Rapid Drying of High-Moisture Paddy Using a Pneumatic Dryer with Corrugated-Surface Drying Column

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Abstract. Combination of corrugated-surface drying column and multipass drying concept (first-pass and second-pass drying) was made to increase the performance of a pneumatic dryer for high-moisture paddy. In this study, different characteristics of the drying column, which could be characterized by the ratio between the corrugated-surface length (C) and the total length (L) of the drying column (or C/L), were proposed. The influences of drying temperature (120ºC, 150ºC, and 180ºC) and value of C/L (0, 0.5 and 1.0) on the dryer performance and energy utilization of the drying process were disscussed. The drying column with a higher value of C/L had higher potential for increasing dryer performance. For the first-pass drying, the drying system using the drying column with corrugated surface could reduce the energy consumption by 14% to 44% compared with the drying system using the drying column without corrugated surface. For the second-pass drying, the drying system using the drying column with corrugated surface consumed more energy, however. The moisture reduction of paddy could also be significantly increased after the second-pass drying.

1 Introduction

Because the moisture content of freshly harvested paddy obtained from the field is rather high, it must be reduced to the safe level to avoid the damage of paddy during storage. Drying is a significant step used to reduce the moisture content of freshly harvested paddy in the rice industry. The freshly harvested paddy may be dried in the first stage to rapidly remove surface moisture from the paddy, and it is subsequently dried in the next stage by the slow drying process. The pneumatic dryer is a traditional means that can be adopt as a first-stage dryer to quickly remove surface moisture from a particulate material including paddy. The pneumatic dryer has successfully been used to dry various high-moisture materials [1-6]. For application to paddy, Kaensup *et. al.* [7] and Nimmol *et. al.* [8] used the pneumatic dryer for eleminating surface moisture of paddy. Despite the potential of this dryer is to quickly reduce the moisture content of paddy, increasing the dryer performance by reducing the moisture content of paddy may still possible. Application of surface roughness, which is an effective method for heat transfer augmentation [9,10], on the drying column of the pneumatic dryer is therefore needed to improve the dryer performance. When surface roughness is applied to the pneumatic dryer, the surface area for heat transfer increases and the turbulent flow pattern of drying medium is also promoted, leading to a greater rate of heat and mass transfer.

A corrugated-surface pipe or corrugated pipe is a common form of surface roughness that has been used for heat transfer augmentation in pipe flow. Recently, it was applied as a drying column to the pneumatic dryer during okara drying [6]. The amount of moisture reduction of the okara clearly increased when the corrugated pipe was applied to the drying system. Although pneumatic drying is a rapid-drying process, the moisture content of the drying material is not much removed compared with its initial moisture content, especially for a high-moisture material. This is because the time that the drying material stays in the dryer is very short [6]. To increase the amount of moisture reduction, the time that the drying material spends in the dryer should be extended; thus, the drying material should be dried for more than one drying pass [6,11–13]. With the use of this drying concept, a partially dried material is again fed into the dryer for further drying.

In this study, the pneumatic dryer for high-moisture paddy was modified using a drying column with different corrugated-surface lengths. The concept of multipass drying was also proposed to increase the degree of moisture reduction of paddy. The dryer performance and energy utilization of the drying process of the dryer were evaluated and discussed.

2 Materials and methods

2.1. Experimental setup

Fig. 1 presented a schematic diagram of the pneumatic drying system for high-moisture paddy. It consisted of a stainless-steel drying column with an inner diameter of 50 mm and a total length of 4000 mm. A high-pressure blower (Norvak, model NVT-400, China) was used to supply the air to the drying column. The inlet air was

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heated by the electric heater rated at 18 kW. A temperature controller (Shinko, model JSC-33A, Japan) was used to control the inlet air temperature (measured at point P_1). A globe valve was used to control the inlet air velocity, and a pitot tube that connected to a multifunction measuring device (Testo, model 445, Lenzkirch, Germany) was used to measure the inlet air velocity at point P_1. Measurement of the pressure drop across the drying column, which was the difference in static pressure between points P_2 and P_3, was caried out using a differential pressure meter (Testo, model 510, Lenzkirch, Germany). Feeding of the moist paddy was made at the hopper using a variable-speed belt feeder. Separation of dried paddy from the moist air was performed at a cyclone.

