneous compounds. 2-acetyl-1-pyrroline, a major constituent of volatiles in fragrant rice was identified and tended to increase in concentration with increasing drying temperature. The three different drying temperatures using fluidized bed dryer were found to have an effect on the flavor profile of Thai jasmine rice. The increase in drying temperature contributed to the formation of new compounds, as well as the loss of other desirable volatiles. Thus, the three different drying temperatures were found to have an effect on the flavor profile of Thai jasmine rice.

Based on the studies cited above, there are indications that complete drying of high moisture paddy using fluidized bed system is possible. However, further investigation is needed in order to fully establish whether such system is feasible in terms of drying efficiency and grain quality.

CONCEPTUAL FRAMEWORK

The conceptual framework of the project is illustrated in Figure 1. It started with the review of recommendations from previous studies of gaps and constraints concerning with the existing mechanical dryers. Popular mechanical dryers (e.g. flatbed and recirculating batch-type) are not suitable in handling high moisture paddy due to clogging of chaff and impurities on the bucket elevators of the dryer. Another issue is the long drying time and small capacity of existing mechanical dryers (e.g. flatbed dryers). This constraint highly contributes to quality deterioration of paddy, specifically during wet season. Therefore, the major challenge on the part of the engineers is to develop a dryer for handling high moisture paddy with faster drying time and large capacity that can cater voluminous wet paddy during wet harvest season.

To address the gaps, the design and development of fluidized bed drying system was used as science interventions. The calculations of airflow rates, temperature needed in the fluidized bed chamber and the ambient air tempering period was critical in in dealing with the stated problem. Thus, the laboratory-scale fluidized bed drying system was developed wherein technical drying parameters were established. Consequently, the project proceeded on the validations of the results to a pilot-scale fully-automated model (500 kg/h) fluidized bed drying system. With this study, the expected output was an efficient pilot-scale model fluidized bed drying system with a capacity of 500 kg/h and establishment of the optimum drying parameters that can then be used in the development of commercial-scale (1ton/h) fluidized bed drying system for complete drying of high moisture paddy.
### Target Goal
- Commercial-Scale Fluidized Bed Dryer for Paddy

### Expected Outputs and Outcomes
- A full-automated fluidized bed dryer with 500 kg/h capacity
- Optimum drying parameters using fluidized bed dryer
- Acceptable quality and HRY recovery of the dried paddy
- Acceptable drying cost of using fluidized bed drying system

### S and T Interventions
- Design and evaluation of a pilot-scale fluidized bed drying system.
- Validation of the established drying parameters (e.g. airflow, temperature, etc.) in the laboratory-scale drying experiments.
- Calculations of temperature, airflow requirements and grain bed depth during short fluidization time and determine the tempering period.

### 2nd Generation Needs
- Efficient mechanical drying technology with low energy requirement
- User-friendly and eco-friendly technology

### Gaps and Constraints
- Long drying time
- High drying cost
- Clogging of chaff and impurities using the existing recirculating dryers
- Low capacity of existing flatbed dryers for paddy
- Problems during inclement weather conditions

### Gains from previous program or projects
- No available drying system that entirely uses fluidized bed dryer for first and second stage drying.
- Fluidized bed drying system offers better solution when drying high moisture paddy. It resulted to a faster and more uniform drying compared to flat-bed and recirculating batch-type dryers.
- Too high drying temperature could result to some physico-chemical changes in rice which may not be acceptable.
- The development of a laboratory-scale fluidized bed dryer established the technical parameters of using fluidized bed drying for high moisture paddy.

---

*Figure 1. Conceptual framework of the project*
METHODOLOGY

Design of the pilot-scale fluidized bed dryer

The major parts of the pilot-scale model are shown in Figure 2.

Figure 2. Component parts of the pilot-scale fluidized bed dryer

The pilot-scale fluidized bed dryer set-up was designed for a complete drying of high moisture paddy. The technical parameters (e.g. temperature, air velocity, etc.) established in the laboratory-scale set-up were used in designing the pilot-scale model.

The pilot-scale model is a continuous flow fully-automated fluidized bed drying system capable of drying 500 kilogram per hour of high moisture paddy. The pilot-scale model is comprised of automatic control system, heating system assembly, drying chamber assembly, tempering assembly, conveyor system assembly and the dust collector system assembly. The effective volume space occupied by the pilot-scale model dryer is 4.9m x 4.67m x 4.5m. The effective drying area of the fluidized bed dryer is 1.2 m x 0.25m.

