Building a model for the paddy columnar dryer and analyzing a reverse-airflow approach to achieve uniform grain temperature

V. H. Nguyen[1, 2*], H. T. Duong[2], M. Gummert[1]

(1. International Rice Research Institute, Laguna 4031, The Philippines;

2. Nong Lam University, Ho Chi Minh City 840000, Vietnam)

Abstract: This study focused on modeling a process for reducing the moisture content of Jasmine paddy from 28% to 14% wet basis in a recirculating cross-flow columnar dryer. The model was built based on experiments with an experimental cross-flow dryer; empirical reduction of a thin layer of moisture content; and the differential equations of mass balance, drying rate, energy balance, and heat transfer rate. The main drying parameters were simulated using MATLAB software. This simulation resulted that a uniform grain temperature of 38 ℃ at both the left-and right-end layers of the drying chamber can be achieved if the drying airflow is reversed at about 2/3 of the drying chamber length.

Keywords: paddy, drying, cross-flow, columnar dryer, modeling, reverse airflow

Citation: Nguyen, V. H., H. T. Duong, and M. Gummert. 2016. Building a model for the paddy columnar dryer and analyzing a reverse-airflow approach to achieve uniform grain temperature. International Agricultural Engineering Journal, 25(1): 64-73.

1 Introduction

Mechanical drying is one of the major technological achievements in rice production that helped Vietnam to become a world rice leading exporter. Drying is an essential step for grain storage to prevent respiration, germination, and mould damage (Xiao and Gao, 2008). However, many grain farmers lose much profit due to poor drying techniques. Therefore, application of a suitable drying technology and selection of appropriate drying conditions are very important. The significant use of mechanical drying of paddy rice contributed to reducing postharvest losses from an average of 5% (MARD, 2004) to about 2% (MARD, 2013). Typical types of mechanical or heated-air dryers used for paddy rice drying were introduced by Gummert and Rickman (2010), such as flatbed, columnar, flash, and fluidized bed dryers.

Received date: 2015-07-04 Accepted date: 2015-10-13

*** Corresponding author: V.H. Nguyen,** Postdoctoral Fellow of the International Rice Research Institute and Associate Professor of Nong-Lam University. Email: hung.nguyen@irri.org.

Over the last 20 years, most dryers in Vietnam were flatbed types because of their simplicities, feasibilities for local manufacturing, and low investment and running costs. Columnar dryers for paddy were introduced in Vietnam in the 1990s, but they were seldom used until recently. The main reason was that they worked effectively only when moisture content was less than 24% wet basis. In the summer-autumn crop, the paddy's moisture content is around 28%–30% wet basis. The paddy is also contaminated with mud and impurities due to manual cutting and threshing. This often clogged the columnar dryers resulting in poor performance. In addition, the investment and operational costs of these dryers were higher compared with flatbed dryers. Currently, with better dryer designs and cleaner paddy coming from combine-harvesters, more columnar dryers have been installed in the high-capacity drying and milling lines of larger rice mills in Vietnam. Most columnar dryers use the cross-flow principle, which performs better than the mix-flow columnar dryers, especially in terms of dried grain quality (Nguyen et al., 2013).

Columnar dryers used for paddy rice drying were presented in several researches. Performance of columnar rice dryer was described by Charun (1993). Structural improvement of this dryer type was revealed by Adesoji and Abiola (2014). There are quite many studies relevant to modeling for paddy drying such as Wongwises (2000), Madhiyanon (2002), Felipe (2003), G. J. Schluterman and T. J. Siebenmorgen (2004), I. E. Saeed et al. (2008), Morteza et al. (2012), and H. K. P. P. Kariyawasam et al. (2014). However, the models or equations of a drying process should be different for every drying condition which is determined by the type of machine, paddy variety, weather condition, drying parameters, etc.

To aid in the development of advanced design for cross-flow columnar dryer, this study was undertaken to establish a process model for reducing the moisture content of Jasmine paddy from 28% to 14% of wet basic moisture content (Mcwb). Two models were described in this paper: (1) a thin-layer drying model determined by an empirical method and (2) a thick-layer drying model built on mathematics based on the first thin-layer to simulate the drying process of one pass in the cross-flow columnar dryer.

2 Materials and methods

2.1 Background for research

Initial inputs for this modeling were based on a technical and economical feasibility study of columnar dryers by Nguyen et al. (2013) and the design and development of a 10 t/batch columnar dryer by the ADB-IRRI-Postharvest project (NLU-IRRI CD10; Tran Van Tuan et al., 2013)(Figure 1).

