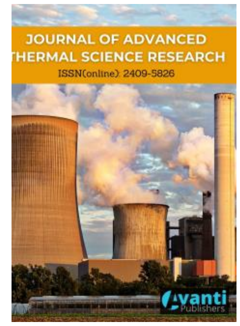
Journal of Advanced Thermal Science Research, 2022, 38-49

Published by Avanti Publishers

Journal of Advanced Thermal Science Research

ISSN (online): 2409-5826



Research on Energy Saving and Environmental Protection Electric Power Grain Circulation Drying System

Guiying Wang[1,*], Fengxiang Qiao[2] and Zhongfen Yue[3]

[1]*Biological and Agricultural Engineering Institute, Jilin University, Changchun 130025, China*
[2]*Changchun MANN+HUMMEL FAWAY Filter Co., Ltd, Changchun 130013, China*
[3]*Changchun Jida Scientific Instrument Equipment Co. Ltd, Changchun 130025, China*

ARTICLE INFO

Article Type: Research Article

Keywords:
Grain drying
Condensation
Electric power
Energy environment protection
Energy conservation protection

Timeline:
Received: January 03, 2022
Accepted: April 05, 2022
Published: June 20, 2022

Citation: Wang G, Qiao F, Yue Z. Research on Energy Saving and Environmental Protection Electric Power Grain Circulation Drying System. J Adv Therm Sci Res. 2022; 9: 38-49.

DOI: https://doi.org/10.15377/2409-5826.2022.09.4

ABSTRACT

A 50-ton/batch electric grain circulation drying system was designed that adopted clean electric energy as a drying heat source. The exhaust gas of the dryer was recycled after condensation and dehumidification. The drying system has the advantages of energy saving and environmental protection. The corn drying test showed that the specific heat consumption was 3185 kJ/kg H_2O in close operating mode, compared to the Chinese standard of 5700 kJ/kg H_2O, and the energy consumption ratio was 44%. This research pioneers a way of saving energy and protecting the environment from drying and comes up with a new thought on how to utilize the waste heat from exhaust gas and the latent heat released by the evaporation of water vapor reasonably.

*Corresponding Author
Email: guiying9602@163.com
Tel: +(86) 13844178220

1. Introduction

According to reports, drying accounts for 10-25% of industrial energy use in developed countries, and the innovation of drying technology focuses on improving energy efficiency and reducing carbon emissions of dryers [1-2]. According to a study of 11 industrial branches in the United Kingdom, drying energy consumption accounts for 11.6% of the total energy consumption. A study by Italian scholars pointed out that drying energy consumption accounts for 64% of grain production and processing energy consumption [3], and Chinese drying energy consumption accounts for about 12% of the total energy consumption of the national economy [4-5], with the increase in Chinese grain production and the acceleration of the process of grain drying mechanization, the energy consumption for grain drying is gradually increasing. In the context of the global fossil energy crisis, the dryer industry has been seeking ways to reduce drying energy consumption, such as increasing the thermal efficiency of heat sources, improving the heat preservation of hot blast stoves, air ducts, dryers, and exhaust gas recovery [6] etc., especially the method of improving energy efficiency through partial exhaust gas recovery is an easy-to-implement and low-cost option [7-9]. According to research, the sensible heat in the exhaust gas of the dryer accounts for about 30% of the total heat consumption, and the latent heat taken away by the evaporation of water accounts for 30% to 50% [10-11]. These two parts of heat are recovered appropriately, which can effectively save energy. In terms of reducing the pollutant emissions of the dryer, the coal-fired hot blast stove has been gradually transformed into a hot blast stove using oil, gas, and biomass [12], and corresponding results have also been achieved. This system recycles all the wet and hot exhaust gas dehumidified by condensation in the drying section and cooling section of the dryer, and uses clean electric energy as the heat source, which is clean and pollution-free. It solves the technical key to energy saving and emission reduction of grain dryers, realizes the clean production process of the grain drying operation, recycles the waste heat of exhaust gas, and develops the latent heat released by the condensation of water vapor, which opens up a clean production road for the grain drying industry with economic, social, environmental, resource coordination and sustainable development [13].

After the dryer structure and auxiliary equipment are determined, its exhaust parameters are mainly related to the ambient temperature and humidity, atmospheric pressure, the types and the initial and final moisture content of the grain [14]. The exhaust gas temperature of the dryer is generally 30-60°C, and the relative humidity is about 50%-80%, which belongs to low-temperature waste heat resources. Although the temperature is not high, the flow is large and continuous, and stable. If reasonable measures are taken to dehumidify the exhaust gas and reuse it, the dryer will achieve a tremendous energy-saving effect. Electric energy is clean, efficient, convenient, and easy to control and convert. If electricity is used as a heat resource for the grain dryers, when the exhaust gas of the dryer is not recycled, it requires a large power configuration. For users, a higher power configuration means higher drying costs. This drying system uses a condenser to condense and dehumidify all the wet and hot exhaust gas discharged from the dryer, then additionally heats them with electric heaters and makes them return to the drying section of the dryer for reuse so that the drying medium forms a closed cycle in the drying system [15]. Temperature and humidity parameters of grain and drying medium can be displayed in real-time, the condensation effect of the drying medium can automatically be controlled by controlling the ratio of the cold and hot fluid flow in the condenser, and hot air temperature can be controlled through the temperature-controlled meter. The index of the condensation effect is reflected by the condensation intensity, which is defined as the absolute humidity difference before and after the exhaust gas condensation.

