Engenharia Agrícola

ISSN: 1809-4430 (on-line)

www.engenhariaagricola.org.br

Scientific Paper
Doi: http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v43n3e20200037/2023

EFFECT OF CONSTANT VOLUME STRUCTURE PARAMETERS ON GRAIN VENTILATION DRYING

Xingzao Ma[1*], Danna Zheng[1], Zhuangdong Fang[2]

[1*]Corresponding author. Lingnan Normal University/Zhanjiang, China.
E-mail: maxz@lingnan.edu.cn | ORCID ID: https://orcid.org/0000-0001-7299-6677

KEYWORDS

ventilation area, theoretical analysis, drying energy consumption, drying uniformity

ABSTRACT

The structural parameters of a grain dryer are directly related to the its energy consumption and quality formation. Therefore, based on the Ergun model, air state parameters and uniformity evaluation method, the effect of changes in the ventilation area on grain airflow resistance, drying energy consumption, drying efficiency and uniformity are theoretically and experimentally studied in this work under the same initial grain weight and air flux. The results show that under the conditions of air temperatures 35℃ and 70℃, the weight of paddy 8.547 kg and the air flux 12.3 $m^3 \cdot h^{-1}$, hot air introduced into the drying chamber with cross-sectional areas of S1 and S2 respectively, the ventilation area enlarged by 2.328 times, the grain airflow resistance decreased by 7.17 and 6.99 times. Enlarging the ventilation area effectively improved the drying rate of paddy, especially at 70℃, while the unit energy consumption was the opposite. It also accelerated the moving speed of the saturated humidity line in the drying layer and improved the drying uniformity of the paddy. These experimental results are in agreement with the theoretical analysis, which provides a reference for the design of grain drying equipment and technology.

INTRODUCTION

Grain drying can be primarily classified as fixed-bed, spouted-bed, and fluidized-bed drying. Fixed-bed drying has a simple structure, low cost, and is easy to apply, but has bad drying uniformity (Souza et al., 2015; Jia et al., 2016). Spouted-bed drying consumes less energy compared with other technologies, and the dryer used in this method has a low bed height and small size (Jittanit et al., 2013). Continuous drying in a fluidized bed enlarges the drying capacity and decreases the energy consumption (Sadaka et al., 2018; Srimitrungroj et al., 2019). Excessive air velocity slightly influences the drying rate, increases energy consumption and wastes high-quality energy (Kumar & Gupta, 2006). No matter which form of drying is used, the main working mode is forcing hot air through the grain with a high-pressure fan. This process will inevitably consume the air pressure of the fan and produce grain airflow resistance（Nalladurai et al., 2002; Sacilik, 2004）, while the energy of the hot air is consumed by the heating of the grain, moisture evaporation, etc.（Li, 2012; Ma et al., 2017）. For a constant volume grain dryer, the structureal parameters are directly related to the system's energy efficiency, drying quality and fan selection.

Many researchers have reported the grain airflow resistance, ratio of air flux to grain mass, airflow rate, grain thickness, ventilation area, and their mutual relations（Yang et al., 1990; Molenda et al., 2005; Kashaninejad & Tabil, 2009; Audu et al., 2018; Audu & Anyebe, 2018; Li et al. 2019. (Liu, 2015) used the CFD-DEM coupled model to explore the change of grain airflow resistance at different airflow rates and different grain depths, and validated the feasibility of CFD-DEM for numerically simulating the grain airflow resistance. (Gao et al., 2017) numerically simulated and analyzed the anisotropic resistance of airflow for mechanical ventilation of wheat, and described the relation between grain airflow resistance, air flux and way of ventilation.

[1] Lingnan Normal University/Zhanjiang, China.
[2] South China Agricultural University/Guangzhou, China

Area Editor: Paulo Carteri Coradi
Received in: 3-12-2020
Accepted in: 7-10-2023

(Kashaninejad et al., 2010) investigated the pressure drop across a column of pistachio nuts (Kalleghochi variety) to determine the effect of moisture content, airflow rate, bed depth and fill method. (Zhang et al., 2014) pointed out that the grain airflow resistance would increase by 4-8 times when the grain thickness doubled under the condition of the same airflow rate. However, the influence of changes in the parameters of a constant volume structure on the energy consumption, drying efficiency and uniformity has rarely been studied.

Therefore, this work attempts to theoretically analyze the effect of changes in the ventilation area on grain airflow resistance, drying efficiency, drying energy consumption and drying uniformity under the same initial grain weight and air flux. A ventilation drying experiment of paddy has been conducted to validate the reliability of the theoretical analysis.