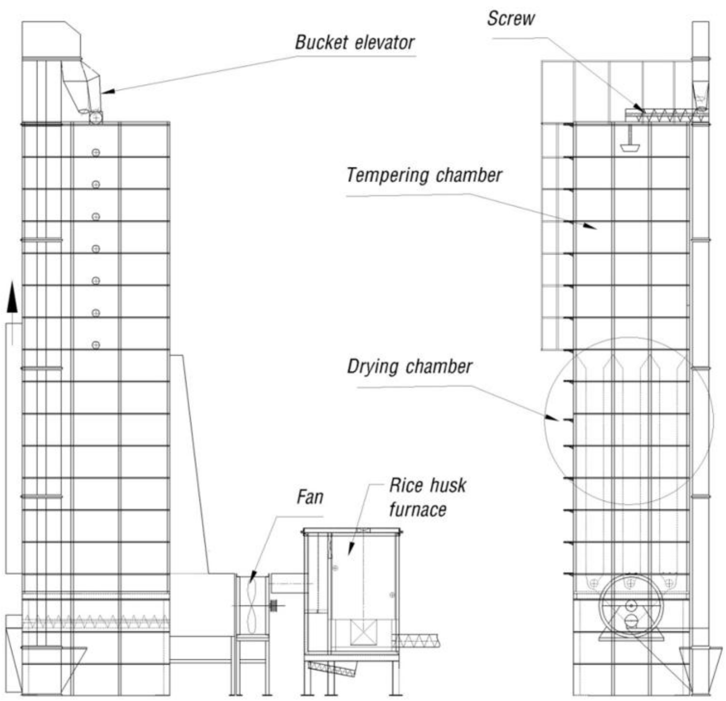

Figure 1 The NLU-IRRI CD10 columnar dryer

Most columnar paddy dryers are the cross-flow type. Designers of this type tend to increase the drying chamber thickness to increase capacity and/or to increase the temperature to speed up the drying. However, increased column thickness and temperature also increase the moisture gradient between grains at the air inlet and outlet of the column. Another objective of the adaptive work was not to damage the grain. Suggested solutions involved either grain reversal or air reversal. A constraint to either of these is the time needed for reversing.

To help optimize the drying process while minimizing the requirement for expensive and time-consuming field trials, modeling of the drying process was done. This simulated the operating parameters such as grain moisture content and grain temperatures at different locations in the drying column as functions of time, air temperature, crossing air speed, and following grain speed.

2.2 Set up experiment

An experimental recirculating columnar dryer was designed and fabricated (Figure 2). The main parts are the heater, fan, tempering chamber, drying chamber, and the bucket elevator for recirculating grain.