The heat pump drying technology developed in the 1970s was first applied in the United States, Japan, Germany, and other countries. In the past ten years, it has also been rapidly developed in China and has been applied to the drying of wood, tea, tobacco, vegetables, and agricultural and sideline products such as fish, and sterilization and drying of biological products such as medicines, scholars at home and abroad have achieved certain research results in heat pump drying kinetics, drying system design and automatic control, heat pump drying mode, drying technology and economic research [17-21]. Although the heat pump grain dryer is energy-saving and clean and has no pollution emission, the single-stage compression heat pump dryer cannot provide drying temperature above 85°C, which cannot meet the requirements of high-temperature drying. The two-stage compression heat pump dryer is under study. In addition, equipment costs are high, maintenance costs are also high, and refrigerant leakage affects the environment [22]. No relevant reports have been found about the dryer system that uses electric energy as the heat source and recycles all exhaust gas after condensation and dehumidification in domestic and foreign works of literature.

2. Materials and Methods

2.1. Experimental Rig

The working principle diagram of this system is shown in Figure **1**. The system includes two processes and two cycles. The two processes are the grain drying process and the condensation process of the drying medium, and the two cycles are grain flow circulation and drying medium flow circulation. The grain flow circulation is the circulation of dried grain between the tempering section, the drying section, the grain discharge section, and the elevator of the dryer. It facilitates the continuous contact of the grain and the drying medium and the exchange of moisture and heat during the process of the circulating dryer. The drying medium flow circulation is a process as follows; the drying medium is heated to a predetermined hot air temperature, then fed into the dryer through the hot fan. Heat and humidity are exchanged between the drying medium and the grain in the drying section. Furthermore, the wet and hot exhaust gas is dehumidified by the multi-stage condensing heat exchanger, then heated by the heater, and then sent to the drying section of the grain dryer for the next cycle of drying. This experimental rig uses a tubular condensing heat exchanger, and the recycled exhaust gas flows through the external condenser heat exchange tube as a hot fluid, and the external cold air flows through the inside of the heat exchanger tube as a cold fluid. Part of the heated cold fluid discharged from the condenser is mixed with the outside cold air and flows into the condenser as a cold fluid. This is to make the cold fluid temperature suitable for the condensation process, and the remaining part is mixed with the condensed and dehumidified exhaust gas as a drying medium and sent to the electric heater for additional heating, and the condensed water is collected in the water tank.

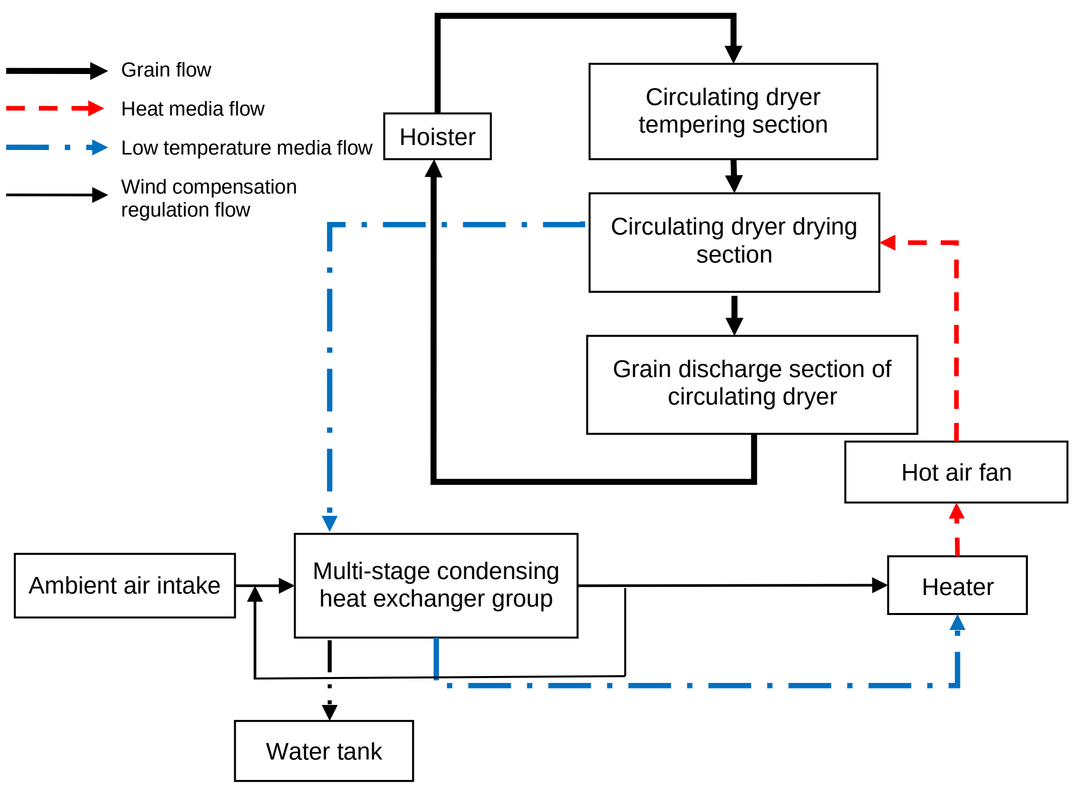


Figure 1: Schematic diagram of drying system.