THEORETICAL ANALYSES AND METHODS

Structural model analysis

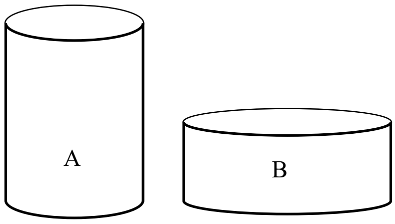


FIGURE 1. Schematic diagram of drying chambers A and B.

Suppose the drying chamber A has 1/2 the bottom area and twice the height of B. The relations between the geometrical dimensions are shown in eqs. (1) – (3):

$$V_1 = V_2 \quad (1)$$

$$S_1 = \frac{1}{2} S_2 \quad (2)$$

$$h_1 = 2h_2 \quad (3)$$

in which:

V_1 and V_2 -grain volumes in drying chambers A and B, m³;

S_1 and S_2 -ventilation areas of drying chambers A and B, m²,

h_1 and h_2 - height of grain in drying chambers A and B, m.

A hot air flux of G is blown from the bottom into drying chambers A and B. The superficial airflow rates are v_1 and v_2, respectively:

$$v_1 = G/S_1 \quad (4)$$

$$v_2 = G/S_2 \quad (5)$$

According to eqs. (1) - (5),

$$v_1 = G/S_1 = 2G/S_2 = 2v_2 \quad (6)$$

For drying chambers A and B, the time required for the hot air to pass through can be derived from eqs. (7) and (8):

$$t_1 = h_1/v_1 \quad (7)$$

$$t_2 = h_2/v_2 \quad (8)$$

Substituting eqs. (3) and (6) into [eq. (7)] yields

$$t_1 = h_1/v_1 = 2h_2/2v_2 = t_2 \quad (9)$$

in which:

v_1 and v_2 - superficial airflow rates in drying chambers A and B, respectively, $m \cdot s^{-1}$;

G - airflow rate, in $m^3 \cdot h^{-1}$,

t_1 and t_2 - time of the hot air flow through the drying chamber, s.

From [eq. (9)], it can be seen that when the initial grain weight and air flux are the same, a change in the ventilation area does not affect the time required for the hot air to flow through the grain. However, in terms of each single grain in the drying chambers, the time difference of its exposure to the hot air is twice, so when the hot air loses its drying capacity in the grain under drying or reaches the same exhaust condition, the impact of the airflow rate can be neglected for the average drying characteristics. At this time, the average drying efficiency is supposed to be the same in both drying chambers. How a change of the geometrical structure will affect the grain airflow resistance, energy consumption of the system and drying uniformity need further exploration.

Grain airflow resistance

During mechanical ventilation of grain, the air pressure of the fan is inevitably consumed and grain airflow resistance is produced (Sacilik, 2004). Too high a grain airflow resistance will cause a failure of the hot air to flow through the grain, resulting in non-uniform ventilation, poor drying quality, and impairment of the fan's life due to the excessive load. Too low a grain airflow resistance will lead to too high an exhaust temperature, which will result in energy waste and a sharp increase in energy consumption of the drying system. Grain airflow resistance models commonly used include Shedd's empirical formulas (Shedd, 1953), Hukill's equation (Hukill & Ives, 1955) and Ergun's model (Ergun, 1952). Of these, the Ergun model [eq. (10)] is the most widely applied.

$$\begin{cases} \dfrac{-\Delta P}{h} = Av + Bv^2 \\ A = \dfrac{150(1-\varepsilon)^2 \mu}{\varepsilon^3 d^2} \\ B = \dfrac{1.75(1-\varepsilon)}{\varepsilon^3 d} \rho \end{cases} \tag{10}$$

in which:

ΔP - grain airflow resistance, Pa;

v - airflow rate, m·s^{-1};

A and B - model coefficients related to the porosity, grain diameter, density and viscosity of the ventilation medium, and can be obtained through experiments;

ε - porosity, %;

d - grain diameter, m;

ρ - density of the ventilation medium, kg·m^{-3},

μ - viscosity of the ventilation medium, Pa·s.