The tempering bin assembly has two stages: ambient air without ventilation and with air ventilation. The dimension of each tempering bin was 1.5m x 1.0m. Tempering bin B was provided by 0.75 Hp blower to immediately supply ambient air ventilation effect to the grain during the second stage of tempering. During unloading of the dried paddy, a 1.6 m length screw conveyor powered by a 1 Hp electric motor was installed. The 4 pieces in-line blower (1 Hp each) was coupled by individual variable frequency drive (VFD) to
regulate the frequency (Hz) of the motor. Thus, it is easier to set the fluidization pattern of the paddy during drying period. The heat source of the pilot-scale model is an LPG combined with 2 inches diameter torch to easily stabilize the drying temperature during experiment. The centralized control system of the pilot-scale model was fully automatic for easier operation and debugging during troubleshooting.

Fabrication, installation and debugging

The technical drawing was prepared through the use of autoCAD software at PHilMech. The pilot-scale model was fabricated at the Agricultural Machinery Division fabrication shop of PHilMech. Field testing was done in Nueva Vizcaya Alay-Kapwa Multi-Purpose Cooperative Grains Center (NVAKGC), Solano, Nueva Vizcaya. Prior to the conduct of field drying experiments, the dryer was thoroughly debugged and tested at PHilMech to ensure the functional integrity and reliability during operation.

Locale and Time of the Study

The design and fabrication was executed at AMDD- PHilMech. The development and fabrication stage was done from January to June 2014. Installation and debugging was conducted from July to August 2014. Field drying experiments were conducted from the second week of August up to November 2014 thus, samples used during the experiments are the wet season period harvests.

Conduct of drying experiments

NVAKGC has continuous palay trading operations throughout the year. Thus, samples used in the drying experiments were the daily procurement of the grains center. The variety and initial moisture contents of the paddy used in the drying trials were presented in Table 1.

About 500 kg of fresh paddy with initial moisture content of around ≥28% (wet basis) was used in every trial. A portion of the fresh paddy sample was taken for initial moisture content and purity determination in the laboratory. Also, when the samples were already dried, a 5-kg sample was taken and sealed to the polyethylene bag for final moisture content and quality analysis. All laboratory analyses were done at PHilMech.
Table 1. Variety and conditions of the samples used in the drying trials.

<table>
<thead>
<tr>
<th>Variety</th>
<th>Initial Moisture Content</th>
<th>Grain Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSICRC 238 (Tubigan 21)</td>
<td>28.00 – 35.00 %</td>
<td>Medium</td>
</tr>
<tr>
<td>NSICRC 152 (Tubigan 10)</td>
<td>30.50 – 34.40 %</td>
<td>Long</td>
</tr>
<tr>
<td>NSICRC 222 (Tubigan 18)</td>
<td>28.00 – 33.25 %</td>
<td>Long</td>
</tr>
<tr>
<td>NSIC RC204H (Mestiso 20)</td>
<td>28.90 – 30.37 %</td>
<td>Long</td>
</tr>
<tr>
<td>NSIC RC180H (Mestiso 15)</td>
<td>28.00 – 29.60 %</td>
<td>Medium</td>
</tr>
</tbody>
</table>

To validate the results generated by Pontawe, et.al. (2013) from the laboratory-scale experiments, the drying parameters applied in the laboratory were also executed in the pilot-scale model drying experiments. The drying conditions used in this study are presented in Table 2.

Table 2. Technical parameters used during the drying experiments

<table>
<thead>
<tr>
<th>Technical Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drying temperature</td>
<td>70, 80, 90, 100</td>
<td>°C</td>
</tr>
<tr>
<td>Grain bed depth</td>
<td>10.16</td>
<td>cm</td>
</tr>
<tr>
<td>Static pressure</td>
<td>6</td>
<td>in. H₂O</td>
</tr>
<tr>
<td>Fluidization time</td>
<td>2, 3</td>
<td>minutes</td>
</tr>
<tr>
<td>Tempering time (ambient air without ventilation)</td>
<td>30</td>
<td>minutes</td>
</tr>
<tr>
<td>Tempering time (ambient air with ventilation)</td>
<td>30</td>
<td>minutes</td>
</tr>
</tbody>
</table>