The external and interior photos of this system are shown in Figure **2**. The system comprises of five parts: dryer, exhaust gas recovery duct, condenser, electric heater, and control system. The dryer is a 50 ton/batch circulating grain dryer with a grain-loading volume of 75.63m^3 and a total installed capacity of 223kw for the entire system. The hot and humid exhaust gas discharged from the drying section is recovered through the air duct to the condenser. The condenser adopts the form of a horizontal tubular heat exchanger, and the outside of the hoist and the dryer of the whole system are insulated with rubber and plastic insulation cotton. The exhaust gas recovery air duct, condenser, and electric heater are installed inside the steel room to reduce heat loss.

(1) External photo of drying system

(2) Internal photo of drying system

Figure 2: Photos of the exterior and interior of the drying system.

The models and measurement accuracy of various sensors and electric energy meters used in the system are shown in Table **1**.

Table 1: The main measuring parameters and instruments of the system.

Measurement Parameters	Air Temperature and Humidity	Air and Grain Temperature	System Weight	Electricity
Measuring instrument	temperature and humidity transmitter	Pt100	TQ-717	DTZY341-GThree-phase four-wire smart energy meter
Measuring range	-40-100°C,0-100%	0-300°C	0-80T	
Measurement accuracy	±0.5°C, ±3%	0.3°C	0.1kg	0.01Kwh

The batch circulating dryer has only one drying section; the size of the drying section is 3600mm×3580 mm×3060 mm(length × width × height), and the volume of the drying section is 39.4m^3. The material that needs to be dried can be dried by exchanging moisture and heat with the drying medium in the drying section. Corn was used in this experiment. The weather conditions on the day of the experiment and corn parameters are shown in Table **2**.

According to the change in the absolute humidity of the drying medium before and after condensation during the test, the working mode is selected. There is an air volume distribution door at the air duct connecting the electric heater and the condenser. When the moisture removal fan is opened, and the air volume distribution door is open, it is an open working mode. When moisture removal fan and the air distribution door both are closed, it is a closed working mode, which is also called a full-circulation working mode. This paper compares and analyzes the energy consumption index and energy-saving effect of the system in the two modes through the corn drying experiment under the stable operation of the test system.

Table 2: Weather situation and corn parameters on the test day.

Test Date	System Working Mode	Project	Parameter
2018.12.28	Open	Ambient temperature Ambient humidity Corn weight Corn initial moisture	-13～-21°C 46% 39.788t 22.5%
2019.1.8	Full-circulation	Wet corn bulk density Ambient temperature Ambient humidity Corn weight Corn initial moisture Wet corn bulk density	691 kg /m^3 -11～-17°C 38% 39.96t 24.9% 700 kg /m^3

The system has three fans. The model of each fan and the motor frequency and corresponding air volume flow selected during the working process in the two modes are as follows:

Table 3: Fan parameters used in the system in different operating modes.

Working Mode	Name	Model	Working Frequency（Hz）	Air Volume Flow（m^3/h）
Open	Hot air fan	4-72-11 N06C	30	5400～7800
	Condensing blower	4-72N0 4A	30(2.5h) 40(8.5h) 50(15h)	1203.6～2225.4 1604.8～2967.2 2006～3709
	Moisture removal fan	4-72N0 3.6A	10	532.8～1053.6
Close	Hot air fan	4-72-11 N06C	30	5400～7800
	Condensing fan	KT30-7	30(3h) 60(34h)	12540 25080
	Moisture removal fan	4-72N0 3.6A	0	0

Remarks: The number in parentheses of the operating frequency is the operating time of the fan at that frequency.

The fans in the system are equipped with frequency converters. The fan frequency is proportioned and set according to the condensation intensity of the condenser during the working process and the drying efficiency in the drying section.

The system uses the total weight method to detect the grain moisture in real-time during the drying process [23], the electronic car weigher measures the initial weight of the grain, and the oven method measures the initial moisture of the grain and then detects the grain weight in real-time through the load cell, and the system calculates the grain moisture in real-time during the drying process.

During the drying process, the control system real-time displays parameters of the drying medium and grain and system power during the drying process with the touch screen and computer. The drying medium parameters include ambient air temperature and humidity, exhaust gas temperature, and humidity before and after condensation. Grain parameters include real-time grain weight, moisture, and temperature, and the main energy consumption of the system is electrical energy consumption. The test stops automatically when the grain moisture reaches the safe storage moisture.

2.2. Performance Analysis

Three indexes evaluate the performance of the drying system: drying rate, unevenness of drying, and unit energy consumption. The energy consumption of the drying process is analyzed from the absolute water potential of the grain and drying medium.

The drying rate is the change in the wet base moisture content of the material per unit time. The calculation formula is as follows:

$$\mu=(M1-M2)/t \tag{1}$$

Where M1 and M2 are the wet base moisture content of the material before and after drying (%), and t is the drying operation time (H) [24].

The unevenness of drying is the largest difference in the moisture content of the material after drying [24]. The measurement method is to sample 5-7 samples at equal intervals in the grain outlet of the dryer and measure the moisture content separately to calculate the unevenness of drying [25].