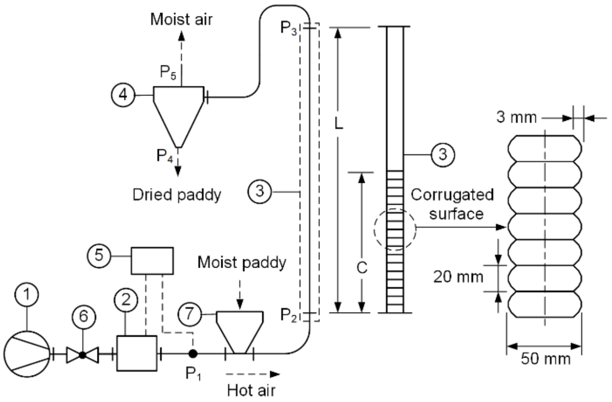

Fig. 1. A schematic diagram of the pneumatic dryer for high-moisture paddy: (1) high-pressure blower, (2) electric heater, (3) drying column, (4) cyclone, (5) temperature controller, (6) globe valve, and (7) hopper.

Different types of the drying column, identified by the ratio between the corrugated-surface length (C) and the total length (L) of the drying column (or C/L), were proposed in this study. The total length of the drying column was the summation of the corrugated-surface length and the smooth-surface length (see Fig. 1). For the drying column with smooth surface, a commercial stainless-steel pipe was used. However, for the drying column with corrugated surface, a commercial stainless-steel pipe was pressed on the external surface, according to the method of Li *et. al.* [9], with a corrugation pitch and a corrugation depth of 20 mm and 3 mm, respectively.

2.2 Materials

Paddy with an initial moisture content of around 30% (d.b.) was used as a test material. The initial moisture content of paddy was prepared by rewetting the paddy and storing it in a refrigerator at 4ºC. To attain thermal equilibrium, the paddy was laid under room condition for 20 min before doing the experiment.

2.3 Methods

After the inlet air velocity and the drying temperature were stabilized at the desired values, the paddy feeding began. After a steady-state condition of the drying system was obtained, a collection of the paddy sample at the cyclone outlet was made. Determination of the moisture content of the paddy sample was carried out by drying the paddy in a hot-air oven at 103ºC for 72 h [14]. The drying conditions were given as follows: the drying column with C/L of 0 (totally smooth-surface drying column), 0.5 (combined smooth-surface and corrugated-surface drying column), and 1.0 (totally corrugated-surface drying column) and the drying temperatures (*T*), measured at point P_1 in Fig. 1, were 120ºC, 150ºC, and 180ºC. The inlet air velocity and paddy feed rate of 25 $\mathrm{m\ s^{-1}}$ and 20 $\mathrm{kg_{dry\ solid}\ h^{-1}}$, respectively, were used in all experiments. The experiments were divided into first-pass drying and second-pass drying. In the case of first-pass drying, the wet paddy was first introduced to the dryer. In the case of second-pass drying, the paddy, which was subjected to first-pass drying, was again fed into the dryer under the same drying conditions.

2.4 Evaluation of specific energy consumption, energy efficiency and paddy mean residence time

The specific energy consumption is the energy needed for evaporating one kg of water from the material being dried. It was computed from the following equation:

$$SEC = E_t/m_w \tag{1}$$

where *SEC* is the specific energy consumption of the drying process ($\mathrm{MJ\ kg_{water}^{-1}}$); E_t is the total energy supplied to the drying system (MJ), which is the summation of the energy consumption of the high-pressure blower and the energy consumption of the electric heater; and m_w is the amount of water removal ($\mathrm{kg_{water}}$), which is calculated from the following equation [15]:

$$m_w = W_p(X_i - X_o)t \tag{2}$$

where W_p is the paddy feed rate ($\mathrm{kg_{dry\ solid}\ h^{-1}}$); X_i and X_o are the inlet and outlet moisture contents of paddy ($\mathrm{kg_{water}\ kg_{dry\ solid}^{-1}}$), respectively; and t is the drying time (h).

The energy efficiency of the drying process is defined as the ratio of the energy needed for evaporating water from the paddy to the total energy supplied to the drying system. It is calculated by the following equation [16]:

$$\eta = (E_{ev}/E_t)\times 100 \tag{3}$$

where η is the energy efficiency of the drying process (%) and E_{ev} is the energy needed for evaporating water from the paddy (MJ), which is calculated as follows:

$$E_{ev} = m_w\lambda \tag{4}$$

where λ is the latent heat of vaporization ($\mathrm{kJ\ kg_{water}^{-1}}$).