The 1 hour ambient air tempering time (30 min without ventilation and 30 min with ventilation) was used to fully cool down the grains exposed to high velocity air and high temperature drying chamber. Initial trials with longer tempering period resulted to a longer drying time while shorter (e.g. < 30 minutes) resulted to large amounts of broken grains during milling due to under dried paddy conditions. On the other hand, drying temperature lower than 70 °C was not considered, because the desired final moisture content of 14% (wet basis) was not attained after the fourth cycle of drying in the laboratory scale fluidized bed dryer (Pontawe, et.al., 2013). In addition, Martinez (2009) concluded that in recirculating batch dryers, paddy can be dried up to 70 °C without significant reduction in the head rice recovery. Moreover, temperatures above 100 °C were not considered in view of its adverse effects on volatiles and starch properties as reported by Martinez (2009). Furthermore, the grain bed depth 10.16 cm was constant for all of the drying trials since, it was the optimum grain thickness in order that the wet grain to fluidize which was established in the laboratory-scale fluidized bed drying experiments (Pontawe et.al., 2013).
Prior to every start of experiment, the moisture content of sample was determined by air oven method (three 25 g sub-samples dried at 105 °C for 72 hours) and Kett moisture meter analyzer. The drying temperature and fluidization time were also set. Meanwhile, the pilot-scale dryer was turned on and allowed to stabilize at 30-32°C ambient temperature, 57-60% relative humidity, 6 inch H₂O static pressure and 4.9 m/s superficial air velocity (1.47 m3/s).

The material flow diagram of paddy during drying experiments is presented in Figure 3.

![Material Flow Diagram](image)

Figure 3. Material flow diagram of the pilot-scale model during drying experiments

The drying process involves loading of a 500 kg high moisture paddy sample (≥28%, wet basis) in the loading bin (1) and conveyed through the venturi-type conveyor (2) to the hopper of the fluidized dryer. The feeding was continuous at a constant feed rate of 17 kg/min inside the drying chamber (3) with hot air for 2 minutes. The sample is then conveyed thru venturi-type conveyor (4) into the tempering bin A (5) for 30 minutes which allows the sample to temper at ambient air conditions without air ventilation. Then immediately air cooling (6) of the samples for 30 minutes followed. Samples were drawn from tempering bin A to tempering bin B by gravitational method. Tempering bin B was provided with a fan for forced air cooling at deep bed cooling (approximately 8 inches grain depth) prior to the next exposure (7) to fluidized bed drying chamber. Complete drying was attained after 2 drying passes with specified drying temperatures and
fluidization time. Dried product was discharged (8) through the screw conveyor powered by a combination of 1 Hp electric motor and 1:60 ratio speed reducer.

Dried samples were brought to PHilMech for laboratory milling analyses following the PAES standards for milled rice quality evaluation. Likewise selected dried samples with the highest milling recovery were sent to CLSU for the consumer’s acceptability tests.

**Conduct of sensory evaluation**

Fifty (50) respondents were randomly selected with 50:50 gender distribution. The age ranged from 16 to 50 years old with a skew towards the middle age consumers. Each sample was steamed at the same degree of heat and level of water. The cooked samples were then served and replicated at 500 grams each with maintained temperature at 65-70°C. The sample that was not consumed within 3 hours after steaming was considered stale and was not used in the evaluation. The respondents evaluated the samples using blind sequential monadic taste test approach. They were given water before tasting the samples to clean their palates and neutralize their taste buds. Data collection was done with structured questionnaire containing both open-ended and hedonic scale questions. Using one-on-one interview, respondents were asked for feedbacks regarding the taste, color, aroma and mouth-feel of the samples.

The analysis for the sensory evaluation results includes key performance indicators (KPI) of the test samples like the overall liking, aroma, taste, color and mouth-feel. A 9 point hedonic scale was used. Duncan Multiple Range Test (DMRT) was used in the comparison among means.

**Drying cost calculation**

The drying cost (P/kg) was calculated following the equation 1. Direct costs like power, labor and the cost of LPG with respect to time and capacity of the pilot-scale were imputed in the calculations. Investment costs like the shed and the cost of the unit will be considered in future studies of the commercial-scale model.

\[
\text{Drying Cost} = \frac{(\text{Fixed Cost} + \text{Variable Cost})}{\text{Capacity}} \quad \text{ (equation 1)}
\]

where:
- FC = Repair cost + Taxes
- VC = Salary + Fuel cost + Power cost

**Analysis of data**

The analysis of Normalized Moisture Content \((\text{NMC})\) was expressed in dimensionless Moisture Ratio \((\text{MR})\) to get the average moisture content of the paddy during drying and tempering period. The \(\text{MR}\) was analyzed following the formula:
\[
MR = \frac{M - M_o}{M_o - M_e} \quad \text{(equation 2)}
\]

where:
- \(M_e\) = Moisture content after drying, \%
- \(M_o\) = Initial moisture content, \%

\[
M_e = \left[ \frac{\ln(1 - RH/100)}{-K(T+C)} \right] ^ {1/N}
\]

as Modified Henderson Equation \quad \text{(equation 3)}

where:
- \(RH\) = Relative humidity, \%
- \(T\) = Temperature, oC
- \(-K\) = 0.000041276 (long grain)
- \(C\) = 49.828 (long grain)
- \(N\) = 2.1191 (long grain)