The unit heat consumption is the heat consumed per kilogram of water evaporated from the material during the drying process, in kilojoules per kilogram (kJ/kg), and the unit energy consumption is the sum of electrical energy and the heat energy consumed per kilogram of water evaporated from the material during the drying process, in kilojoules per kilogram (kJ/kg) [24]. This test system only consumes electrical energy. The calculation of unit heat consumption only uses the electrical energy consumption of the electric heater, and the unit energy consumption is calculated as the total energy consumption of the electric heater and the system appliances.

From the perspective of moisture migration dynamics, the grain drying process is analyzed, and the relationship between the direction of moisture migration and the heat energy consumption is judged according to the absolute water potential of the grain and air [16]. Moisture evaporates and migrates from the grain to the air, resulting from heat conversion and transfer of work. The ability of moisture to migrate from the surface of the grain to the air reflects the comparison of the absolute water potential of the grain and the air. Water potential is used as the basis for determining the direction of water movement in the system. The water in the system will spontaneously migrate from areas with higher water potential to areas with lower water potential. The absolute water potential of grain is a function of temperature, moisture content, and grain type. The calculation formula is as follows:

$$E_{jg}=(8.31\times(t_g+273)\times\ln\left(\exp\left(\frac{\left(\frac{D}{222}\times\left(e^{\frac{B_1-M}{A_1}}-e^{\frac{B_2-M}{A_2}}\right)+0.9845\right)\times\left(1737.1-\frac{474242}{273+t_g}\right)+D\times\left(1-e^{\frac{B_1-M}{A_1}}\right)-68.57}{87.72}\right)\times 133.3\right)/18 \tag{2}$$

Where t_g is grain temperature, °C, M is grain wet base moisture content, %, A_1、A_2、B_1、B_2、D are the fitting coefficients of different grains in different states of desorption and adsorption, this experiment uses corn as a test and $A_1=4.393$, $A_2=4.845$, $B_1=7.843$, $B_2=3.858$, $D=203.892$.

The absolute water potential of air is a function of temperature and relative humidity, and the calculation formula is as follows：

$$E_{ja}=8.31\times(t_\alpha+273)\times\ln\left(100\times\exp\left(\frac{87.72\times\lg(RH_\alpha)+0.9845\times\left(1737.1-\frac{474242}{273+t_\alpha}\right)-270.57}{87.72}\right)\times 133.3\right)/18 \tag{3}$$

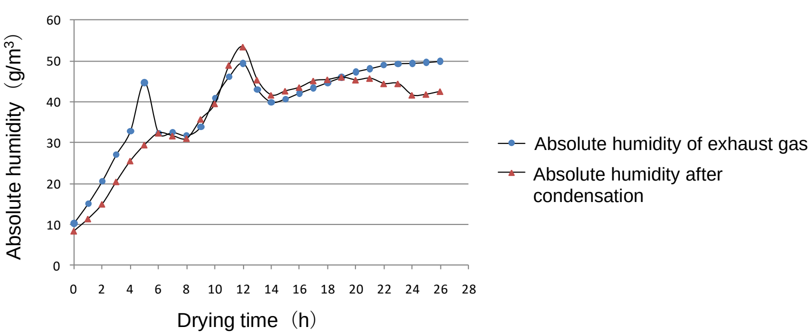
Where t_α is air temperature, °C, RH_α is air relative humidity, %.

3. Results and discussion

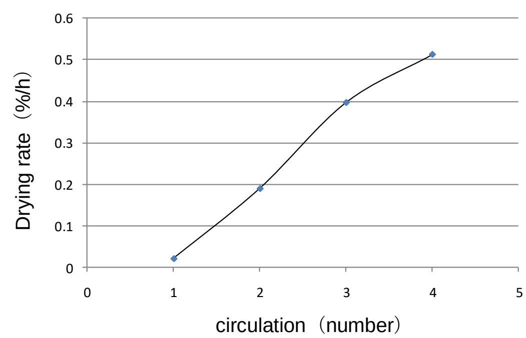
3.1. Relationship between Exhaust Gas Condensation Intensity and Drying Rate

The corn is cyclically dried in this drying system in the open working mode. The absolute humidity of the exhaust gas before and after condensation during the drying process is shown in Figure **3**(a). In order to study the influence of the condensation intensity on the drying rate during the drying process, the test was carried out for 26 hours in the open working mode. The condensation intensity was changed by changing the frequency of the hot air blower and the condensing air blower. The change in the condensation intensity was divided into three stages. The first stage is the 6 hours before drying, during which the condensation intensity increased gradually;

the second stage is the 13 hours of the drying process in which the condensation effect was not obvious; the third stage is the 7 hours after drying where the condensation effect was good, and the condensation intensity increased significantly. It can be seen from the running time of the condensate fan in each frequency range in Table **3** that it takes a period of the buffer adjustment process to adjust the air volume by frequency to change the condensing intensity. After the fan frequency is adjusted, the condensing effect is not immediately apparent. This experiment adopts the intermittent grain discharge method for drying. The grain discharge cycle is 1800 seconds, and the grain discharge time is 497 seconds. According to the amount of grain in the drying section, the frequency of grain discharge, and the single grain discharge volume, the corn in the drying section can be completely discharged in about 7 hours, which can be called a drying cycle. In this experiment, about four drying cycles were carried out. The first stage is the first drying cycle, the second stage is the second and third drying cycles, and the third stage is the fourth drying cycle. Each cycle's average drying rate change curve showed a gradual increase, which can be appreciated in Figure **3**(b). Generally, grains dry at a decreasing rate, but the drying rate of this system gradually increases because of the influence of the condensation. This reflects the influence of the humidity of the drying medium on the drying. The fourth drying cycle in this test has the best condensation intensity, having a drying rate of 0.5%/h, which meets the requirements of T/CAMDA 6-2019 Grain Drying Center Acceptance Technical Specifications [26]: when corn is dried by cyclic drying, the drying rate should be 0.4~ 1.6%/h. Grain dehydration will become more and more difficult, but the system can maintain a more significant drying rate by increasing the condensation intensity, so controlling the drying rate through the condensation intensity is an effective measure. The specific relationship between the two needs further study.