It can be seen from [eq. (10)] that the grain airflow resistance has a linear relation with the grain thickness, and a non-linear relation with the airflow rate. When the initial grain weight and air flux are fixed, changing the ventilation area, the grain thickness and airflow rate will change correspondingly, while the grain airflow resistance can be calculated by eqs. (11) and (12):

$$\frac{-\Delta P_1}{h_1} = Av_1 + Bv_1^2 \tag{11}$$

$$\frac{-\Delta P_2}{h_2} = Av_2 + Bv_2^2 \tag{12}$$

Substituting eqs. (3) and (6) into [eq. (11)], and then simplifying the equation, yields

$$\frac{-\Delta P_1}{h_2} = 4Av_2 + 8Bv_2^2 \tag{13}$$

According to eqs. (12) and (13),

$$\frac{\Delta P_1}{\Delta P_2} = \frac{4Av_2 + 8Bv_2^2}{Av_2 + Bv_2^2} \in [4,8] \tag{14}$$

Equation (14) shows that when the initial grain weight and air flux are the same, doubling the ventilation area will decrease the the grain airflow resistance by 4-8 times. Therefore, enlarging the ventilation area may effectively reduce grain airflow resistance, and further decrease the energy consumption of ventilation. Meanwhile, a fan of lower power can be selected to reduce the equipment cost.

State parameter of drying medium

The drying process of grain is a result of heat and mass transfer between the grain and the medium. The capacity of a medium to take moisture directly is related to the drying efficiency and energy consumption of the system. Hot air, as wet air formed by mixing dry air and vapor, is particularly an ideal mixture in which vapor can be overheated or saturated and may change in the state under certain conditions depending on the temperature of the wet air and partial pressure of the vapor. The pressure of the wet air equals the partial pressure of dry air plus the partial pressure of the vapor, as shown in [eq. (15)]. The relative humidity is the ratio of the partial pressure of the vapor in the wet air to the pressure of saturated vapor at the same temperature, as shown in [eq. (16)]. The saturated vapor pressure of the wet air is correlated with the corresponding temperature and can be found by [eq. (17)], while the moisture content of the wet air can be found by [eq. (18)]:

$$p = p_a + p_v \tag{15}$$

$$\varphi = p_v / p_s \tag{16}$$

$$p_s = 133.3224 \times \exp(18.7509 - \frac{4075.16}{236.516 + t}) \tag{17}$$

$$d = 0.622 \cdot \frac{\varphi p_s}{p - \varphi p_s} \tag{18}$$

Equation (18) can be simplified into

$$p = \varphi \cdot \frac{p_s(0.622 + d)}{d} \tag{19}$$

in which:

p - pressure of the wet air under the standard atmospheric pressure, Pa;

p_a - partial pressure of dry air, Pa;

p_v - partial pressure of vapor, Pa;

φ - relative humidity, %;

t - temperature of hot air, ℃,

d - moisture content, kg·kg-1.

It can be seen from eqs. (17) and (19) that since p_s is correlated with the temperature, when d and t remain the same and the vapor in the air is not condensed, the relative humidity φ is in direct proportion to the atmospheric pressure p, which means when the atmospheric pressure increases by a percentage, the relative humidity will also increase by the same percentage, i.e.,

$$(p + \Delta p) = (\varphi + \Delta\varphi) \cdot \frac{p_s(0.622 + d)}{d} \tag{20}$$

in which:

Δp - variation of grain airflow resistance, Pa;

$\Delta\varphi$ - variation of relative humidity, %.

Under the same initial grain weight and air flux, when changing the ventilation area, the grain airflow resistance will change by 4-8 times that of the grain thickness. Therefore, it can be inferred that under the same initial grain weight and air flux, enlarging the ventilation area and reducing the grain thickness may increase the capacity of the drying medium to take moisture from the grain, thereby improving the drying efficiency and decreasing the drying energy consumption.

Saturated humidity line

For grain deep-bed drying, as hot air flows from the inlet through the grain to the outlet, the hot air has its relative humidity gradually increased until it gets saturated and loses its drying capacity. This saturated humidity line gradually develops to the top of the drying tower. When the saturation humidity line moves too slowly and exceeds the limit time of grain germination and mildew under the corresponding temperature, the drying quality will be affected. If there is no saturated relative humidity line or the relative humidity of the outlet air is very low, it will increase the drying energy consumption. (Li et al., 1996) studied the characteristics of deep-bed drying of wheat, explored the movement of the saturated humidity line through the grain layer depth, and the drying capacity on both sides of the saturation humidity line was determined. After the hot air reached saturation, the relative humidity was kept at 100%, the drying ability would be lost or condensed when flowing through the grain layer, and even lead to grain mildew. (Yang et al., 2007) researched how the ratio of air flux to grain mass would affect the drying rate and found that the time required for the saturation relative humidity line to move out of the grain layer was positively correlated with the amount of dry grain that has begun to dry. The drying conditions and the initial moisture content of grain had a significant impact on the moving time. Based on the ratio of air flux to grain mass, the rule governing the motion of the saturation humidity line was obtained. According to the literature, when the air flux and initial grain weight grain were the same, enlarging the ventilation area or reducing the grain thickness may shorten the time required for the saturated humidity line to move through the grain, improve the uniformity of the grain's drying, and improve the quality of the grain's drying.