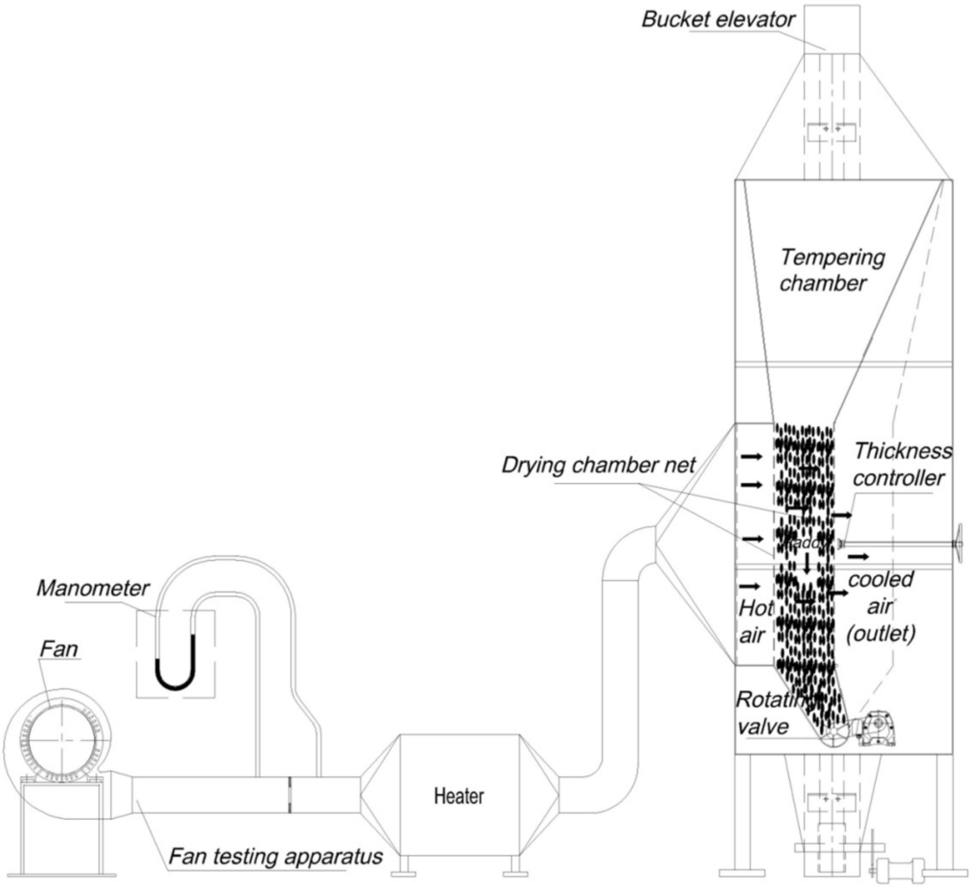

Figure 2 Schematic design of experimental columnar dryer

The main components can be controlled and adjusted. For example, a screw was used to adjust the drying chamber's thickness from 15 cm to 30 cm. A rotating valve controlled the speed of the vertical grain flow in the range of from 1 m/h to 2 m/h. Air for drying was heated by electrical resistance and the drying air temperature can be controlled automatically from 30 ℃ to 60 ℃. Drying air speed was measured by a fan-testing apparatus (Figures 3 and 4) and controlled by an electric motor connected to an inverter range. This kept the air flow between 1 m^3/(s t) and 2 m^3/(s t) of paddy at a static pressure of from 30 mm to 50 mm H_2O as introduced by Tumambing (1993) and in line with grain drying experiences in Vietnam. However, this adjustability was only used for initial detection of the input parameters and for further research. For the research reported here, the input parameters were set at 25 mm for the drying chamber thickness, 45 ℃ for air temperature, and 1 m^3/(s t) for the air flow.

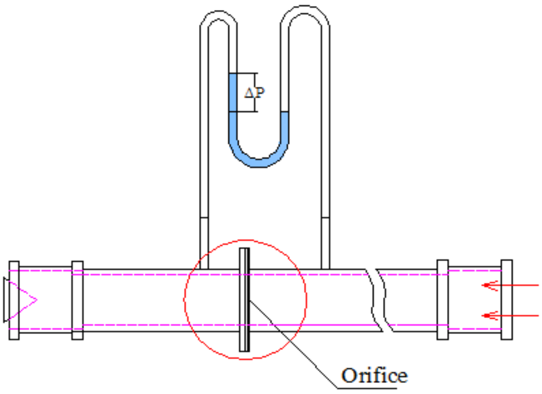

Figure 3 Scheme for drying air measurement

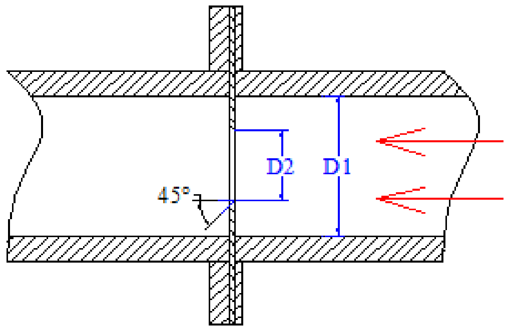

Figure 4 Schematic drawing of the orifice

2.3 Basic of modeling

With a cross-flow columnar dryer, the movement of air crossing through the paddy flowing vertically due to gravity is shown in Figures 5 and 6. Where in Figure 5, L_1, L_2, L_3, L_4, L_5 are the five layers of the drying chamber as simulated in the model.

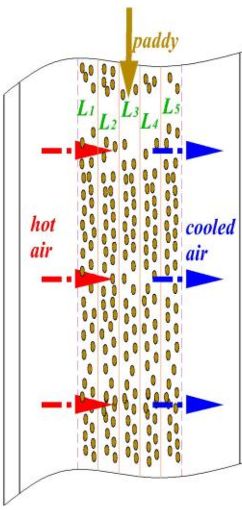

Figure 5 Movement of air and paddy in a columnar dryer

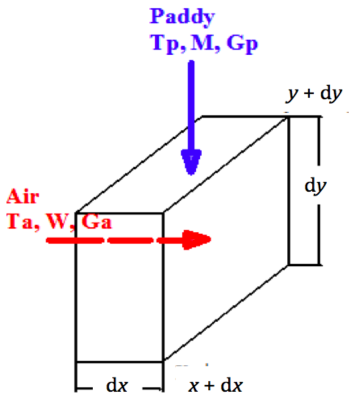

Figure 6 A particle (dx, dy) of grain in the drying chamber.

The thin-layer drying model was selected by comparing the results of experiment with similar paddy drying research models shown in Table 1. In the equations shown in Table 1, MR is the moisture content ratio; M is the grain moisture content (%); M_e is the equilibrium moisture content (%); M_0 is the initial moisture content (%); k, n, a, b are the empirical coefficients; t is the drying time (h); T is the drying air temperature (℃), Rh is the relative humidity (%); M_{db} is the moisture content (dry basic); and M_{wb} is the moisture content (wet basic).