The Head Rice Yield (HRY) values (equation 4) were transformed into dimensionless form so called Head Rice Yield Reduction Ratio (HRYR) values. The highest HRYR value is 1.0 while the lowest is 0.0. An HRYR value near 1 indicates that all the kernels in the samples are broken. An equation of HRYR (equation 5) was developed by Martinez (2003) to describe the reduction in head rice yield based on his study on the batch type-bed drying tests.

\[
HRY = \frac{HR}{HR+B}
\]

\quad \text{(equation 4)}

where \(HR\) is the head rice recovery and \(B\) is the broken rice recovery after milling.

\[
HRYR = \frac{HRY_c - HRY}{HRY_c}
\]

\quad \text{(equation 5)}

where:
- \(HRYR\) = head rice yield reduction ratio, dimensionless
- \(HRY_c\) = head rice yield of control sample, \%
- \(HRY\) = head rice yield of paddy dried to fluidized bed dryer, \%

The total energy required to dry the paddy using the fluidized bed dryer was calculated following the equations below:

\[
E_H = \frac{\text{Total henat energy consumption, MJ}}{\text{Amount of moisture removed, kg}}
\]

\quad \text{(equation 6)}

\[
\text{Total heat energy consumption} = \frac{\rho_s A v_c (T_a - T_{amb})}{1000 \text{ eff}_b}
\]

\quad \text{(equation 7)}

Where:
- \(E_H\) = specific heat energy consumption, MJ/kg
- \(A\) = area of the drying bin, m\(^2\)
The value 1000 converts the energy unit from KJ to MJ. The $Eff_b$ is equal to 0.90.
RESULTS AND DISCUSSION

The fully-automated pilot-scale fluidized bed dryer

The developed fully-automated pilot-scale model of the fluidized bed dryer system is displayed in Figure 4. The heat was supplied by a 50-kg Liquefied Petroleum Gas (LPG) through the 2-inches diameter torch. LPG and fired-torch were used as heat source to attain and stabilize easily the different drying temperature settings (e.g. 70-100°C) during drying experiments. The 4.9 m/s superficial air velocity was being supplied by a 4 high static pressure in-line axial blower. The blower was connected with an individual Variable Frequency Drive (VFD) to regulate the frequency (hz) of the electric motor thus, controlling the air velocity of the blower is easy and manageable.

Figure 4. The fully-automated pilot-scale model fluidized bed dryer

There were two venturi-type conveyor installed in the pilot-scale model. The first one was from the loading bin to the fluidized bed hopper to eliminate grain clogging and choking due to impurities. The second conveyor was from the discharge output of the fluidized bed (drying chamber) to the tempering bin. The conveyor was coupled to a cyclone to control the air velocity that carries the grain. The discharge mechanism from the tempering bin to the loading bin of the fluidized bed dryer was a combination of a 1 HP electric motor and speed reducer. There were shuttering devices present before and after the fluidized bed. This is to regulate the residence time and the thickness of the grains that is entering and discharging from the fluidized bed. All of the electric motors and the VFD were controlled by fully-automated controllers for the safety and easiness during operation.
The optimum technical drying parameters generated using the pilot-scale model fluidized bed dryer is presented in Table 3. The optimum parameters were quantified based on the merit of the quality of the final product, which was the Head Rice Yield recovery and sensory attributes (e.g. color and taste). Drying temperature of 70°C with 2 minutes fluidization time at 6 in. H₂O static pressure, 10.16 cm grain depth, 4.9 m/s superficial air velocity (1.47 m³/s airflow rate) was the optimum drying parameters that resulted to high Head Rice Yield recovery and accepted by the consumers in terms of the color and taste of the milled product.

Table 3. Technical parameters established for the operation of the fluidized bed dryer

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drying temperature (°C)</td>
<td>70</td>
</tr>
<tr>
<td>Airflow rate (m³/s)</td>
<td>1.47 (4.9 m/s)</td>
</tr>
<tr>
<td>Static pressure (inch H₂O)</td>
<td>6</td>
</tr>
<tr>
<td>Grain depth (cm)</td>
<td>10.16</td>
</tr>
<tr>
<td>Fluidization time (minute)</td>
<td>2</td>
</tr>
<tr>
<td>Ambient tempering (minute)</td>
<td>30</td>
</tr>
<tr>
<td>Forced air tempering (minute)</td>
<td>30</td>
</tr>
</tbody>
</table>

Drying rate of paddy on the fluidized bed drying system

Figure 5 shows a typical moisture reduction curve relative to time of paddy dried to pilot-scale model fluidized bed dryer. Wet paddy with 30.95% (wet basis) initial moisture content ($MC$) dried with 70°C drying temperature at 2 min fluidization, 10.16 cm grain depth, 4.9 m/s air velocity and 60 min tempering period was dried after 2 passes (124 min) in the pilot-scale fluidized bed dryer.