Evaluation of the uniformity

In the field of grain drying, how to evaluate the uniformity of moisture content in a grain drying layer is one of the important methods to study the quality of the grain drying. This evaluation is commonly performed by way of regression analysis, variance analysis, range estimation or otherwise as provided in the principles of mathematical statistics. Compared with the above methods, the uniformity evaluation method can objectively and simply evaluate the uniformity of grain in the grain drying layer. The standard deviation was used to observe the variation of a set of data, as shown in [eq. (21)]:

$$S = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \tag{21}$$

in which:

S - standard deviation;

n - total number;

x_i - value of the i th data,

$\bar{x}$ - average value.

A larger standard deviation suggests a greater variation in the data; a smaller standard deviation suggests a smaller variation. The variation coefficient C_v can be used for evaluating data: the calculation can be done by

$$C_v = \frac{S}{\bar{x}} \cdot 100\% \tag{22}$$

in which:

C_v - variation coefficient, %.

A smaller variation coefficient of the dataset suggests higher uniformity in the data; a larger variation coefficient suggests less uniformity. However, the variation coefficient is non-intuitive. It may be more intuitive to evaluate the uniformity, which may be calculated by [eq. (23)]:

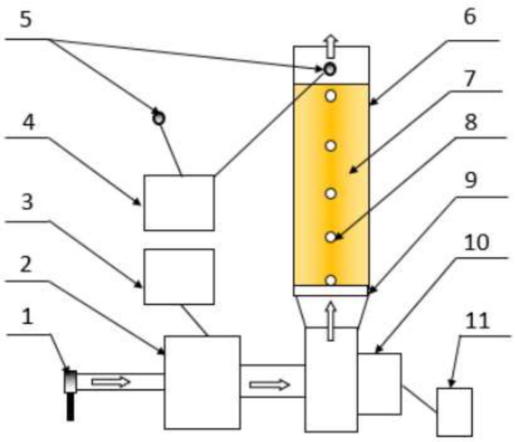
$$J = 100\% - C_v \tag{23}$$

in which:

J - drying uniformity, %.

Uniformity is expressed in percentage. A larger number indicates better uniformity. The uniformity index can directly reflect the uniformity of the data. Namely, the uniformity of a dataset or multiple datasets can be directly and easily evaluated by using the uniformity index.

Experimental device and methods



Note: 1. Anemoscope 2. Heater 3. Temperature control system 4. Data-collecting system 5. Temperature-humidity sensor 6. Dryer 7. Paddy 8. Sampling/testing hole 9. Screen 10. Centrifugal fan 11. Transducer

FIGURE 2. Schematic diagram of testing device.

The experimental paddy was selected from the w74 indica paddy of South China Agricultural University with an initial moisture content of 24.36%w.b. and removeal of impurities. During the test, the average temperature and average relative humidity were 26.1℃ and 62.9% respectively. The dryer was self-made in the laboratory. Before each test, the drying chambers, with cross-sectional areas of S1 and S2, were filled with paddy of the same quality by natural accumulation at the same height. The ventilation area was changed by changing the cross-sectional area of the drying chamber. The air medium heated by the heater was introduced into the drying chamber by a centrifugal fan for ventilation drying. Each group of tests was repeated three times, assuming that the porosity and compaction degree of the drying bed remain unchanged.

Before each test, the drying chamber was filled with the same mass of the grain, then the ventilation area was changed, and a centrifugal fan was used for paddy ventilation drying. During drying with hot air at 70℃, the grain was weighed every 0.5 h and the average moisture content of the grain was calculated. Meanwhile, grain samples were taken from sampling holes for testing the moisture content. When drying at 35℃, this was measured once every 1 h. The grain airflow resistance was measured with a Micro pressure differential gauge after each time of sampling during stable operation of the fan, and the average value was calculated. A temperature-humidity sensor was installed at the exhaust outlet, and real-time records of the variation in the temperature and humidity of the exhausted air were maintained until the average moisture content of the grain basically met the condition for safe storage. The initial moisture content of the paddy was determined by the oven method, and the moisture content of the paddy during drying was determined by a halogen moisture tester. The test instrument and setting table are shown in Table 1 and Table 2.