The paddy mean residence time is defined as the ratio of paddy holdup within the dryer to paddy feed rate [17]. To evaluate the paddy holdup, the drying system was first operated as described earlier until reaching steady state at each condition. Feeding of the paddy into the drying system via the hopper and operation of the high-pressure blower were then simultaneously stopped. Collection of the paddy at the cyclone outlet was made and the amount of collected paddy was measured by an electric balance to obtain the holdup. Finally, the paddy mean residence time was calculated by [17]:

$$\tau = m_p/W_p \qquad (5)$$

where τ is the paddy mean residence time (s); m_p is the paddy holdup (kg); W_p is the paddy feed rate (kg s^{-1}).

3 Results and discussion

3.1 Moisture reduction of paddy

Fig. 2 showed the moisture reduction of paddy, which was the difference between the initial and the final moisture contents of paddy at each drying pass and the final moisture content of paddy after either first-pass or second-pass drying.

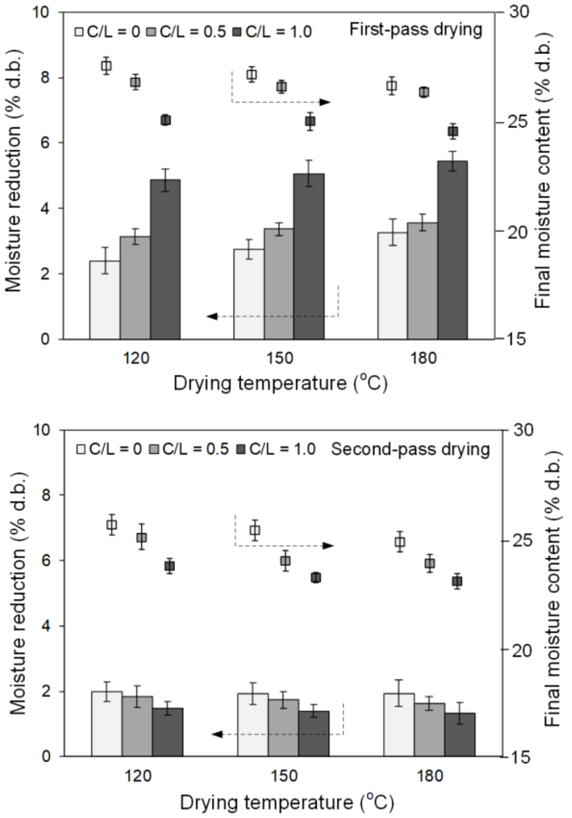

Fig. 2. Moisture reduction and final moisture content of paddy at different drying conditions.

For the first-pass drying, raising the drying temperature led to a greater amount of moisture reduction of paddy. This was because higher drying temperature caused a larger temperature difference between the hot air and paddy surface, leading to a higher potential of heat and mass transfer. This also gave the dried paddy with lower final moisture content. However, statistical analysis showed that the influence of drying temperature on the moisture reduction and final moisture content of paddy was found to be insignificant. This may be because duration that paddy stayed in the drying system was very short. The rate of heat absorbed by the paddy at different drying temperatures was then not much different. Higher value of C/L also led to a greater amount of moisture reduction and lower final moisture content of paddy. This was because a higher degree of turbulence was created in the drying column at a higher value of C/L (longer corrugated-surface length), leading to a higher rate of heat and mass transfer [9,10]. At a fixed drying temperature, the amount of moisture reduction of paddy at C/L=1.0 was significantly higher than that at C/L=0 and C/L=0.5. The amount of moisture reduction of paddy at C/L=0 and C/L=0.5 was also not significantly different.

For the second-pass drying, the influence of drying temperature on the moisture reduction of paddy was also not significant. This is probably because the large amount of moisture content was removed during the first-pass drying and the internal moisture remaining in the kernels was not able to convey to the surface of the paddy due to the internal resistance of the kernel structure [18]. The amount of moisture content at the paddy surface was therefore less than that in the kernels [19], leading to only a small amount of moisture could be removed from the paddy surface. It was also found that the higher values of C/L led to a smaller amount of moisture reduction. The reason for this observed phenomenon is the same as that mentioned in the case of the influence of drying temperature. Statistical analysis showed that the effect of C/L value on the moisture reduction of paddy was not significant in this case, however. The effects of the drying temperature and the value of C/L on the final moisture content of paddy for the second-pass and first-pass drying were similar. The final moisture content of paddy obtained after second-pass drying was lower than that after first-pass drying, as expected.

The maximum amount of moisture reduction of 5.4% (d.b.) was found during the first-pass drying at 180ºC. This maximum amount was noted when drying was performed using the drying column with C/L=1.0.