Table 1 Thin-layer models for paddy drying

Equation No.	Authors	Model	Constants
(1)	Agrawal and Singh (1977)	$MR = (M - M_e)/(M_o - M_e) = \exp(-k \times t^n)$	$k = 0.2958 + 0.01215 \times T - 0.44565 \times Rh$ $n = 0.13365 + 0.009468 \times T + 0.0193653 \times Rh - 0.000177431 \times Rh^2$ Range: $32°C \leq T \leq 51°C$; $19\% \leq Rh \leq 85\%$
(2)	Wang and Singh (1978)	$MR = (M - M_e)/(M_o - M_e) = \exp(-k \times t^n)$	$k = 0.1579 + 0.0001746 \times T - 0.0001413 \times Rh$ $n = 0.6545 + 0.002425 \times T + 0.0007867 \times Rh$
(3)	Wongwise and Thongprasert (2000)	$MR = (M - M_e)/(M_o - M_e) = \exp(-a \times t^b)$	$a = \exp(-6.0405 + 1.368 \times \ln(T) - 0.6587 \times \ln(M_{db}))$ $b = 0.449 - 0.00096 \times Rh + 0.008 \times M_{db}$

Equilibrium moisture in rough rice (paddy) is based on the Modified Henderson equation (Thompson et al., 1968) shown in Equation (4).

$$M_e = [\ln(1-Rh/100)/(-K(T + C))]^{1/N} \quad (4)$$

The respective constants for paddy is referred in ASAE (1988) as follows:

$K = 1.9187.10^{-5}$

$N = 2.4451$

$C = 51.161$

Moisture content on a wet and dry basis can be expressed as Equation (5) and Equation (6).

$$M_{wb} = M_{db}/(1 + M_{db}) \quad (5)$$

$$M_{db} = M_{wb}/(1 - M_{wb}) \quad (6)$$

The cross-flow drying model was built based on the above thin-layer drying model and the differential equations of drying rate (Equation (7)), mass balance (Equation (8)), energy balance (Equation (9)), and heat transfer rate (Equation (10)), which are shown in Table 2 (Bala, 1997).

Table 2 Differential equations of the cross-flow columnar drying process

Equation No.	Title	Differential equations	Nomenclature explanation
(7)	Drying rate equation	$dM/dt = -k(M - M_e)$	G_p: Flow rate of grain (kg/ph.m^2) G_a: Mass flow rate of air (kg/ph.m^2) h_{cv} : Volumetric heat transfer coefficient (W/m^2 ℃) c_a: Specific heat of air (kJ/kg ℃) c_{pl}: Specific heat of water (kJ/kg ℃) c_{pw}: Specific heat of water vapor (kJ/kg ℃) H: Humidity (%) L_{fg}: Latent heat of vaporization of moisture from grain (kJ/kg)
(8)	Mass balance equation	$dH/dx = (-G_p/G_a)(dM/dy)$	
(9)	Energy balance equation	$dT_a/dx = -\{[h_{cv} + G_a .c_{pw}.(dH/dx)].(T_a - T_p)\}/(G_a c_a + G_a c_{pw}H)$	
(10)	Heat transfer rate equation	$dT_p/dy = -[h_{cv}.(T_a - T_p) - G_a.(L_{fg} + (c_{pw} - c_{pl})).T_g.(dH/dx)]/(G_p c_p + G_p c_{pl} M)$	

3 Results and discussion

3.1 Building the thin-layer drying model

To establish the thin-layer drying model, an experiment was implemented with the input parameters based on paddy industrial drying technologies and the NLU-IRRI CD10 columnar dryer used in the Mekong Delta as follows:

- Drying air temperature: $T_a = (45 \pm 1)$ ℃
- Drying thickness: 0.25 m
- Rate of tempering/drying time in chamber: 50 min /30 min
- Input paddy moisture content: $(28 \pm 1)\%$ (Jasmine variety)

The results are shown in Table 3. With the principle of columnar drying described in the methodology section, grain is recirculated and undergoes about six drying/tempering passes in one drying batch. In each pass, the grains after drying at high temperature (45 ℃) were recirculated and tempered in the tempering chamber while flowing down to the drying chamber for the next drying pass. The drying air temperature was selected based on the pilot test results described in the background section above and also revealed in Adesoji and Abiola (2014). This drying process is shown in

Figure 7. However, incorporating this thin-layer concept into the columnar drying model with its succeeding passes involving drying and tempering would be very complicated. So, we measured the paddy moisture content Mt (%) every drying hour using the parameters shown in Table 3 and assumed the regression without the tempering phase in a continuous curve as shown in Figure 7.

