Exergy analysis of an electric grain drying system with internal circulation of the drying medium of corn

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Abstract: In recent decades, exergy analysis has become an important tool to assess drying systems and optimise drying processes. This research work uses a corn drying experiment to analyse the exergy performance of a newly developed drying system, where, all exhaust air recirculated is dehumidified by condensation to achieve energy savings and environmental protection. The results show that under the experimental conditions, the exergy efficiency of the drying process was 34.03%–64.90%, and the drying rate of corn was stable at 0.3%–0.4% when the condensation intensity was 1.1–4.9 g/m^3. The improvement potential rate of the drying process was 109 kJ/s–115 kJ/s and 37 kJ/s–52 kJ/s when the drying temperature was 90°C–100°C and below 90°C, respectively. The sustainability index was 1.5–2.8. With increasing drying air temperature, the exergy efficiencies of the drying process and the sustainability index decreased, but the improvement potential rate increased.

Keywords: exergy analysis; electric grain drying system; internal circulation of the drying medium; drying characteristics.

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1 Introduction

At present, the world is facing a crisis of limited fossil energy and increasingly severe environmental problems due to fossil energy use. Countries worldwide are developing low-carbon agricultural economies in various manners; thus, agricultural mechanisation in China must pursue green development, clean energy production, energy conservation and environmental protection according to the associated energy conditions (Liu and Han, 2010; Li, 2016; Chen, 2019; Liu and Yang, 2012). With the increase in grain output in China, the demand for mechanised grain drying increases daily. Drying is a process that requires high-energy consumption. In Canada, France and the USA, drying operations consume approximately 10–15% of the total national industrial energy consumption; in Germany and Denmark, drying operations consume 20–25% of the total national industrial energy consumption (Tohidi et al., 2017); and in China, it accounts for 12% of the total energy consumption of the national economy (Weng et al., 2014). The drying process has high energy consumption, high cost and low thermal efficiency, which hinder the development of grain drying mechanisation. Adapting to China's national conditions, the development of energy savings and environmental protection grain dryers is an urgent problem to solve.

To design high-efficiency and energy-saving grain dryers, scholars worldwide have analysed the associated energy exchange and energy loss to identify methods to improve the drying equipment and processes, increase the dryer energy efficiency and reduce energy consumption. Exergy analysis has been widely used in recent decades as a potential tool to improve the energy efficiency, cost efficiency, resource utilisation, environmental friendliness, and sustainability and optimise the system design and control (Dincer, 2011; Stougie, 2014; James et al., 2020). Exergy is considered a connection of energy, the environment and sustainability; with increasing system exergy efficiency, system sustainability increases, and environmental impact decreases (Dincer, 2011). Exergy analysis of the newly designed drying system is helpful to evaluate its energy savings and environmental protection index.