![Figure 5. Moisture reduction of paddy dried to fluidized bed dryer at 70°C and 2 min fluidization time with 30.95% (wet basis) initial $MC$ (error bars ±0.38).](image-url)
The reduction of the wet paddy was a ladder-like plot with a very steep decline during each short fluidization period (2 minutes) and relatively small decrease in $MC$ during tempering period. This indicates that the moisture continues to release from the grain up to 5% (wet basis) during tempering time. This phenomenon is due to the effect of the residual heat content acquired by the grain during the short fluidization stage (Thakur and Gupta, 2006). It can also be observed that major portion of the grains’ moisture was released during fluidization period (1st and 2nd passed) until a pseudo-equilibrium in $MC$ during the last tempering period was observed.

**Effects of drying temperature on the drying rate of paddy**

Figure 6 shows the Normalized Moisture Content ($NMC$) of paddy dried in the pilot-scale model fluidized bed dryer with different drying temperatures at 2 minutes fluidization time, 10.16 cm bed depth, 4.9 m/s superficial air velocity and 29.27% (w.b.) average initial MC of the samples.

![Figure 6. Normalized moisture content of paddy dried to fluidized bed dryer at different drying temperatures with 2 minutes fluidization time.](image)

The $NMC$ was expressed in dimensionless Moisture Ratio (kg d.m./kg sample) which represent the average moisture content of the paddy with time given. The study found that with the increase in drying temperature, the drying rate has been found to be increasing and the equilibrium moisture content to be decreasing as what was also observed by Srinivas and Setty (2013) in the drying behavior of binary mixture of solids in batch fluidized bed dryer.
The increase in temperature also increases heat input to the system and hence increases the rate of evaporation of moisture from the moist surface of the grain. Results also showed that the three drying temperatures (70, 80 and 90°C) used, completely dried (≤14%, wet basis) high moisture paddy (≥28%, wet basis) after 124 minutes (2.067 hours) of drying, while the highest (100°C) dried the wet paddy after one pass (62 min). A progressive significant moisture reduction rate until it reached pseudo-equilibrium moisture content (Thakur and Gupta, 2006) was also plotted towards the final tempering period (2nd pass) in the pilot-scale fluidized bed dryer using the four drying temperatures. Nevertheless, the results validated the NMC of the paddy dried during the study of Pontawe, et. al. (2013) in the laboratory-scale fluidized bed dryer using the four drying temperatures (70, 80, 90 and 100°C), 2 min fluidization time, 10.16 cm grain depth, 4.9 m/s superficial air velocity and 60 min tempering period.

The observed variation in the final moisture content of the sample was due to the variety and conditions of the samples used during the trials, nevertheless it was all recorded ≤14% (w.b.). It was also noted during the study that the drying should be stopped sometime earlier than the point when the sample moisture content reaches equilibrium with the drying air condition, because some of the moisture continues to release from the sample due to the effect of residual heat content acquired by the grain. This was observed using 100°C drying temperature. Moreover, the two highest temperatures (90 and 100°C) displayed higher moisture reduction rates during the first stage of fluidization compared to the two lowest (70 and 80°C) drying temperatures. The results confirmed the study of Tirawanichakul, et.al. (2004) that the moisture reduction is independent of an initial moisture content indicating that the main part of moisture content (>25 %, wet basis), existed only on the exterior surface, thus allowing easier water removal without any interference of disordered void spaces inside grain kernel during drying.

Effects of the residence period on the drying rate of paddy

Effect of fluidization time on the pilot-scale model batch-type fluidized bed dryer has been studied at two drying temperatures, 10.16 cm grain bed depth and 4.9 m/s superficial air velocity. Only two fluidization time (2 and 3 minutes) were considered because Pontawe, et.al. (2013) previously concluded in the laboratory-scale fluidized bed drying that lower and upper than these two established fluidization time in combination to 70 and 80°C drying temperatures gave truncated quality on the milling recovery of the dried paddy. Figure 7 displays that variations in the fluidization time have no effect on the drying rates of paddy in drying to the pilot-scale fluidized bed dryer.
However, it is important to highlight that using a higher temperature (80°C) and longer exposure time (3 minutes), the moisture reduction in the first cycle of drying is more pronounced until it reached a pseudo-equilibrium moisture content (14%, wet basis). A similar effect was observed by Srinivas and Setty (2013) that due to the longer exposure of the material to the drying air convective mass transfer of moisture from solids to air increases resulting to an increase in the drying rate. Moreover, the moisture reduction is independent of initial moisture content that during the first stage of drying the moisture content existed on the exterior surface of the grain is easier to remove without any interference of disordered void spaces inside grain kernel during drying (Tirawanichakul, et.al. 2004).