Table 3 Parameters for building the thin-layer model.

t, h	T_a, ℃	T_{db}, ℃	T_{wb}, ℃	*Rh*, %	M_o, %	M_t, %	M_e, %	*MR*
1	47	27.5	23.5	28	28	22.4	8.3	0.72
2	48	30.0	25.0	28	28	20.4	8.3	0.61
3	47	31.0	26.5	32	28	18.0	8.9	0.48
4	47	34.0	27.0	34	28	16.1	9.1	0.37
5	47	33.5	27.0	34	28	14.9	9.1	0.31
6	46	34.0	27.0	35	28	14.2	9.3	0.26

Legend: *t* is drying time (h), T_a is drying temperature (℃), T_{db} and T_{wb} are air temperature measured by dry bulb – wet bulb thermometer.

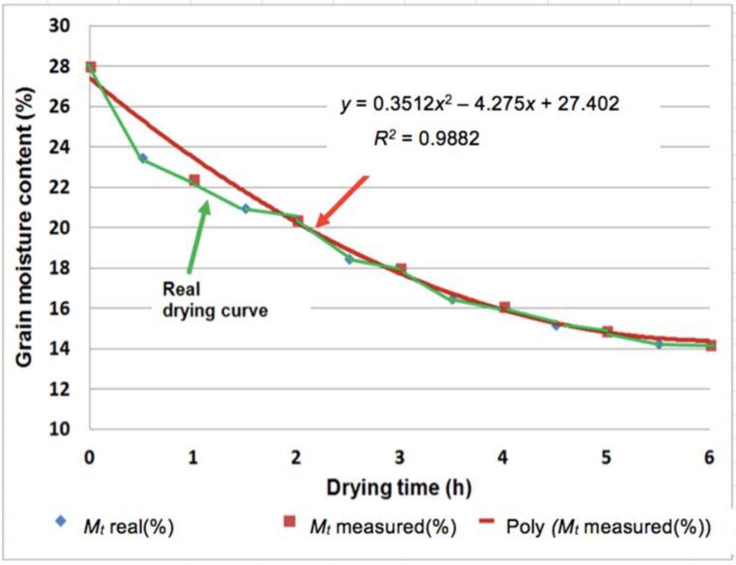

Figure 7 Real and regression grain moisture content during recirculating columnar drying

Based on the results, a regression model of MR (t) was established and compared with the existing models shown in Figure 8. The differences calculated by the variance coefficient (S^2x) between the empirical model and the Agrawal and Singh (1977), Wang and Singh (1978), Wongwise and Thongprasert (1990) models were 0.003, 0.59, and 0.159, respectively.

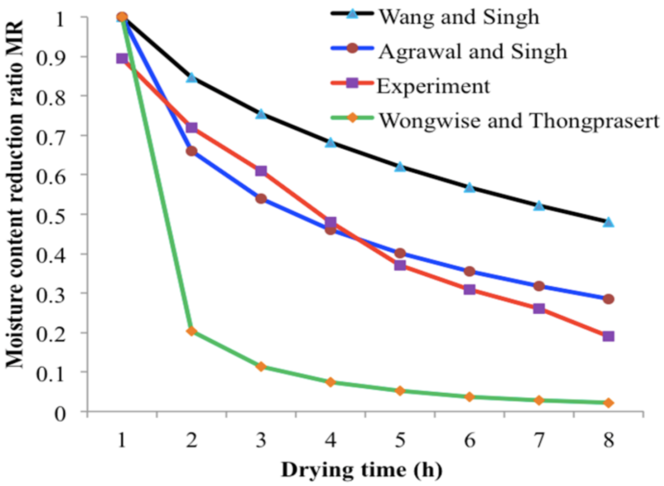

Figure 8 Regressions of different thin-layer models.

The Agrawal and Singh (1977) model was selected as the thin-layer drying model for this study because it had the smallest difference in comparison with the empirical model.

3.2 Building the cross-flow drying model

To build the cross-flow drying model, firstly, the thin layer model was selected as described in above section. With the equilibrium moisture content indentified based on the modified Henderson equation, the equation of drying rate (Equation (7)) was solved. Then, the input data for the equations Equations (8), (9), and (10) were identified based on the experimental conditions such as paddy input moisture content of 28%; grain temperature of 28℃; drying air temperature of 45℃; and ambient air relative humidity of 70%. Then, the differential equations including mass balance, energy balance, and heat transfer rate were solved based on the MATLAB software. This modeling resulted to a differential equation of grain moisture (Equation (11)), drying air humidity (Equation (12)), drying air temperature (Equation (13)), and grain temperature (Equation (14)).

- $M(t) = 18.69 \exp(-0.42t^{0.567}) + 9.31$ (11)
- $\mathrm{d}H/\mathrm{d}t = -674.65\, \mathrm{d}M/\mathrm{d}t$ (12)
- $\mathrm{d}T_a/\mathrm{d}t = -514.8\{[(8.5 + 1136.27(\mathrm{d}H/\mathrm{d}x)(T_a - T_p)]/(606.01 + 1136.27 H)\}$ (13)
- $\mathrm{d}T_p/dt = -1.12\ \{[8.5(T_a - T_p) - 601.2\ (2388.69 - 2.57T_p(\mathrm{d}H/\mathrm{d}x)]/(1516.32 + 3918.01M)\}$ (14)

Paddy grain moisture content (M_c) and its ratio (MR) over time in a drying batch were simulated as shown in Figure 9. Moisture content decreased rapidly during the first 2 h, from 28% $M_c$wb to 18% $M_c$wb, and its speed (MR) was reduced afterwards. The process of this model resembles the empirical regression model shown in Figure 7.