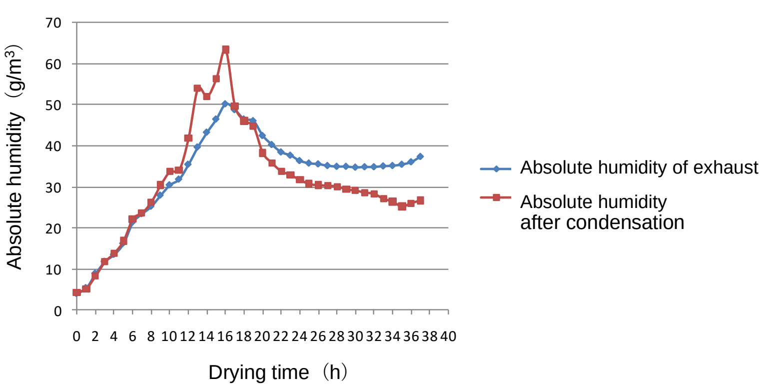


(a) Absolute humidity change curve

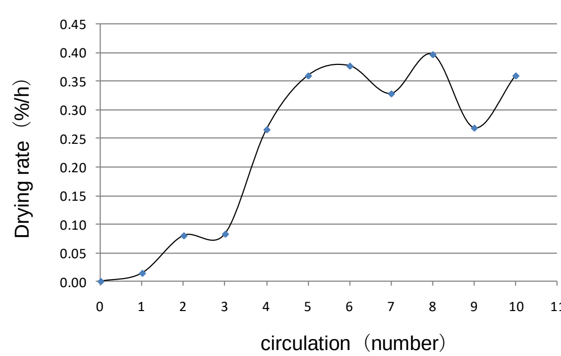


(b) Drying rate change curve

Figure 3: Absolute humidity and drying rate curve in open operating mode.



(a) Absolute humidity curve



(b) Drying rate curve

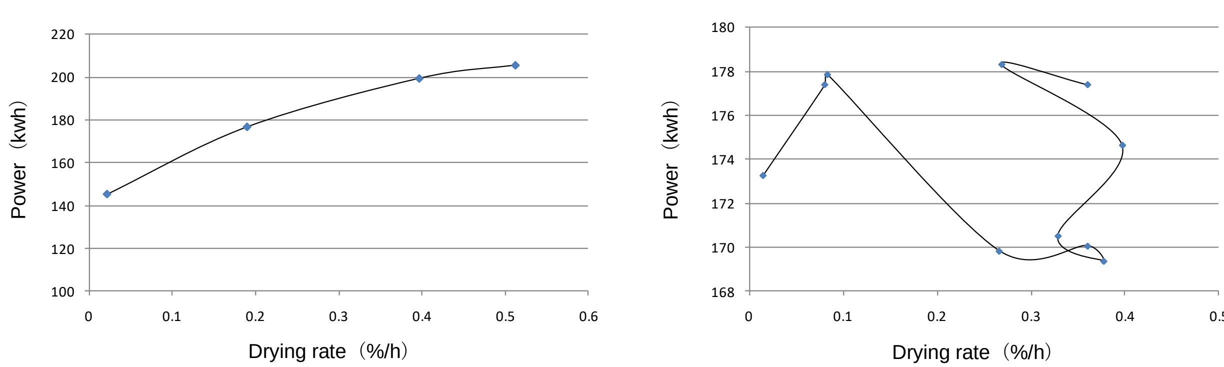
Figure 4: Absolute humidity of drying medium before and after condensation and drying rate curve in close operating mode.

In the closed working mode, according to the condensation intensity change curve, the 37 hours of the test are divided into two stages. The first 17 hours are the first stage; the condensation effect is insignificant or unstable in this stage, and the last 20 hours are the second stage, during which the condensation effect is gradually enhanced. This experiment also uses the cyclic drying method of intermittent grain discharge. In order to improve the productivity of the dryer, the grain discharge cycle is shortened in this experiment. The grain discharge cycle was 900 seconds and the grain discharge time was 480 seconds. The average circulation of each cycle was 3.5 hours, and the change of the grain discharge cycle did not affect the study of the relationship between energy consumption, condensation intensity, and the drying rate in this experiment. The first stage includes nearly 5 cycles, and the second stage includes nearly 6 cycles. In the first stage, especially the first four cycles, the condensation effect was not obvious, and the drying rate was less than 0.1%/h. and the fourth to sixth cycles was the unstable stage of condensation, but the drying rate increased. Since the sixth cycle started, the condensation intensity gradually increased, and the drying rate basically changed between 0.35-0.4%/h. The comparison of the two graphs shows that it meets the law that the drying rate is fast when condensation strength is good. The flow of cold and hot fluid through the condenser can be changed by changing the frequency of the hot air blower and the condensing blower, and the condensation intensity can be controlled by controlling the flow rate. Further, the drying rate can be controlled.