In the literature, the exergy analysis of the drying process includes the performance evaluation of the dryer and analysis of the relationship between drying condition and exergy characteristic of the system to optimise the process control of the dryer. The representative research results regarding using energy and exergy analyses to evaluate the grain dryer are as follows. Silva et al. (2021) conducted the energy and exergy analysis of corn drying of a mixed cabin solar dryer, and they concluded that the average thermal efficiency of the dryer was 21%, the exergy efficiency was 10–66%, both presented opposite trends, and thermal efficiency increases when the exergy efficiency decreases. Li et al. (2020b) conducted energy and exergy analyses of a combined infrared radiation counterflow circulation dryer by corn drying experiments, and the results showed that the exergy efficiency of the entire drying system was 5.16–38.21%. Li et al. (2020a) conducted an exergoeconomic analysis of corn drying of a novel industrial drying system and concluded that the exergy efficiency of the drying chamber was 14.81–40.10%, and the combustion chamber should be improved first. Sarket et al. (2015) conducted energy and exergy analyses of industrial fluidised bed dryers by paddy drying experiments and concluded that the exergy efficiency was 46.99–58.14%, only 31.18–37.01% of exergy was utilised for paddy drying, and a large amount of the remainder was wasted. The research results of the relationship between grain drying process parameters and exergy characteristic parameters are as follows. From the energy and exergy analyses of maize drying of a mixed flow dryer, Mondal et al. (2019) found that the amount of exergy inflow, outflow and loss increased with increasing drying temperature. From the energy and exergy analyses of a vertical fluidised bed dryer by paddy drying experiments, Pattanayak and Mohapatra (2019) concluded that the exergy evaporation rate first increases from zero to a certain value and subsequently continuously decreases. The effect of the wall temperature, air velocity and bed height on the exergy efficiency of wall-heated fluidised bed dryers was studied by Yogendrasasidhar and Setty (2018), who found that the exergy efficiency increased with increasing wall temperature and air velocity and decreased with increasing bed height. From the exergy analysis of rough rice drying of a convective dryer, Beigi et al. (2017) revealed that the exergy efficiency of the drying chamber increased with increasing drying air temperature and flow rate. From the exergy analysis of rough rice drying of a plug flow fluidised bed, Khanali et al. (2013) reported that the exergy efficiency of the drying process decreased with increasing drying air temperature and decreasing feed mass flow rate and weir height. Moreover, the selection of the reference state is very important for the exergy analysis of the drying process, and exergy characteristic parameters will vary when the temperature of the reference state increases (Sheikhshoaei et al., 2019). For the exergy analysis of the drying system in this paper, since the drying section and condenser were located in the insulation room, the temperature and humidity in the insulation room were considered the reference states in the exergy analysis process.

An important reason for the low thermal efficiency of grain dryers is that exhaust emissions discharge a large amount of input heat energy (Sadjad et al., 2016). Therefore, from an energy saving point of view, exhaust air recirculation is a widely used waste heat recovery method for convective driers. Exhaust air circulation is easy to implement and inexpensive. Because full recirculation of exhaust air in a drying system requires additional energy to dehumidify the exhaust air (Mandegari and Pahlavanzadeh, 2013), partial recirculation of exhaust air is more commonly used (Ziegier et al., 2016). The exergy analysis and research results of partial recirculation of exhaust air in drying systems are as follows. Zohrabi et al. (2020) compared the drying characteristics and exergetic efficiency indices of poplar wood chip drying of a convective dryer under three different real-time control schemes based on exergy. Zohrabi et al. (2019) used the exergy concept to evaluate the performance of a pilot-scale convective dryer operating at two drying air temperatures (55–70°C), two air volume flow rates (360–450 m^3/h), and six exhaust air recycle fractions (0–100%). Afzali et al. (2019) optimised the process of a continuous conveyor infrared hot air dryer with an air circulation system by analysing the exergy characteristic parameters such as the exergy efficiency, exergy loss and improvement potential under different air recirculation percentages, air temperatures and infrared power levels. Amantéa et al. (2012) analysed the exergy characteristics of grain dryers with air recirculation using numerical simulation and concluded that air recirculation could increase the energy efficiency by at least 25%. Considering the efficiency, drying speed and residence time, a recirculation of 75–90% by weight of the exit air is appropriate.

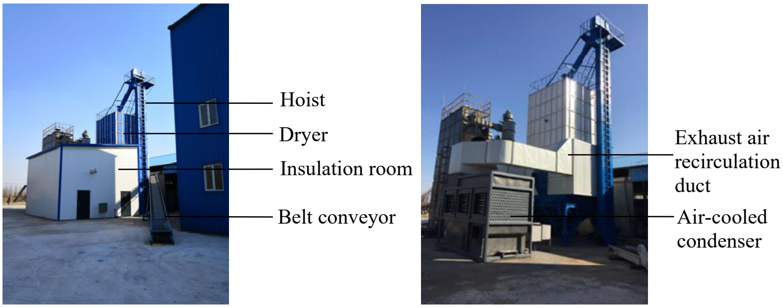
For the electric grain drying system in this study, the drying medium forms a closed loop (Wang et al., 2020; Wu et al., 2019). All exhaust air discharged from the drying system is recovered and dehumidified through a condenser and subsequently heated recycling. The drying system has the advantages of energy savings and no pollutant emissions. From the thermal system point of view, the system working process includes the grain drying process and the condensation and dehumidification process of wet air. The entire system is a complex thermodynamic system of multifield coupling and multiphase interactions associated with heat, moisture and flow. In this study, an exergy analysis was performed on a newly designed batch electric grain drying system with full recirculation of exhaust air to evaluate the energy-saving effect of the system, analyse the exergy performance of the drying and condensing process, and determine the influence of the drying air temperature on the drying exergy efficiency and the influence of the condensation intensity on the condensation exergy efficiency. Exergy analysis studies on grain drying systems with full recirculation of exhaust air and dehumidification by condensers have not been reported in the literature. This study can provide useful guidance to improve the design of new electric grain drying systems with full recirculation of exhaust air and optimise the grain drying process parameters and drying control systems based on exergy optimisation.