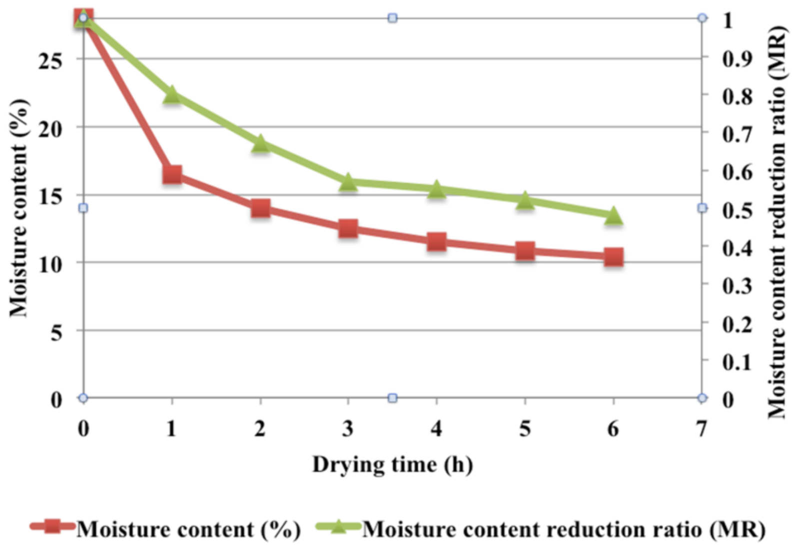

Figure 9 Grain moisture content *M (t)*

In each pass of the experimental recirculating columnar dryer, grain is flowing through the drying chamber in 0.8 h (in case of this simulation). Flowing grain gets in contact with the heated air crossing through the drying chamber. For this simulation, grain in the drying chamber is divided into five layers. Grain temperatures $T_p(t)$ of the five different layers (L_1, L_2, L_3, L_4, L_5) were distributed following the vertical air movement as shown in Figure 5. The grain temperatures of the first through fifth layers are shown in Figure 10 correspondingly at the thickness of 5 cm, 10 cm, 15 cm, 20 cm, and 25 cm, respectively. Within 0.8 h passing through the drying chamber, grain temperature in each layer increased linearly from 0℃ to about from 34℃ to 38℃ depending on the layer position (the earlier the grain layers contact the hot air, the hotter the grain temperature becomes).

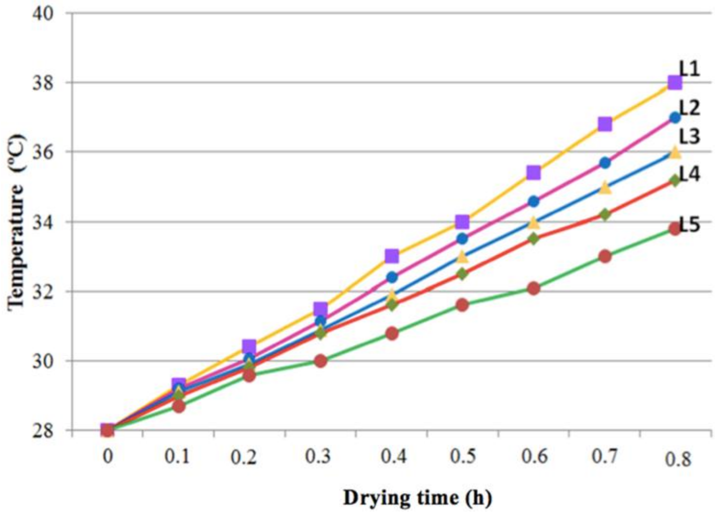

Figure 10 Grain temperatures of five layers over drying time of a pass of grain flowing through the drying chamber

In principle, as shown in Figure 2, the drying air flows across through the thick layer of paddy, so the temperatures of the grain layers were different. The grain layer closest to the hot air obviously had the highest temperature. To solve this problem, the airflow was reversed as shown in Figure 11 to equalize the temperatures of the different grain layers. In Figure 11, and corresponding to Table 4, the drying process in one pass is simulated in two layers, layer 1 at the left border and layer 2 at the right. The air temperature (T_a) and grain temperature (T_p) are determined at the four heights of the drying chamber. The temperature is named by the position of the height and layer. For example, T_{a11} and T_{p11} are the air and grain temperatures, respectively, at the point of height 1 and layer 1. Temperatures of all points at the different heights and layers are shown in Table 4.