3.2 Pressure drop and paddy mean residence time

Table 1 showed the pressure drop of hot air and the paddy mean residence time. For both the first-pass and the second-pass drying, the drying temperature did not have any significant effect on the pressure drop and paddy mean residence time. The pressure drop increased when the value of C/L increased. This was because at higher values of C/L (longer corrugated-surface length), a greater flow resistance to paddy flow was generated in the drying column [9]. Therefore, the amount of paddy holdup in the drying system was larger, leading to longer mean residence time of paddy in the drying system.

Table 1. Pressure drop of hot air and paddy mean residence time under different drying conditions.

C/L	***T*** **(°C)**	**Pressure drop (Pa)**		**Mean residence time (s)**	
		First-pass drying	**Second-pass drying**	**First-pass drying**	**Second-pass drying**
0	120	70.0 ± 2.0^{a}	69.3 ± 1.5^{a}	3.13 ± 0.29^{a}	3.10 ± 0.30^{a}
	150	69.7 ± 1.2^{a}	69.3 ± 2.5^{a}	3.13 ± 0.31^{a}	3.07 ± 0.31^{a}
	180	69.7 ± 2.5^{a}	69.2 ± 2.0^{a}	3.12 ± 0.25^{a}	3.08 ± 0.13^{a}
0.5	120	123.0 ± 3.6^{b}	122.7 ± 2.1^{b}	3.89 ± 0.15^{b}	3.81 ± 0.21^{b}
	150	122.3 ± 3.8^{b}	121.0 ± 3.6^{b}	3.82 ± 0.11^{b}	3.80 ± 0.30^{b}
	180	122.0 ± 5.0^{b}	120.7 ± 3.1^{b}	3.82 ± 0.21^{b}	3.76 ± 0.26^{b}
1.0	120	142.7 ± 2.1^{c}	142.0 ± 3.0^{c}	3.96 ± 0.21^{b}	3.89 ± 0.20^{b}
	150	142.3 ± 3.5^{c}	141.3 ± 3.2^{c}	3.95 ± 0.25^{b}	3.89 ± 0.36^{b}
	180	141.3 ± 2.1^{c}	141.0 ± 3.6^{c}	3.92 ± 0.17^{b}	3.86 ± 0.25^{b}

Different letters in the same column indicate that the values ware significantly different at a 95% confidence level ($p < 0.05$).

3.3 Specific energy consumption

Fig. 3 illustrated the specific energy consumption (SEC) of the drying process at different drying conditions. For the first-pass drying, the SEC at a fixed value of C/L tend to decrease with an increase in the drying temperature. This is because when drying with higher temperatures, the energy consumption of the electric heater increased due to the longer operation period, while the energy consumption of the high-pressure blower was nearly the same. Consequently, the total energy consumption of the drying process increased. At the same time, the moisture reduction, which directly affected the amount of water removal, also increased. Because the increase in the total energy consumption in this case was lower than the increase in the amount of water removal, the SEC value computed from equation (4) was decreased. However, statistical analysis showed that the SEC values at various drying temperatures were not significantly different. The SEC significantly decreased with an increase in the value of C/L. Although using the drying column with higher value of C/L led to higher energy consumption of the high-pressure blower, the amount of water removal in this case was also larger. Combining these observations together, the SEC value was then reduced.

For the second-pass drying, the drying temperature had no significant effect on the SEC values. This was because the amount of water removal and total energy consumption obtained at various drying temperatures were not significantly different. However, the SEC values increased with an increase in the values of C/L. This may be because the total energy consumption significantly increased as the values of C/L increased, while the amount of water removal increased slightly. The SEC values of the drying process for the second-pass drying were obviously higher than those for the first-pass drying at all drying conditions. This indicated that the second-pass drying of paddy was not suitable when focusing on the energy consumption. The difference between the SEC values of the first-pass and the second-pass drying was larger when the drying process was carried out at higher value of C/L.