2 Materials and methods

2.1 Drying equipment

Photographs of the experimental rig are shown in Figure 1. The batch recycling grain dryer designed drying capacity was 50 tons of corn, and the loading capacity of this experiment was 39.98 tons of corn. The system work process included two processes and two circulation paths. The two processes are the drying process of the grain and the condensation process of the drying medium. The two circulation paths are the grain flow circle and drying medium flow circle. In the drying process, grain absorbs heat from a drying medium, and water evaporates from the grain with heat and mass exchange between them. In the condensation process, wet and hot exhaust gas encounters colder conditions, and water vapour in the exhaust gas is liquefied and releases heat in a heat transfer process, where cold and hot fluids are run through a condensing tube. In other words, these processes include the heat exchange process between a cold fluid and the condensing pipes, heat exchange process between a hot fluid and the condensing pipes, and heat conduction through the pipes. During system operation, grains cyclically flow among the hoister, dryer, screw conveyor and hoister, and the drying medium cyclically flows among the hot-air blower, drying section, condenser, heater and hot-air blower. In this paper, the condensation intensity refers to the difference between the absolute humidity of the exhaust gas discharged from the dryer and that after condensation through the condenser.

Figure 1 Physical photos of drying system, (a) external view of the dryer system (b) interior view of the dryer system (see online version for colours)



(a) (b)

The test system is mainly composed of a batch circulating drying host, a multistage condenser, an electric heater, fans, air ducts and the control system. The fans include a hot-air fan, condensate fan and moisture removal fan; the air ducts include a hot-air supply duct and an exhaust recovery duct. The control system includes a main control cabinet and sensor detection devices.

The power of each component of the experimental rig is shown in Table 1, and the characteristics of each sensor are shown in Table 2.

Table 1 The power of each component of the experiment rig

Serial number	*Parts*	*Power (kW)*
1	Electric heater	192
2	Thermal fan motor	11
3	Hoisting machine	7.5
4	Condensing fan motor	5.5
5	Exhaust fan motor	3.0
6	Water pump	1.1

Table 2 The model and place of manufacture of the measuring instrument

Sensor's name	*Model*	*Character*	*Manufacturer*
Temperature and humidity transmitter	106WS	Temperature – 40–100°C, Humidity 0–100% Power supply 12–24 V/DC, Output 4–20 mA	Beijing
Temperature probe	PT100	0–300°C	Beijing
Load cell	TQ-717	0–20T	Beijing
Anemometer	Testo 410-2	Resolution ratio 0.1m/s Accuracy ± (0.2 + 2% measured value) m/s	Germany
Grain moisture meter	PM-8188-A	Corn moisture detection range 6.0–40.0%	Japan
Power metre	DTZY341-G	Accuracy 0.01 kwh	Changsha