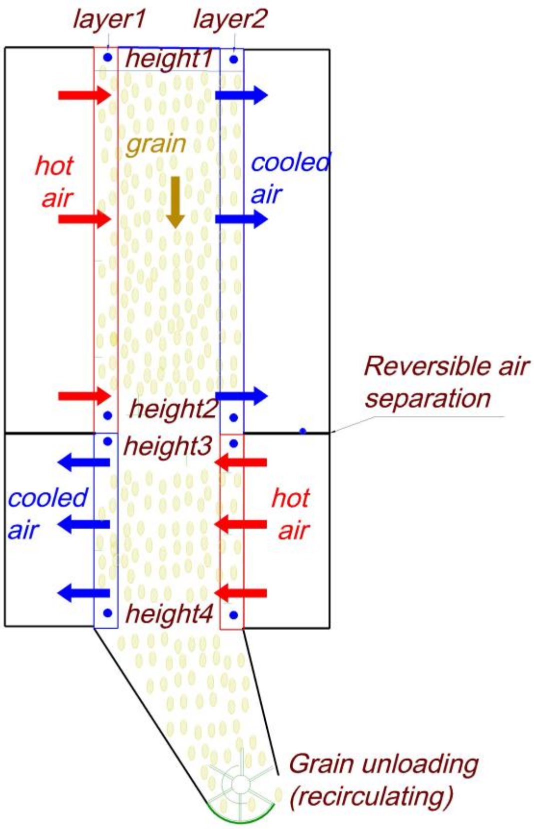

Figure 11 Solution for reversing the drying air

Table 4 Air temperature T_a(℃) and grain temperature T_p (℃) at different positions in the air-reversible chamber

Drying chamber	Positions (overtime)	Horizontally (*x*) *t* (*x*=0) = 0	*t* (*x*=250) = 0.03 min
Before air reversal	Height 1 Vertically (*y*) *t* (*y*=0) = 0	$T_{a11} = 45$ $T_{p11} = 28$	$T_{a12} = 39$ $T_{p12} = 28$
	Height 2 *t* (*y* = 960 mm) = 0.8 h	$T_{a21} = 45$ $T_{p21} = 38$	$T_{a22} = 39$ $T_{p22} = 33.8$
After air reversal	Height 3 *t* (*y* = 960 mm) = 0.8 h	$T_{a31} = T_{a22} = 39$ $T_{p31}=T_{p21} = 38$	$T_{a32} = T_{a21} = 45$ $T_{p32}=T_{p22} = 33.8$
	Height 4 *t* (*y*=1380 mm) = 1.15 h	$T_{a41} = 39$ $T_{p41}= 38.4$	$T_{a42} = 45$ $T_{p42} = 38$

Using the columnar drying model established in this research, the time for reversing the air flow was predicted with the objective of having a uniform temperature in both the left- and right-border grain layers. With the input parameters of grain and drying air shown in Table 4 used in the simulation, the result indicated that the air needs to be reversed at 0.8 h after a total drying time in one pass of 1.15 h, or at about 2/3 of the drying chamber length, to have similar grain temperatures of approximately 38 ℃ in both the left- and right-end layers. Using this configuration, the grain temperature at any location did not exceed 45 ℃ at any time of the process so grain quality would be maximized. From this enhancement, the height of drying chamber or drying temperature could also be increased without causing grain breakage. The model has been verified using the limited data collected from the test rig only, however additional verification is needed. Hence more testing is required to further verify the model using rice samples of different variety and with different initial moisture contents in order to develop the model into a tool for further optimizing the performance of recirculating column dryers.

4 Conclusions

An experimental cross-flow recirculating columnar dryer was used to establish a model of the drying process of paddy. Simulation of this model resulted in the differential equations of mass balance, drying rate, energy balance, and heat transfer rate for paddy grain flowing through a pass of a cross-flow recirculating columnar drying chamber. The simulation in this modeling experiment showed that a uniform grain temperature of 38 ℃ at both the left- and right-end layers can be achieved if the drying airflow is reversed at about 2/3 of the drying chamber length.

Further studies will focus on empirical research to evaluate this model for of drying paddy in recirculating columnar dryers. An experimental reversible air columnar dryer will be designed based on the result of this study to evaluate and demonstrate the improvement in drying performance.

Acknowledgements

The research group acknowledges the support of the ADB-IRRI Postharvest Project, namely “Bringing about a Sustainable Agronomic Revolution in Rice Production in Asia by Reducing Preventable Pre- and Postharvest Losses”

[References]

[1] Agrawal, Y. C., and R. P. Singh. 1977. Thin layer drying studies on short grain rough rice. *ASAE paper, St. Joseph, MI: ASAE*. No.77: 3531.