TABLE 1. Testing instruments for the experiment.

Manufacturer	Name and model	Measuring range	Precision
Delta	Frequency converter VFD002M43B	2.2 kw	-
Guangzhou Jiegao Ventilation Equipment Plant	Centrifugal fan	2.2 kw	-
Fietser	Electronic scale DY-718	0~30 kg	1 g
Smart	Anemoscope 100836	0.001~ 45 m/s	0.01 m/s
Testo	Micro pressure differential gauge TESTO510	0~10 kPa	1 Pa
Ason	Temperature-moisture sensor AM2301	0~100%, -40~80℃	±3%, ±0.5℃
Changzhou Xingyun	Halogen water-measuring meter	0~100%	0.01%
Independent development	Data-collecting system	-	-
Independent development	Temperature-control system	-	-

TABLE 2. Test settings.

Cross-sectional areas of drying chamber (m^2)		Area ratio	Hot air drying temperature (℃)		Airflow rate ($m^3 \cdot h^{-1}$)	Test details
S1	0.02955	1:2.328	T1	35	12.3	The drying chamber was weighed at fixed times, moisture content of sample grain was measured taken from sampling holes, grain airflow resistance and the current of the fan were measured.
S2	0.06878		T2	70		

RESULTS AND DISCUSSION

Grain airflow resistance

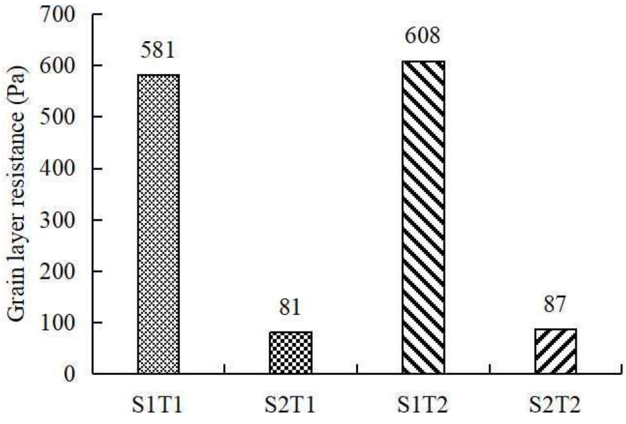


FIGURE 3. The relation between grain airflow resistance and ventilation area under conditions of the same initial paddy weight and air flux.

It can be seen from Figure 3 that enlarging the ventilation area significantly reduces the grain airflow resistance. Under drying conditions of 35℃ and 70℃, the reduction of the grain layer resistance were 7.17 and 6.99 times, respectively, which is consistent with the result of theoretical analysis. The grain airflow resistance when drying at 70℃ was greater than at 35℃, which could mainly be attributed to the expansion of air due to exposure to heat that had increased the dynamic viscosity of air to form greater resistance in the pressure chamber of the centrifugal fan, thereby requiring greater pressure for the air to flow through the grain. The test result also suggests that enlarging the ventilation area can significantly reduce the energy consumption of the fan.

Analysis of drying energy consumption

According to Figure 4, enlarging the ventilation area effectively accelerates the drying of the grain, particularly when drying at 70℃, and hence decrease the drying energy consumption.

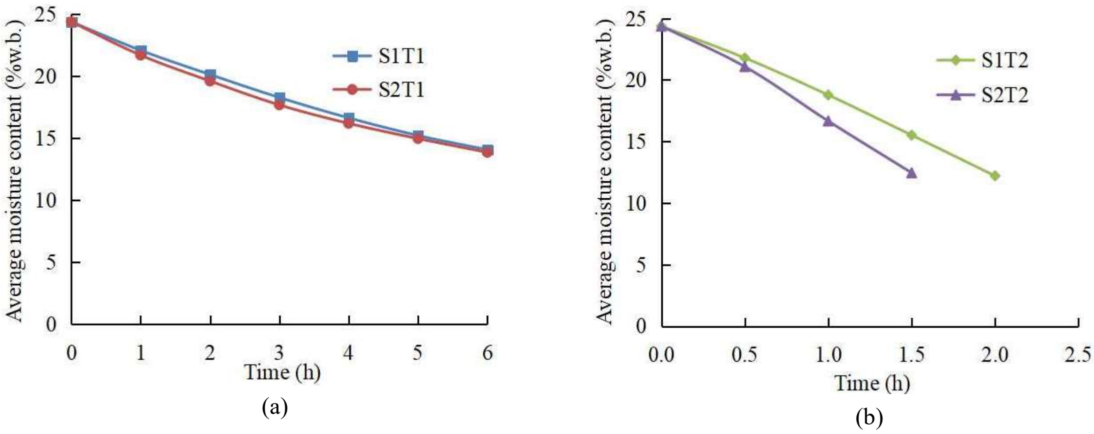


FIGURE 4. Variation of average moisture content of paddy with time in the drying chamber under different ventilation areas and different drying temperatures (a) 35℃ and (b) 70℃.