Energy Requirement

Fluidizing is very effective way of maximizing the surface area of drying within a small total space. Rapid mixing of the grains results in nearly homogeneous drying and high heat and mass transfer rates between the air and the grains due to the high air velocity (Thakur and Gupta, 2006). Figure 8 shows the specific heat energy required to dry a kilogram of wet paddy using fluidized bed dryer with 2 min fluidization time at different drying temperatures and variations in the initial moisture contents of the paddy.
Figure 8. Specific heat energy requirement (MJ/kg) of paddy dried using the pilot-scale fluidized bed dryer at different drying temperatures with 2 min fluidization time and 60 min tempering period.

The analysis of the heat energy requirement only involves the paddy when it is being exposed to hot-air. The paddy was further subjected to two-stages tempering period: tempering period with only surrounding air conditions (without air ventilation) and with air ventilation (cooling stage). Thus, during the first stage of tempering period only thermal effects apply, that is, heat is transferred from the grain to the surrounding air and due to this effect; moisture is released from the grain until the grain residual temperature comes in equilibrium with the surrounding environment. During the second stage of tempering, forced air was supplied to facilitate the release of moisture form the grain until the vapor pressure of grain moisture become equal to the vapor pressure of the surrounding air. Therefore, the two-stages of tempering period facilitate removal of considerable amount of moisture without any energy input.

In this study, the calculated specific heat energy consumption of the pilot scale fluidized bed dryer was only 2.84 MJ/kg. The result supports the earlier findings of Pontawe, et. al. (2013) on their experiments using the laboratory-scale fluidized bed dryer set-up. Substantially, it is important to highlight the low energy requirement of the developed pilot-scale fluidized bed dryer. Also, the calculated energy requirement was compared to flatbed mechanical dryer, and was found to be comparable (Flores, 2010). Furthermore, the drying experiments comparing the drying time of the developed pilot-scale fluidized bed dryer and recirculating dryer are presented in Table 4.
Table 4. Drying time comparison of fluidized bed dryer and recirculating dryer.

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Fluidized bed dryer</th>
<th>Recirculating batch dryer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Moisture Content of the paddy (% wet basis)</td>
<td>31.5</td>
<td></td>
</tr>
<tr>
<td>Variety</td>
<td>NSICRC 216</td>
<td></td>
</tr>
<tr>
<td>Drying time (h)</td>
<td>2.07</td>
<td>12</td>
</tr>
<tr>
<td>Final Moisture Content (% wet basis)</td>
<td>14.1</td>
<td>14.5</td>
</tr>
</tbody>
</table>

The drying time of paddy in fluidized bed dryer was 2.07 hours. In the recirculating dryer it was 12 hours. The long drying time for recirculating batch-type dryer includes the down time (around 2 hours) due to clogging of the paddy on the elevator. The results implied 82% reduction on the drying time of wet paddy dried to fluidized bed dryer. On the other hand, the electric power requirement for the pilot-scale model fluidized bed dryer was 21.5 kW-h/batch (2.07 hours drying time) with 2 min fluidization time at 70°C drying temperature and 6 in. H₂O static pressure. With this power requirement, scaling up the pilot-scale into commercial-scale of 1ton per hour capacity would require 25Hp electric motor. However, the high power requirement of the dryer could be compensated by its high capacity. For example, 1ton/h capacity fluidized bed dryer can dry 12 tons of wet paddy for 1 batch (12 hours) of drying operation. Thus, comparing it to flatbed dryer that requires 10Hp electric motor for 1 batch (12 hours) of drying 5 tons of wet paddy (Asuncion, et.al., 2014), fluidized bed drying is an advantage, since 3 flat bed dryers (equivalent to 30Hp) is needed to attain the 12tons capacity per batch of drying (≤ 14%, w.b.) paddy.

Therefore, the versatility of the developed pilot-scale fluidized bed dryer was supported by its low energy requirement connives with the huge reduction on the drying time of wet paddy which can be easily scaled-up for higher drying capacity (1ton/h) for better handling (no grain clumping) of high moisture paddy.