The drying rate is fast when condensation strength is good. As the drying process progresses, the evaporated grain moisture gradually enters the drying medium, the absolute moisture content of the drying medium increases, the wet capacity decreases, and the ability to absorb moisture decreases. However, as the condensation process progresses, the absolute moisture content of the drying medium gradually decreases, the wet capacity gradually rises, and the ability to absorb moisture gradually rises. However, after increasing the flow rate of the cold fluid, the condensation intensity of the change in absolute humidity before and after condensation cannot be reflected immediately, and a buffer adjustment process is required for some time.

3.2. The Relationship between Drying Rate and Energy Consumption

It can be seen from Figure **5**(a) that in the open working mode, the energy consumption increases with the increase of the drying rate, but the increasing trend gradually becomes flat, i.e., the increasing speed is getting smaller and smaller. Therefore, under the premise of guaranteeing grain quality, the condensing intensity should be increased by increasing the frequency of the condensing fan during the drying process to obtain a larger drying rate, and then to increase the drying output. Figure **5**(b) shows the relationship between energy consumption and drying rate in the closed cycle drying mode. From the curve, it can be seen that the energy consumption of the first three drying cycles increases with the increase of the drying rate. The energy consumption decreases at the beginning of the fourth drying cycle, and the drying rate is between 0.27～0.4%/h. The fourth to seventh drying cycle is the stage with lower energy consumption. Starting from the seventh drying cycle, the energy consumption increases but the drying rate decreases. This is because, in the closed cycle drying mode, the condensing effect is not good; as the drying process progresses, the grain moisture is gradually absorbed by the drying medium, the moisture content of the drying medium gradually increases, the drying capacity is weak, and the energy consumption is high. As the condensation intensity increases, the moisture content of the drying medium decreases, the capacity of the drying medium to hold water is enhanced, the drying rate gradually increases, and the energy consumption gradually decreases. After reaching a certain value, the condensation intensity increases due to the decrease in the residual enthalpy of the exhaust gas. The need to supplement the heat gradually



(a) Open working mode **(b) Closed working mode**

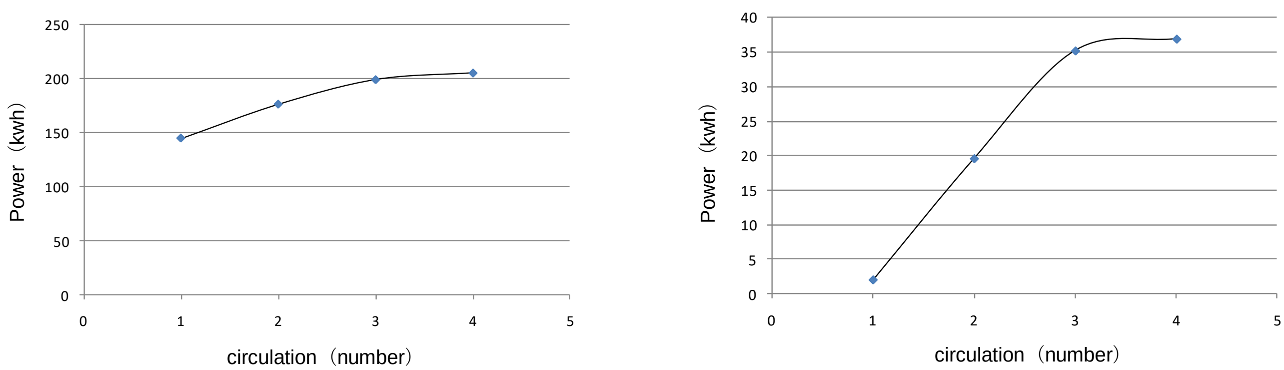
Figure 5: Relation between drying rate and energy consumption.

increases, so the energy consumption increases, and the increase in the drying rate is not obvious. Hence, the closed-cycle drying process has an ideal drying rate and energy-saving stage.

Comparing the energy consumption curves with the drying rate in the two working modes, in the open working mode, the drying rate is between 0.02-0.51%/h, and the hourly energy consumption is between 145-206kwh. In closed working mode, the drying rate is between 0.01-0.4%/h, and the hourly energy consumption is between 169-178kwh. When the drying rate is between 0.27-0.38%/h, there is the lowest hourly energy consumption, i.e., 169kwh, in closed working mode, but the hourly energy consumption in open working mode is greater than 180kwh. Hence, the closed working mode is more energy-saving.