2.2 Test procedure

Before the test began, corn was sieved to remove impurities and dust; then, the drying system control programme was started. The system entered the running state, grains were loaded by belt conveyors and a hoister, and raw grain samples were taken to measure the initial moisture and bulk density. The initial and target moisture contents were input into the programme. When the feeding had completed, we started the screw conveyor and discharging motor, set the frequency of the discharging motor to 30 Hz, manually tested the feeding speed at the frequency, calculated the grain discharge period and time, input them into the programme, started the hot fan, and set the fan frequency to 35 Hz. The dryer subsequently entered the pre-heating stage. When the grain temperature reached 30°C, we started the condensing fan and set its frequency to 50 Hz, and the system entered the cycle drying stage. In the course of drying, the control system controlled the temperature by proportion integral differential adjustment, and the temperature difference of the hot air that entered the drying section did not exceed 3°C. The control system automatically monitored the grain moisture by weighing (Gao, 2014). When the grain moisture reached the target moisture, the system automatically stopped heating. We closed the exhaust recovery duct, opened the cooling door, fully opened the condensing fan and moisture removal fan, and initiated the cooling stage. When the grain temperature reached the setpoint, we closed the cooling door, rotated the grain outlet mechanism to connect it with the grain discharging belt conveyor, and started the motor to discharge grain. After discharging the grain, we stopped in sequence the motor, hoister, and screw conveyor. The hot fan continued to run for 30 minutes. We stopped the fan after the waste heat was discharged, and the test was completed.

To further verify the moisture content of the corn by the oven method, samples were taken every hour during the drying process and every half hour during the late cooling phase, and condensate water was discharged every two hours and weighed. When the test data were analysed, one data point was extracted every hour to perform exergy analyses. When analysing the relationship between the exergy efficiencies of the drying or condensing process and the operating conditions, 5 test data points were collected and averaged at each required temperature or drying rate point to make the experimental data more universal.

2.3 Theoretical analysis

Exergy analyses were performed for the two main processes: drying and condensing. Considering the entire grain drying system as a complex thermodynamic system, when performing exergy analyses, the drying medium wet air was considered a continuous and steady flow of fluid, and the system was assumed to be airtight and have no leakage. Pressure and momentum changes were ignored in the process. According to the conservation of mass, the dry air and moisture remained constant in mass after passing through the dryer and condenser.

This experimental system is a batch cycle drying operation mode. One cycle takes 4 hours; i.e., the grains need 4 hours from entering the drying section to discharging from the drying sanction. The average drying rate of a cycle is as follows:

$$\theta = \frac{M_{ini} - M_{fin}}{4} \times 100 \tag{1}$$

where M_{ini} and M_{fin} are the initial and final wet basis moisture contents of each cycle, respectively. The exergy equation was applied to the grain drying system in this paper, ignoring the changes in gravity, momentum and pressure. The exergy equation of the grain was simplified to the following exergy equation in the form of the exergy rate:

$$\dot{E}\chi_g = \dot{m}_g C_g \left[(T - T_0) - T_0 \ln \frac{T}{T_0} \right] \qquad \text{(Beigi et al., 2012)} \qquad (2)$$

where $\dot{m}_g$ is the mass flow rate of corn during the experimental process, which was 0.304 kg/s in this experiment; C_g is the specific heat of corn, which is a function of the moisture content of corn and expressed as follows:

$$C_g = 1.549 + 0.0264 M_g \qquad \text{(Shao et al., 1985)} \qquad (3)$$

The exergy rate of the drying medium was expressed as follows:

$$\dot{E}\chi_a = \dot{m}_a \begin{pmatrix} [C_a + \omega_a C_v](T - T_0) - T_0 \\ \left\{ [C_a + \omega_a C_v] \ln\left(\frac{T}{T_0}\right) - (R_a + \omega_a R_v) \ln\left(\frac{P}{P_0}\right) \right\} \\ +T_0 \left\{ \begin{vmatrix} (R_a + \omega_a R_v) \ln\left(\frac{1 + 1.6078\omega_0}{1 + 1.16078\omega_a}\right) \\ +1.6078\omega_a R_a \ln\left(\frac{\omega_a}{\omega_0}\right) \end{vmatrix} \right\} \end{pmatrix} \qquad \text{(Beigi et al., 2017)} \quad (4)$$

where C_a is the specific heat of air, which can be calculated as follows:

$$C_a = 1.0004 + 188\omega_a \qquad \text{(Pattanayak and Mohapatra, 2019)} \qquad (5)$$

Here C_v is the mean specific heat of vapour, which is equal to 0.864 kJ/kg·K.