Drying cost analysis

The drying cost per bag of wet paddy dried in the pilot-scale model fluidized bed dryer is presented in Table 5. The drying cost incurred P0.63 to dry a kilogram of wet paddy in the pilot-scale fluidized bed dryer. The costs include the repair and maintenance, depreciation and taxes as part of the fixed costs while variable costs include the salaries of the operator and laborer (loading and unloading only), fuel cost and electricity cost. The operator is only part-time, since the fluidized dryer has a full-automated-control system. Potentially, the drying cost can be lowered further to P0.31/kg (P15.50/bag) when the heat source of the dryer is replaced by a biomass furnace. Thus, the commercial-scale fluidized bed dryer will be heated by a biomass furnace.
Table 5. Drying cost per bag of using fluidized bed dryer

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Cost/Batch</td>
<td>430.52</td>
</tr>
<tr>
<td>Repair and Maintenance (P/batch)</td>
<td>133.33</td>
</tr>
<tr>
<td>Depreciation cost (P/batch)</td>
<td>215.00</td>
</tr>
<tr>
<td>Taxes, licenses, &amp; insurances (P/batch)</td>
<td>82.19</td>
</tr>
<tr>
<td>Variable Cost/Batch</td>
<td>3,329.48</td>
</tr>
<tr>
<td>Salary and wages (P/batch)</td>
<td>500.00</td>
</tr>
<tr>
<td>- salary of operator</td>
<td>175.00a</td>
</tr>
<tr>
<td>- salary of laborer</td>
<td>240.00b</td>
</tr>
<tr>
<td>Fuel Cost (LPG) (P/batch)</td>
<td>2,799.50</td>
</tr>
<tr>
<td>- kg of consumption/batch</td>
<td>50.90</td>
</tr>
<tr>
<td>- cost/kg</td>
<td>55.00</td>
</tr>
<tr>
<td>Power Cost (P/batch)</td>
<td>214.98</td>
</tr>
<tr>
<td>- consumption (kW-hr/batch)</td>
<td>21.50c</td>
</tr>
<tr>
<td>- cost (P/kW-hr)</td>
<td>10d</td>
</tr>
<tr>
<td>Total Operating Cost (P/batch)</td>
<td>3,760.00</td>
</tr>
<tr>
<td>Drying Cost (P/kg)</td>
<td>0.63e</td>
</tr>
<tr>
<td>Drying Cost (₱/kg)</td>
<td>0.31f</td>
</tr>
</tbody>
</table>

* Part-time salary wage of Nueva Vizcaya Alay-Kapwa Multi-purpose Cooperative
* Payment for the loading and unloading only (120 bags)
* Power consumption of the blowers of the fluidized bed dryer and the tempering bin
* Based on Nueva Vizcaya Electric Cooperative power rate (2014)
* Based on the full capacity of 500kg/hr for 12 hours of operation per batch
50 kg is equals to 1 bag
f Potential drying cost when Biomass Furnace will be used as heat source (@ ₱8/bag of rice hull)

Head Rice Yield (HRY) of dried paddy

The Head Rice Yield Reduction Ratio (HRYR) of paddy dried in pilot-scale model fluidized bed dryer with 60 minutes tempering time, 10.16 cm grain depth, 4.9 m/s superficial air velocity relative to different drying temperatures and fluidization time were compared (Figure 9). The values of HRYR ranged from zero (0) to one (1). The value 0.0 denoted no reduction in HRY while 1.0 denoted that all kernels in the sample were broken.
Figure 9. Head rice yield reduction ratio of samples dried in the pilot-scale fluidized bed dryer in relation to the different drying temperatures

It can be seen that an increase in drying temperature and fluidization time resulted in an increase in HRYR value (approaching 1), which indicates that more broken kernels were present in the sample. The results suggested that the lowest drying temperature (70°C) with different fluidization time (2 and 3 min) at 10.16 cm grain depth, 4.9 m/s air velocity and 60 min tempering time has the highest Head Rice Yield Recovery. Nevertheless, although drying temperatures of 90 and 100°C resulted in high moisture reduction rate, there was a decreasing effect on HRY (Islam, et.al., 2003) and exceeding the 5% Philippine Agricultural Engineering Standards (PAES) limits for Brokens. Meanwhile, paddy dried at 70°C temperature, 2 min fluidization time, 10.16 cm grain depth, 4.9 m/s air velocity and 60 min tempering period attained the lowest HRYR and below the PAES limits for Brokens. Thus, samples subjected for sensory evaluation analysis were the samples only dried with 70°C drying temperature at 2 min fluidization period.