3.3. Analysis of Water Potential and Energy Consumption During the Drying Process

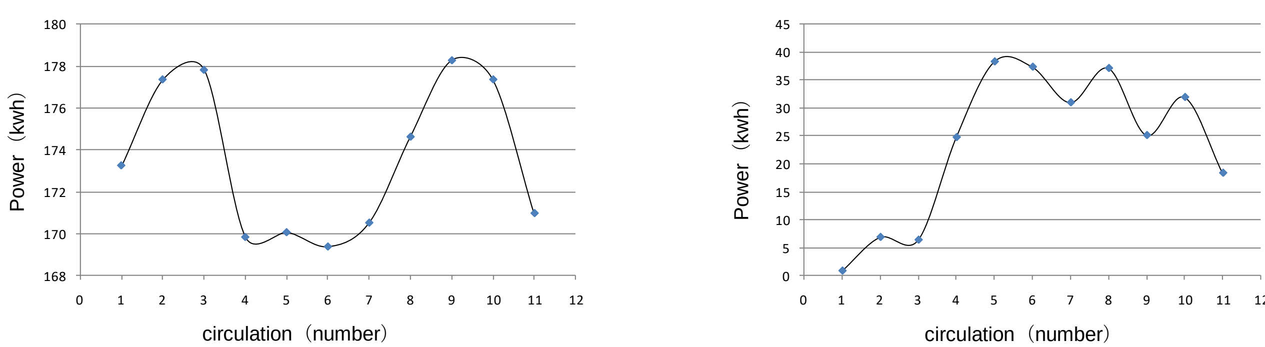
The difference between the grain water potential and the air water potential during the grain drying process is calculated according to the water potential calculation formula. This difference is theoretically equal to the thermal energy required to dry the grain, water migrates from higher to lower levels of water potential, when the grain water potential is higher than the air water potential, water migrates from grain to air, when the grain water potential is lower than the air water potential, water migrates from air to grain, when the two water potentials are equal, water does not migrate.



(a) Actual energy consumption **(b) Theoretical energy consumption**

Figure 6: Actual energy consumption and theoretical energy consumption by analyzing water potential in open operating mode.

It can be seen from the Figure **6** that in the open working mode, the actual power consumption during the drying process averages between 145-205kwh per hour, and through water potential analysis, theoretically, the average hourly supplementary power is between 2-37kwh, which accounts for 1.4%-18.0% of the actual energy consumption. Actual energy consumption includes heat dissipation, the efficiency of various machine components,



(a) Actual energy consumption **(b) Theoretical energy consumption**

Figure 7: Actual energy consumption and theoretical energy consumption by analyzing water potential in close operating mode.

etc. However, water potential analysis can provide a reference for energy consumption requirements during the drying process.

It can be seen in Figure **7** that in the closed working mode, the actual power consumption during the drying process averages between 169-178kwh per hour, and through water potential analysis, theoretically, it needs to replenish electric energy between 1-38kwh per hour on average, which accounts for 0.6%-21.3% of the actual energy consumption. The lowest actual energy consumption is located at the highest point of energy demand analyzed by water potential theory, where energy efficiency is the highest. During the drying process, the drying system can be operated in the highest range of theoretical analysis of water potential by controlling the drying temperature, condensation intensity, etc., in order to make the system more energy-saving.

When comparing the energy consumption curves of the open and closed modes, it is found that the open mode has a larger energy consumption range, the closed mode has a smaller energy consumption range, and there is a working range with lower energy consumption. Under the condition of selecting suitable drying process parameters, the closed mode is more energy-efficient.

3.4. Analysis of Unevenness and Energy Consumption of Grain after Drying

In this paper, through the corn drying experiment, the three drying indicators, i.e., grain drying unevenness, specific heat consumption, and specific energy consumption, are obtained to evaluate the drying performance of the system. The open working mode is shown in Table **4**, and the closed working mode is shown in Table **5**.

Table 4: Drying performance index of the system in open operating mode.

Name	Process Measurement Value	Measured Value	Standard Value
Unevenness of drying	13.6%、13.8%、13.7%	0.2%	≤1%
Specific heat consumption（kJ/kgH_2O）	1202.4kwh/1281kg	3379	≤5700
Specific energy consumption（kJ/kgH_2O）	1447.6 kwh/1281kg	4068	—

Remarks: Symbol in the table "—" indicates no determined value.

Table 5: Drying performance index of system in close operating mode.

Name	Process Measurement Value	Measured Value	Standard Value
Unevenness of drying	14.3%、14.8%、14.5%、14.1%	0.7%	≤1%
Specific heat consumption（kJ/kgH_2O）	592.8kwh/670kg	3185	≤5700
Specific energy consumption（kJ/kgH_2O）	731.2 kwh/670kg	3929	—

Remarks: Symbol in the table "—" indicates no determined value.

Comparing Tables **4** and **5** shows that the unevenness of grain after drying is good in this drying system, and the moisture content is relatively uniform. This is the advantage of circulating drying, and the energy-saving effect is significant. The specific heat consumption in open operating mode is 41% of the standard value, it is 44% in close operating mode. The condensation intensity, the drying rate, and the drying energy consumption can be controlled by controlling the frequency of the hot air blower and the condensing blower, and the whole drying process has no pollutant emission.

4. Conclusion

The control system monitors in real-time and controls the temperature and humidity parameters of the drying medium by controlling the working intensity of the condenser to make it suitable for the drying process. The parameters of the drying medium, grain, and environment air during the working process are graphical displays in the curve interface of the control system. The grain moisture in the drying process is monitored in real-time by the total weight method. According to the water potential parameters calculated from the parameters of grain and hot air during the system's working process, energy consumption trends can be analyzed, and energy consumption can be derived. This drying system is especially suitable for cold or semi-cold areas with a natural cold source. It can work in both open and closed modes by controlling the air distribution door system. Choose the closed working mode if the cold fluid can provide the required condensation intensity. Otherwise, choose the open working mode. The use of clean energy electric energy as the heat source device provides easy, precise, and stable control and has no tail gas emissions. It is also green and environmentally friendly and has no pollution.