R_a and R_v are the gas constant and vapour gas constant and equal to 0.287 kJ/kg·K and 0.462 kJ/kg·K, respectively.

The subscript 0 represents the reference state of the exergy analyses of the drying process and condensation process. The exergy reference state of the corn drying system in this study was considered the condition of the thermal insulation room, where the drying section was located. The temperature and humidity were measured in real time, and the ambient pressure was $P_0 = 1.01 \times 10^5$ Pa.

The rate of exergy used for drying corn $\dot{E}_{\chi e}$ was calculated as follows:

$$\dot{E}_{\chi e} = \left(1 - \frac{T_0}{T_g}\right) \dot{Q}_e \qquad \text{(Beigi et al., 2017; Khanali et al., 2013)} \qquad (6)$$

The rate of heat transfers due to evaporation $\dot{Q}_e$ was calculated as follows:

$$\dot{Q}_e = 0.0397 * (2{,}500 + 1.842 T_{da,out} - Cw * T_{g,ini}) \qquad \text{(Shao et al., 1985)} \qquad (7)$$

The factor 0.0397 denotes that during the drying process, 0.0397 kg of water was removed per second on average. C_w is the specific heat by weight at a constant pressure of water, which is equal to 4.2 kJ/kg·°C, and $T_{g,ini}$ is the initial temperature of corn.

The exergy efficiency of the drying process is calculated as follows:

$$\psi_d = \frac{E_{\chi e}}{E_{\chi da,\,in}} \times 100 \qquad \text{(Khanali et al., 2013)} \tag{8}$$

Similar to the definition of the exergy efficiency of the drying chamber, the ratio of the exergy rate of substances at the inlet and outlet of the condenser is defined as the exergy efficiency of the condensation process in this paper and expressed by the following equation (Khanali et al., 2013):

$$\psi_c = \frac{E_{\chi ca,\,out} + E_{\chi w,\,out}}{E_{\chi ca,\,in}} \times 100 \tag{9}$$

The exergy rate of condensate water is the output material of the condenser, and its exergy rate can be calculated as follows:

$$\dot{E}\chi_w = \dot{m}_w C_w \left[\left(T - T_0 \right) - T_0 \mathrm{In} \frac{T}{T_0} \right] \qquad \text{(Beigi et al., 2017)} \tag{10}$$

To evaluate the design improvement potential and sustainable development performance of the two important operational processes (the drying process and condensation process), the improvement potential rate and sustainable index are introduced. The improvement potential rates of the drying process $I\dot{P}_d$ and condensation process $I\dot{P}_c$ are defined as follows (Khanali et al., 2013):

$$I\dot{P}_d = \left(1 - \psi_d\right)\left(\dot{E}\chi_{d,in} - \dot{E}\chi_{d,out}\right) \tag{11}$$

$$\dot{E}\chi_{d,in} = \dot{E}\chi_{g,in} + \dot{E}\chi_{a,in} \tag{12}$$

$$\dot{E}\chi_{d,out} = \dot{E}\chi_{g,out} + \dot{E}\chi_{a,out} \tag{13}$$

$$I\dot{P}_c = \left(1 - \psi_c\right)\left(\dot{E}\chi_{c,in} - \dot{E}\chi_{c,out}\right) \tag{14}$$

$$\dot{E}\chi_{c,in} = \dot{E}\chi_{ca,in} \tag{15}$$

$$\dot{E}\chi_{c,out} = \dot{E}\chi_{a,out} + \dot{E}\chi_{w,out} \tag{16}$$

In this study, the heat source of the grain drying system used clean electric energy. All exhaust air was recirculated, and there was no pollutant emission during the drying process. To measure the environmental impact, the sustainable index of the drying process (SI_d) and condensing process SI_c in the exergy analysis were used and are expressed as follows (Khanali et al., 2013):