**Sensory analysis**

Table 6 presents the mean scores of the sensory evaluation analysis of paddy dried to fluidized bed dryer at 70 oC temperature, 2 min fluidization, 10.16 cm grain depth, 4.9 m/s superficial air velocity and 60 min tempering period compared to air dried (as control). The results showed that there is no significant difference at α = 0.05 between the products dried in the pilot-scale fluidized bed dryer (Product A) and air dried (Product B). This implied that the product A is equally liked in terms of color, aroma, taste and mouth-feel.
Table 6. Mean scores on the color, aroma, taste and mouth-feel of paddy dried in fluidized bed dryer.

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Product</th>
<th>Mean</th>
<th>Mean Std Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over-all liking</td>
<td>A</td>
<td>6.7292a</td>
<td>0.19465</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>6.9167a</td>
<td>0.18792</td>
</tr>
<tr>
<td>Color</td>
<td>A</td>
<td>6.9800a</td>
<td>0.19057</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>7.3400a</td>
<td>0.17982</td>
</tr>
<tr>
<td>Aroma</td>
<td>A</td>
<td>6.5510a</td>
<td>0.17990</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>6.2449a</td>
<td>0.28050</td>
</tr>
<tr>
<td>Taste</td>
<td>A</td>
<td>6.9800a</td>
<td>0.19270</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>6.8800a</td>
<td>0.24014</td>
</tr>
<tr>
<td>Mouth-Feel</td>
<td>A</td>
<td>6.2245a</td>
<td>0.26609</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>6.4286ab</td>
<td>0.24046</td>
</tr>
</tbody>
</table>

Note: Product A= Dried to fluidized bed dryer; Product B= Air dried; Mean with the same script is not significantly different at α =0.05

Considering largely the influence of color and taste in buying preference of consumers to milled rice, the paddy dried to fluidized bed dryer is comparable to air dried.

CONCLUSION AND RECOMMENDATIONS

The developed pilot-scale fully automated fluidized bed dryer system offers better and faster alternative in drying high moisture paddy. The versatility of the developed pilot-scale fluidized bed dryer was supported by its low energy requirement (2.84 MJ/kg), acceptable drying cost (P0.63/kg) connives with substantial reduction on the drying time (82%) that can be easily scaled-up for higher drying capacity (1ton/h) for better handling (no grain clumping) of high moisture paddy. Only the milled product dried to 70°C drying temperature with 2 min fluidization time, 10.16 grain depth, 4.9 m/s superficial air velocity and 60 min tempering period passed the PAES limits for HRY recovery. The major factors that influenced consumer’s preferences in buying milled rice, like color and taste, have no significant differences to air dried paddy.

Furthermore, future work will be optimization of the results in a commercial - scale model with 1 ton/hour input capacity and the validation of P0.31/kg (P15.50/bag) drying cost with the use of multi-fuel biomass fed furnace as heat source of the fully-automated fluidized bed dryer system.
REFERENCES


The Philippine Center for Postharvest Development and Mechanization, known then as the National Postharvest Institute for Research and Extension (NAPHIRE), was created on May 24, 1978 through Presidential Decree 1380 to spearhead the development of the country’s postharvest industry.

As a subsidiary of the National Grains Authority in 1980, the agency’s powers and functions were expanded in line with the conversion of NGA to the National Food Authority.

In 1986, PHilMech moved to its new home at the Central Luzon State University compound in Muñoz, Nueva Ecija.

The agency was transformed from a government corporation into a regular agency through Executive Order 494 in 1992. It was renamed the Bureau of Postharvest Research and Extension (BPRE).

For years now, PHilMech is engaged in both postharvest research, development and extension activities. It has so far developed, extended and commercialized its research and development outputs to various stakeholders in the industry.

With Republic Act 8435 or Agriculture and Fishery Modernization Act (AFMA) of 1997, PHilMech takes the lead in providing more postharvest interventions to empower the agriculture, fishery and livestock sectors.

Pursuant to Executive Order 366 or the government’s rationalization program in November 2009, BPRE became the Philippine Center for Postharvest Development and Mechanization (PHilMech) with twin mandates of postharvest development and mechanization.

**For more information, please contact:**

**Director IV**  
Philippine Center for Postharvest Development and Mechanization  
CLSU Compound, Science City of Muñoz, Nueva Ecija  
Tel. Nos.: (044) 456-0213; 0290; 0282; 0287  
Fax No.: (044) 456-0110  
Website: www.philmech.gov.ph

**PHilMech Liaison Office**  
3rd Floor, ATI Building  
Elliptical Road, Diliman, Quezon City  
Tel. Nos.: (02) 927-4019; 4029  
Fax No.: (02) 926-8159