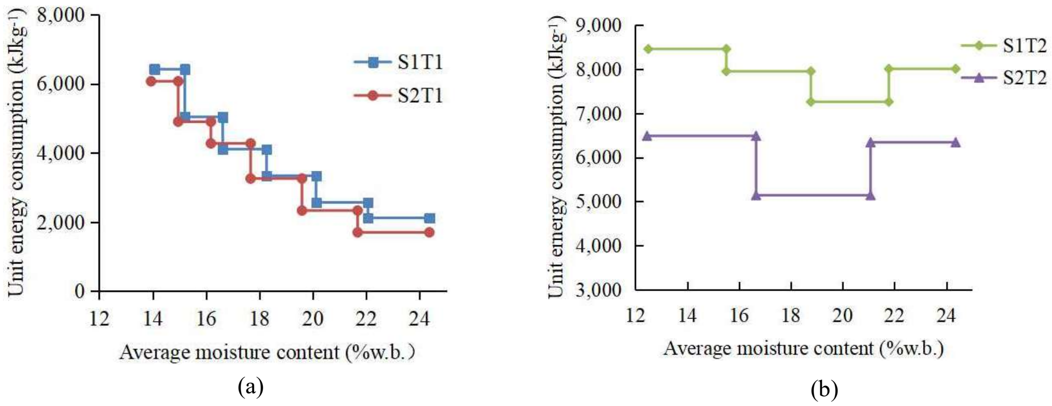
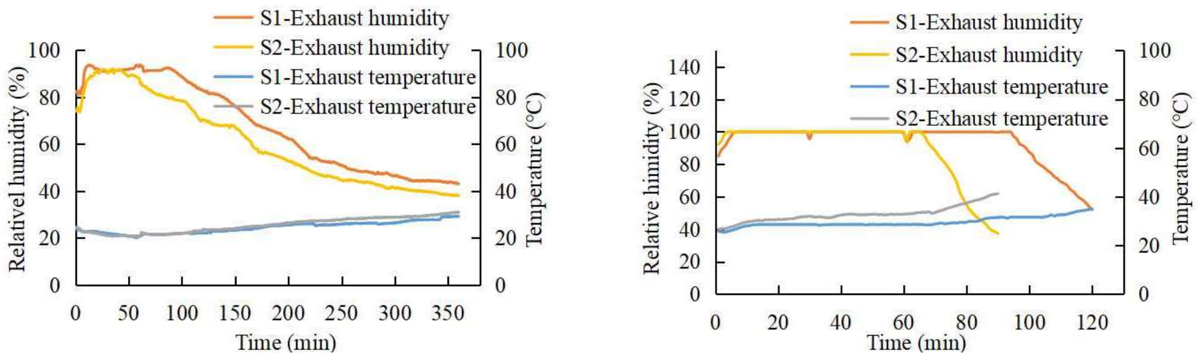


FIGURE 5. Variation of unit energy consumption with average moisture content of paddy under different ventilation areas and different drying temperatures (a) 35℃ and (b) 70℃.



(a) (b)

FIGURE 6. Variation of exhaust temperature and relative humidity with time under different ventilation areas and different drying temperatures (a) 35℃ and (b) 70℃

According to Figure 5, when the grain was dried at 35℃, the unit energy consumption continuously increased as the average moisture content decreased; when the grain was dried at 70℃, the unit energy consumption was high at the very beginning mainly because of the rise in the grain temperature, and later also went up as the average moisture content decreased, which is consistent with the analytical results of the thermal energy structure and moisture-binding energy of grain drying by (Li et al., 2014).

Saturated humidity line

Figure 6 shows that the exhaust was basically not saturated at 35℃. Namely, no saturated humidity line was formed, moisture was insufficiently taken away, and the drying efficiency was low. At 70℃, the exhaust became saturated quickly at the very beginning of the drying, the time required for the saturated humidity line to move out of the grain experienced a significant change as the ventilation area changed, the time required with the ventilation area of S2 shortened by 29 minutes compared with that with the ventilation area of S1. Therefore, it can be inferred that enlarging the ventilation area shortens the time required for the saturated humidity line to move through the grain, improving the drying efficiency and help ensure the quality of the drying.