$$SI_d = \frac{1}{1 - \psi_d} \tag{17}$$

$$SI_c = \frac{1}{1-\psi_c} \tag{18}$$

2.4 Experimental uncertainty analysis

The reproducibility and validity of the data obtained during the corn drying experiment were verified by uncertainty analysis. The uncertainty or error of the experimental system mainly arises from the measurement accuracy of the sensor itself and the effect of the high-temperature drying and higher humidity where sensors were installed on the performance of the sensors. The uncertainty of the load cell was affected by the air flow and changes in temperature and humidity inside the dryer. To check the accuracy of the thermocouple, grain moisture metre and load cell, temperature and humidity data of hot air and ambient air, corn moisture data, and machine and grain weight data were collected over a time period. The mean value and standard deviation of all observed data were obtained. The variable Xi is uncertain and can be expressed as follows (Mondal et al., 2019; Sarker et al., 2015):

$$X_i = X_{mean} \pm \delta X_i \tag{19}$$

where X_i is the actual value of the variable, X_{mean} is the mean of the measurements, and δX_i is the uncertainty in the measurement. The percentage of uncertainty is expressed by the following equation (Mondal et al., 2019):

$$\%Uncertainly = \frac{\delta X_i}{X_{mean}} \times 100 \tag{20}$$

The percent uncertainties of all instruments were calculated and are shown in Table 3. The percent uncertainty was in the range of 4.08%. According to Yamamura et al. (2009), for the reproducibility of an experiment, uncertainty values below 5% are considered acceptable.

Table 3 List of measuring instruments with their specifications, accuracies and uncertainties of measured quantities

Name of instrument	*Accuracy*	*Standard deviation*	*Uncertainty (%)*
Temperature and humidity transmitter	±0.5°C	0.06	4.08
	±3%	1.34	2.10
Temperature probe	±0.15°C	0.07	2.00
Load cell	±0.05kg	0.029	0.09
Grain moisture meter	±0.5%	0.18	1.31

3 Results and discussion

3.1 Analyses of system drying and condensing characteristics

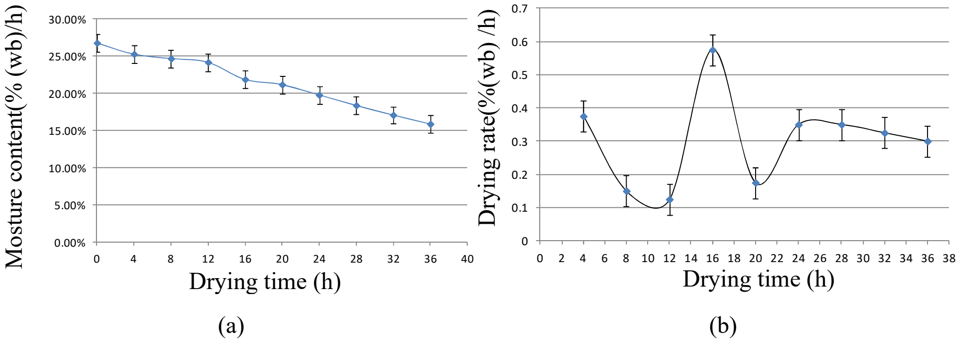
This drying system has a drying cycle every four hours on average, the average moisture content of each cycle represents the moisture content of that cycle, and the moisture content change curve of corn during the drying process in this experiment is shown in

Figure 2(a). To investigate the drying rate of corn, the average drying rate of each cycle was obtained by equation (1), and the change curve of the drying rate with drying time is shown in Figure 2(b).

During the experiment, we adjusted the frequency of the condensing fan to find the ideal condensation intensity and subsequently ensured that the drying medium humidity was in a certain range to achieve the desired drying rate, as shown in Figure 2(b). The drying rate was unstable at the beginning of the test: it fluctuated within 0.1–0.6% (wb)/h due to the uneven initial moisture content of corn and the frequency modulation of the condensing fan; i.e., the temperature and humidity of the drying medium were changing at this stage. After 24 hours of drying, a more stable drying rate of 0.3–0.4% (wb)/h was observed. At this point, the frequency of the thermal fan was 35 Hz, and the frequency of the condensing fan was 50 Hz. From the drying mechanism, a constant rate of dehydration was achieved in a range of the temperature and humidity of the drying medium, and good corn quality after drying could be obtained.