The waste heat of the exhaust gas and the latent heat of vaporization released by the condensation of water vapor are utilized by the method of condensation heat increase. By selecting the appropriate condensation intensity, the suitable condensation intensity range in the closed working mode of the system under the test conditions is 1-5g/m^3. The drying rate is 0.27-0.38%/h, and the energy consumption ratio was 44% compared to the Chinese standard of 5700 kJ/kg H_2O.

References

[1] Mustaffar A, Phan A, Boodhoo K. Hybrid heat pipe screw dryer: A novel, continuous and highly energy efficient drying technology. Chem Eng Process. 2018; 128: 199-215.https://doi.org/10.1016/j.cep.2018.04.035.

[2] Tohidi M, Sadeghi M, Torki-Harchegani M. Energy and quality aspects for fixed deep bed drying of paddy. Renew Sust Energ Rev. 2017; 70:519-528. https://doi.org/ 10.1016/j.rser.2016.11.196.

[3] Chen KJ, Chen QC, Zhang Y. Energy consumption for grain drying in china. Transactions of the CSAE 2005; 21(5): 173-177.

[4] Liu DY, Cao CW. Explore the new development path of drying technology in China. General machinery 2006; (7): 15-17.

[5] Zhang DY. Saving energy and reducing pollutants in the drying systems. Chemical Machinery 2009; 36(3): 195-199.

[6] Li X Q. Study on the design of energy saving and environmental protection grain dryer. China Plant Engineering 2019; (2): 198-199.

[7] Afzali F, Darvishi H, Behroozi-khazaei N. Optimizing exergetic performance of a continuous conveyor infrared-hot air dryer with air recycling system. Appl Therm Eng. 2019; 154:358-367. https://doi.org/10.1016/j.applthermaleng.2019.03.096

[8] Zohrabi S, Seiiedlou SS, Aghbashlo M, *et al*. Enhancing the exergetic performance of a pilot-scale convective dryer by exhaust air recirclation. Drying Technol. 2019; 38(4): 518-533. https://doi.org/10.1080/07373937.2019.1587617

[9] Ziegler T, Jubaer H, Schütz. Increasing the energy efficiency of batch-type drying with partial air recirculation. Chem Ing Tech. 2016; 88(1-2): 208-214. https://doi.org/10.1002/cite.201400150

[10] Di K, Li J. New technology and equipment of energy saving and emission reduction on grain drying system in China. Cereal & Feed Industry 2011; (12): 16-21.

[11] Di K, Li J, Ma YX, *et al*. Approaches to energy saving in grain drying process. Drying Technology & Equipment 2005; 3(4): 207-210.

[12] Gao SC, Wang DH, Zhao XG, *et al*. Application and practice of rice husk pellet filling molding fuel in grain drying system. Grain Processing 2018; 43(3): 26-27.

[13] Qu XR. Cleaner production and circular economy. Beijing: Qinghua University Press 2011.

[14] Zhan ZX, Xing ZQ, Wei B, *et al*. Test & research on the used hot-blast parameters of grain drier. Transactions of the CSAE 2000; 16(3): 88-90.

[15] Wu WF. etc. Energy-saving condensing, circulating and heating batch type recirculating grain drying device, Chinese patent: 208943774. 2019.

[16] Chen SY. Study on heat and humidity migration and granary aeration management based on absolute water potential. Changchun: Biological and Agricultural Engineering Institute, Jilin University, 2016.

[17] Shen JB, Guo T, Tian YF, etc. Design and experimental study of an air source heat pump for drying with dual models of single stage and cascade cycle. Appl Therm Eng. 2018; 129: 280-289. https://doi.org/10.1016/j.applthermaleng.2017.10.047

[18] Chapchaimoh K, Poomsa-ad N, Wiset L, etc. Thermal characteristics of heat pump dryer for ginger drying. Appl Therm Eng. 2016; 95:491-498. https://doi.org/10.1016/j.applthermaleng.2015.09.025

[19] Zlatanovic I, Komatina M, Antonijevic D. Experimental investigation of the efficiency of heat pump drying system with full air recirculation. J Food Process Eng. 2017; 40: e12386. https://doi.org/10.1111/jfpe.12386

[20] Zhang Y L, Yin K D, Long C S, *et al*. Application and prospects of the agricultural product drying using the heat pump in china. Journal of Agricultural Mechanization Research, 2014; (5): 1-7.

[21] Song XY, Zhong Y, Deng Y. Status and development trend of heat pump drying technique. Journal of Shanghai Jiaotong University 2014; 32(4): 60-66.

[22] Lou Z, Liu Q, Zhao Y Q, *et al*. Application of air source heat pump drying technology in post-harvest treatment of agricultural products. Agricultural Engineering 2017; 7(5): 68-72.

[23] Gao HF. The research on on-line moisture detection and control system based on the total weight detection for grain circulate drying [D]. Changchun: Biological and Agricultural Engineering Institute, Jilin University, 2014.

[24] GB/T 14095-2007, Technical terms for drying agricultural products [S].

[25] Q/ZCL 14-2013, Technical specification for inspection and acceptance of complete set of grain drying equipment [S].

[26] T/CAMDA 6-2019, Technical specification for acceptance of grain drying center [S].