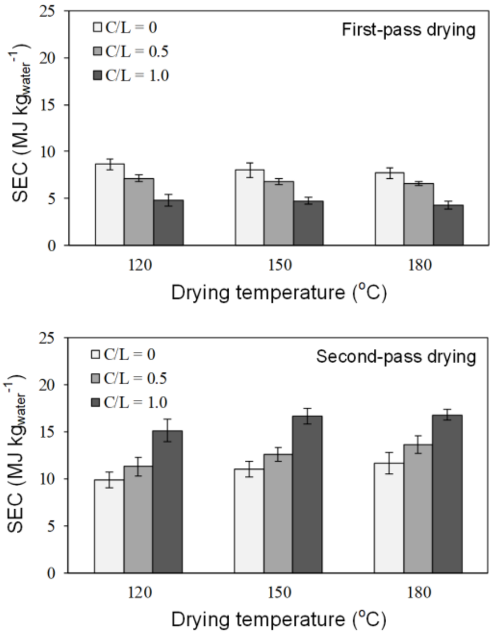

Fig. 3. Specific energy consumption of drying process at different drying conditions.

In this study, the SEC values for the first-pass and the second-pass drying were in the ranges of 4.3 to 8.7 MJ kg_{water}^{-1} and 9.9 to 16.8 MJ kg_{water}^{-1}, respectively. The lowest SEC value of 4.3 MJ kg_{water}^{-1} was bserved during the first-pass drying at 180°C and C/L=1.0. For the first-pass drying, using the drying column with C/L=0.5 and C/L=1.0 could save the energy consumption by 14% to 17% and 41% to 44%, respectively, compared with the drying column without corrugated surface (C/L=0). This implied that when the surface moisture of paddy is still high, the totally corrugated-surface drying column (C/L=1.0) is an efficient technique for energy saving. However, for the second-pass drying, the drying system using the drying column with corrugated surface consumed more energy.

3.5 Energy efficiency

Fig. 4 presented the energy efficiency of the pneumatic dryer at different drying conditions. For the first-pass drying, the effect of drying temperature on the energy efficiency was found to be insignificant. This was because the amount of water removal at different drying temperatures were insignificantly different. Although increasing the value of C/L led to an increase in the total energy consumption, the energy efficiency of the drying process still increased. This was due to the larger amount of water removal obtained from drying with a higher value of C/L. For the second-pass drying, the effect of the drying temperature on the energy efficiency was the same as that of the first-pass drying. However, the energy efficiency decreased with an increase in the value of C/L. This may be because the amount of water removal was obviously smaller when the drying column with a higher value of C/L was applied to the dryer.

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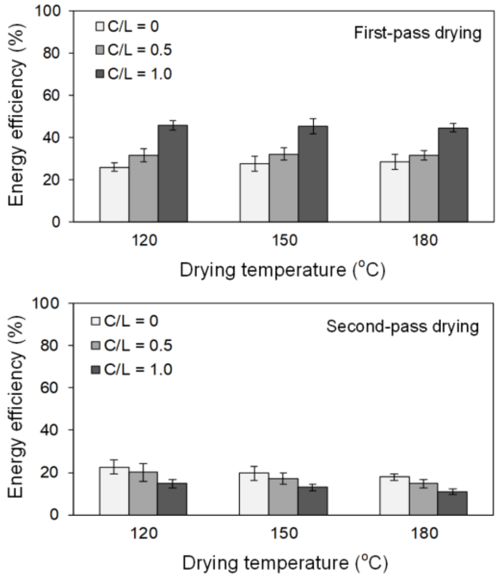

Fig. 4. Energy efficiency of pneumatic dryer at different drying conditions.

The energy efficiency for the first-pass drying was higher than that for the second-pass drying at all drying conditions. This was because for the first-pass drying, the moisture content of paddy at the beginning was very high. The moisture removal could easily occur when the energy supplied to the drying system was absorbed by the paddy. This meant that most of the supplied energy was used to evaporate water in the paddy, leading to higher energy efficiency. The phenomenon was different for the second-pass drying, where most of the surface moisture was eliminated after the first-pass drying. Most of the supplied energy in this case was thus used for heating the structure of paddy instead of evaporating the moisture, leading to lower energy efficiency. The highest energy efficiency of about 46% was observed during the first-pass drying at 180°C and C/L=1.0.

4 Conclusion

Modification of the pneumatic dryer for high-moisture paddy was carried out by introducing surface roughness to the drying column. The drying column with different corrugated-surface lengths, expressed in terms of C/L, and the multipass drying schemes were applied to the drying process. The effects of drying temperature and the value of C/L on the performance and energy utilization of the drying process were evaluated. It was found that the characteristic of the drying column had more significant effect on the dryer performance and energy utilization than the drying temperature. The drying column with C/L=1.0 showed significant potential for improving the dryer performance and energy utilization of the drying process.

This research was funded by King Mongkut’s University of Technology North Bangkok. Contract no. KMUTNB-60-GOV-069).

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