For this electric grain drying system in this study, as the experiment proceeded, the water evaporated from the corn continued to enter the drying medium; then, some of it was condensed into water; therefore, the humidity ratio of the drying medium gradually increased during the drying process. According to Chen et al. (2020), corn is dried at gradually increasing air temperature and humidity to obtain an optimal comprehensive drying goal, which includes energy savings and corn quality indices.

Figure 2 Changes in moisture content of corn and drying rate with drying time (standard error bars), (a) moisture content change curve (b) drying rate change curve (see online version for colours)

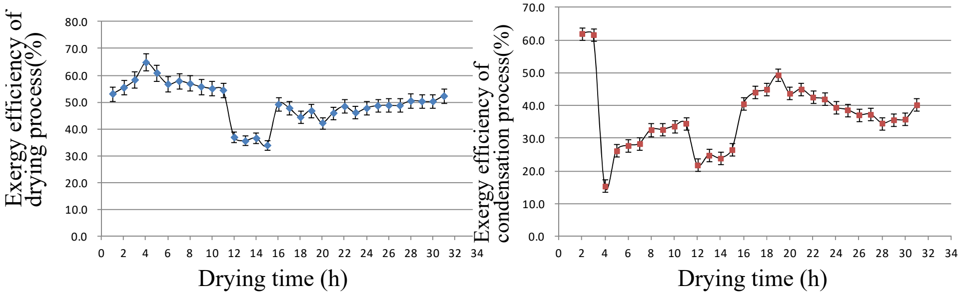


3.2 Exergy efficiency analyses of the drying and condensation processes

Under the test conditions of this system, in the first 16 hours of the drying process, the condensation effect was not stable, and the exergy efficiency of the drying process rapidly increased at the beginning of the drying process and tended to decrease later [as shown in Figure 3(a)]. The change trend was identical to that described by Zohrabi et al. (2020) and Li et al. (2020b). From 16 hours after drying, the condensation intensity was suitable, the drying rate was stable, the dehydration of corn was constant, and the exergy efficiency slightly increased, as mentioned by Afzali et al. (2019). Exhaust air circulation had a higher influence on the exergetic efficiency than the other parameters. The exergy efficiency during the drying process was 34.03–64.90%. When the drying medium temperature was 90–100°C, the exergy efficiency was lower than 40%, and it gradually increased over 16 hours of drying to 42–52%. The exergy efficiency during the drying process was similar to the value of 32.72–63.26% of an infrared-hot air dryer with an air recycling system, which was described by Afzali et al. (2019). Our value was higher than the exergy efficiency of corn drying by a mixed flow dryer described by Mondal et al. (2019), which was 11.61–20.87% and 8.54–19.53% for the temperature range (40–80°C) and air velocities of 3.0 and 6.0 m/s, respectively. Our value was also higher than the exergy efficiency of corn drying of the infrared radiation counterflow circulation dryer described by Li et al. (2020b), which was 5.16–38.21%. Our value was also higher than the exergy efficiency of paddy drying of industrial fluidised bed dryers described by Sarker et al. (2015), which was 31.18–37.01%. Thus, exhaust air recycling can improve the exergy efficiency of the system, as concluded by Amantéa et al. (2012).