[2] ASAE. 1988. Agricultural Engineers’ hand book. *American Society of Agricultural and Biological Engineers, St. Joseph, MI: ASAE*. 35th edition: 294-306.

[3] Bala, B. K. 1997. Drying and storage of cereal grains. *Oxford & IBH publishing Co. Pvt. Ltd.*

[4] Felipe, C. A. A., and M. A. S. Barrozo. 2003. Drying of Soybean Seeds in a Concurrent Moving Bed: Heat and Mass Transfer and Quality Analysis. *Drying Technology*, 21(3): 439-456.

[5] Gummert, M., and J. Rickman. 2010. Options for "Heated air

drying". Available at: http://www.knowledgebank.irri.org/training/fact-sheets/postharvest-management/drying-fact-sheet-category/options-for-heated-air-drying-fact-sheet.

[6] Likitrattanaporn, C. 1993. Evaluation of the performance of the non-mixing columnar rice dryer. Available at: http://agris.fao.org/agris-search/search.do?recordID=TH1998001271.

[7] Kariyawasam, H. K. P. P., K. S. P. Amaratunga1, B. F. A. Basnayake, L. B. M. D. L. Priyadarshana, D. D. K. Galahitiyawa, and K. G. W. U. Karunasinghe. 2014. Rice Grain Cooling Using Intermittent Adsorption and Desorption of Water Vapour: Development of a Mathematical Model. *Tropical Agricultural Research*, 25(4): 487–501.

[8] Madhiyanon, T., S. Soponronnarit, and W. Tia. 2002. A Mathematical Model for Continuous Drying of Grains in a Spouted Bed Dryer. *Drying Technology*, 20(3): 587-614.

[9] Ministry of agriculture and rural development of Vietnam (MARD). 2004. A survey on post harvest status in the Mekong Delta of Vietnam. Report of Danida ASPS.

[10] Ministry of agriculture and rural development of Vietnam (MARD). 2004. Current status and strategies on Food Lossesin Viet Nam. *APEC Seminar on Strengthening Public-Private Partnership to Reduce Food Losses in the Supply Chain*, 5–8 August 2013, Chinese Taipei.

[11] Morteza, G., M. Rajabi-Hamane, and S. J. Hashemi. 2012. Optimization of Drying–Tempering Periods in a Paddy Rice Dryer. *Drying Technology*, 30(1): 106–113.

[12] Hung, N. V., V. T. Tran, T. Q. Truong, and L. Q. Vinh. 2013. Technological and economic evaluation of column dryer in the Mekong Delta. *Final report of Rice post harvest ADB-IRRI-VN project., 2013*: 30-50.

[13] Olaniyan, A. M., and A. A. Alabi. 2014. Conceptual Design of Column Dryer for Paddy Rice including Fabrication and Testing of Prototype. *International Journal of Basic and Applied Science*, 2(3): 11-20.

[14] Saeed, I. E., K. Sopian, and Z. Z. Abidin. 2008. Thin-Layer Drying of Roselle (I): Mathematical Modeling and Drying Experiments. *Agricultural Engineering International: the CIGR Ejournal*, 2008(10): Manuscript FP 08 015.

[15] Schluterman, G. J., and T. J. Siebenmorgen. 2004. Air and Rice Property Profiles within a Commercial Cross−Flow Rice Dryer. *American Society of Agricultural Engineers*, 20(4): 487−494.

[16] Thompson, T. L., R. M. Peart, and G. H. Foster. 1968. Mathematical Simulation of Corn Drying: A New Model. *Trans. of the ASAE*, 11(4): 582 - 586.

[17] Tran, V. T., N. V. Hung, N. V. Xuan, N. H. Tam, Q. V. Le, T. Q. Truong, and H. H. Phan. 2013. Design and development of the 10-ton/batch columnar paddy dryer. Proceedings of International Workshop on Agricultural Engineering and Post-harvest Technology for Asia sustainability. *Science and Technics Publishing House*, 2013 (12): 152–163.

[18] Tumambing, J. A. 1993. Mathematical modelling and design of a continuous fluidises bed dryer for pre-drying of paddy in the humid tropics. The thesis submitted for the degree of Doctor of Philosophy, The University of New South Wales, 40-42.

[19] Wang, C. Y., and R. P. Singh. 1978. A single layer drying equation for rough rice. *ASAE Paper, St. Joseph, MI: ASAE*. No. 78:3001

[20] Wongwises, S., and M. Thongprasert. 2000. Thin layer and deep bed drying of long grain rough rice. *Drying Technology*, 18(7): 1583–1599.

[21] Xiao, H. W., and Z. J. Gao. 2008. Research progress in the effects of drying on feeding maize and processing quality. Transactions of the Chinese Society of Agricultural Engineering, 24(7): 290-295. (in Chinese with English abstract)