Evaluation of drying uniformity

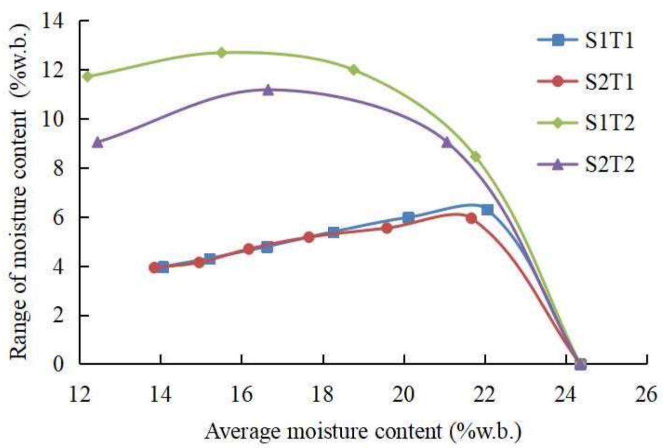


FIGURE 7. Variation of the range of moisture content with average moisture content under different drying conditions

Figure 7 shows that at 70℃, the range of grain moisture content between upper and lower levels in the drying chamber rapidly increased at the beginning when the average moisture content decreased, and later slowly reduced. At 35℃, the range of grain moisture content between upper and lower levels in the drying chamber also increased quickly at the beginning, and later gradually became stable. Thus, enlarging the ventilation area can effectively reduce the range of grain moisture content between upper and lower levels, and the range of grain moisture content under drying at 35℃ was far lower than that at 70℃.

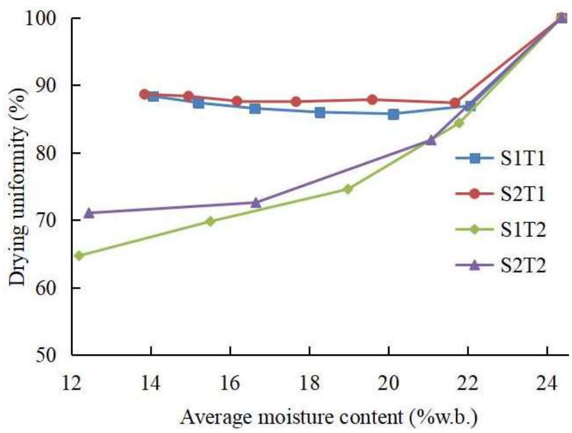


FIGURE 8. Variation of drying uniformity with average moisture content under different drying conditions.

Figure 8 shows that the uniformity of paddy drying decreased with a decrease in the average moisture content, and tended to be stable in the later stage, under the drying condition of 35℃, the uniformity of paddy moisture content in the drying layer was significantly better than that of 70℃. Enlarging the ventilation area can effectively improve the uniformity of paddy drying, especially at 70℃.

CONCLUSIONS

The ventilation area is one of the constant volume structural parameters, which is the key parameter for designing a grain dryer. Through theoretical analysis, it can be shown that under the same initial grain weight and air flux, enlarging the ventilation area can effectively reduce the drying energy consumption and improve the drying uniformity. On this basis, enlarging the ventilation area by 2.328 times, an experimental study was carried out under the drying conditions of 35℃ and 70℃. The experimental results were consistent with the theoretical analysis, which verifies the reliability of the theoretical analysis.

ACKNOWLEDGEMENTS

The authors extend thanks to the Guangdong Provincial Department of Education Youth Innovative Talents Project (Grant no. 2017KQNCX123), Zhanjiang Science and Technology Plan Project (Grant no. 2017A03013 and 2022A01058). Lingnan Normal University Special Project (Grant no. ZL1806) for their financial support, which was indispensable to the execution of this study.

REFERENCES

Audu J, Awulu JO, Anyebe SP (2018) Modeling and optimization of airflow resistance through a dry bed of Bambara nuts. Agricultural Engineering International: CIGR Journal 20(4): 169–177.

Audu J, Anyebe SP (2018) Pressure drop and airflow resistance of African yam beans (Sphenostylis Stenocarpa). Australasian Journal of Agricultural Engineering 01(01):6-10.

Ergun S (1952) Fluid flow through packed columns. Chemical Engineering Progress 48(2): 89-94.

Gao S, Wang YC, Qiu HY, Yang J (2017) Numerical simulation for anisotropic resistance of wheat under the condition of mechanical ventilation. Journal of the Chinese Cereals and Oils Association 32(02): 116-119.

Hukill WV, Ives NC (1955) Radial airflow resistance of grain. Agricultural Engineering 36(5): 332-335.

Jia C, Wang L, Guo W, Liu C (2016) Effect of swing temperature and alternating airflow on drying uniformity in deep-bed wheat drying. Applied Thermal Engineering 106: 774-783.

Jittanit W, Srzednicki G, Driscoll RH (2013) Comparison between fluidized bed and spouted bed drying for seeds. Drying Technology 31(1): 52-56.

Kashaninejad M, Tabil LG (2009) Resistance of bulk pistachio nuts (ohadi variety) to airflow. Journal of Food Engineering 90(1): 104-109.

Kashaninejad M, Maghsoudlou Y, Khomeiri M, Tabil LG (2010) Resistance to airflow through bulk pistachio nuts (kalleghochi variety) as affected by moisture content, airflow rate, bed depth and fill method. Powder Technology 203(2): 359-364.

Kumar AK, Gupta AK (2006) Stationary versus fluidized-bed drying of high moisture paddy with rest period. Drying Technology 24 (11) :1443-1456.

Li CY, Shao YJ, Kamide J (1996) Measuring the drying characteristics of wheat in a deep-bed from continuous drying air dynamics. Journal of South China Agricultural University 17(01): 102-107.

Li CY, Mai ZW, Fang ZD (2014) Analytical study of grain moisture binding energy and hot air drying dynamics. Transactions of the Chinese Society of Agricultural Engineering 30(07): 236-242.

Li CY, Ma XZ, Fang ZD, Zhang Y (2014) Thermal energy structure of grain hot air drying and analytical method. Transactions of the Chinese Society of Agricultural Engineering 30(9): 220-228.

Li CY (2012) Exergy evaluation theory of hot air drying system for grains. Transactions of the Chinese Society of Agricultural Engineering 28(12): 1-6.

Li T, Li CJ, Li CY, Xu FY, Fang ZD (2019) Porosity of flowing rice layer: Experiments and numerical simulation. Biosystems Engineering 179: 1-12.

Liu LY, Hao SY, Zhang M, Liu DM, Jia FG, Quan LZ (2015) Numerical simulation and experiment on paddy ventilation resistance based on CFD-DEM. Journal of Chinese Agricultural Mechanization 46(8): 27-32, 158.

Ma XZ, Fang ZD, Li CY (2017) Energy efficiency evaluation and experiment on grain counter-flow drying system based on exergy analysis. Transactions of the Chinese Society of Agricultural Engineering 33(22): 285-291.

Molenda M, Montross MD, McNeill SG, Horabik J (2005) Airflow resistance of seeds at different bulk densities using Ergun's equation. Transactions of the ASAE 48(3): 1137-1145.

Nalladurai K, Alagusundaram K, Gayathri P (2002) Airflow resistance of paddy and its byproducts. Biosystems Engineering 83(1): 67-75.

Sacilik K (2004) Resistance of bulk poppy seeds to airflow. Biosystems Engineering 89(4): 435-443.

Sadaka SS, Luthra K, Atungulu GG (2018) Evaluation of the performance of a custom-made fluidized bed drying system. Applied Engineering in Agriculture 34(6):1027-1037.

Shedd CK (1953) Resistance of grains and seeds to air flow. Agricultural Engineering 34(9): 616-619.

Souza G, Miranda RF, Lobato FS, Barrozo M (2015) Simultaneous heat and mass transfer in a fixed bed dryer. Applied Thermal Engineering 90: 38-44.

Srimitrungroj T, Soponronarit S, Prachayawarakorn S, Nathakaranakule A (2019) Evaluation of new parboiled rice process using humidified hot air fluidized bed drying. Drying technology, 37(8), 1044-1052.

Yang X, Williams DA (1990) Airflow resistance of grain sorghum as affected by bulk density. Transactions of the ASAE 33(6): 1966-1970.

Yang Z, Luo XW, Li CY (2007) Study on optimal ratio of air flux to grain mass for rough rice drying. Journal of Chinese Agricultural Mechanization 38(05): 122-125.

Zhang Y, Li CY, Ma XZ, Li JM, Zou XJ, Wang RF (2014) Experiment and numerical simulation of layer resistance parameters in dryer. Journal of Chinese Agricultural Mechanization 45(07): 216-221.