The exergy efficiency changes of the condensation process are shown in Figure 3(b). In this test, the condensate fan was started 3 hours after the drying process started. Therefore, in the first three hours, only the heat loss of air at the inlet and outlet of the condenser passed through the condenser. There was little difference in temperature and humidity of air at the inlet and outlet or in the exergy rate of the air, so the exergy efficiency was relatively high. After condensation started, the temperature at the condenser outlet rapidly dropped, and the exergy efficiency rapidly decreased. As the drying process continued, the drying medium was gradually heated, and both temperature and humidity ratio of the exhaust air gradually increased. Since the condensation effect had only started, the gradient of the decrease in temperature of the outlet air of the condenser was not large, but the humidity ratio greatly increased. Therefore, the exergy rate of the outlet air increased and was greater than that of the exhaust air due to the temperature increase. Therefore, the exergy efficiency of the condensation process increased gradually. In the high-temperature section, the temperature difference between inlet and outlet air of the condenser increased, which decreased the exergy efficiency. However, with the stabilisation of the condenser and enhancement of the condensation effect, the gradient of the air temperature drop at the condenser outlet was greater than that of the exhaust air due to the temperature increase, and the exergy efficiency gradually decreased. Therefore, the degree of the drying and condensation process can be determined from the change trend of the exergy efficiency of the condensation process.

Figure 3 Changes in the exergy efficiency of drying and condensation process with drying time (the former with percentage error bar, the latter with standard error bars), (a) exergy efficiency of drying process (b) exergy efficiency of condensation process (see online version for colours)



a) (b)

The exergy efficiency of the system was mainly affected by the drying process when the condensation process was stable. Therefore, for the exergy analysis of this system, the exergy efficiency of the drying process should be emphasised.

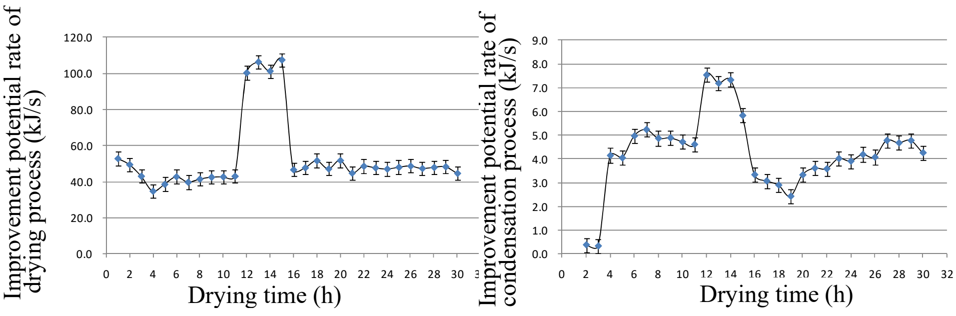
As shown in Figure 4(a), the improvement potential rate of the drying process was higher: 109–115 kJ/s when the drying medium temperature was 90–100°C and 37–52 kJ/s for the remaining time, which implies that the potential for improvement in the design of drying processes was great, especially when the drying medium temperature was high. The improvement potential rate for a drying medium temperature of 90–100°C was approximately twice that of 70–80°C, which is much higher than the improvement potential rate of 1–11 kJ/s of the mixed flow drying process of maise in Mondal et al. (2019) and 76.24–133.02 J/s of the plug flow fluidised bed drying process of rough rice in Khanali et al. (2013). The reason is that the volume of the drying section of this drying system was 75.63 m^3, which is far greater than 0.0625 m^3 and 0.008 m^3 in those two studies. A larger system has a larger contact area with the ambient environment, a longer air duct, more heat loss, and a larger improvement potential.

As shown in Figure 4(b), the improvement potential rate of the condensation process was relatively low (within 0.3–7.5 kJ/s). The condenser could satisfy the condensation effect required by the drying medium, so the improvement design of the drying system should focus on the drying process.

As shown in Figure 5(a), the change in the sustainability index of the drying process with drying time was similar to that of the exergy efficiency. The sustainability index of the drying process was 1.5–2.8 under the test conditions. This value was greater than the values of 1.05–1.61 of corn drying of the infrared radiation counterflow circulation dryer described by Li et al. (2020b), 1.09–1.26 of the mixed flow maises drying process described by Mondal et al. (2019) and 1.05–1.42 of paddy drying of the convective dryer described by Beigi et al. (2017). This result also shows that exhaust air recirculation reduced the impact of the drying process on the environment and increased the sustainability index of the drying process.

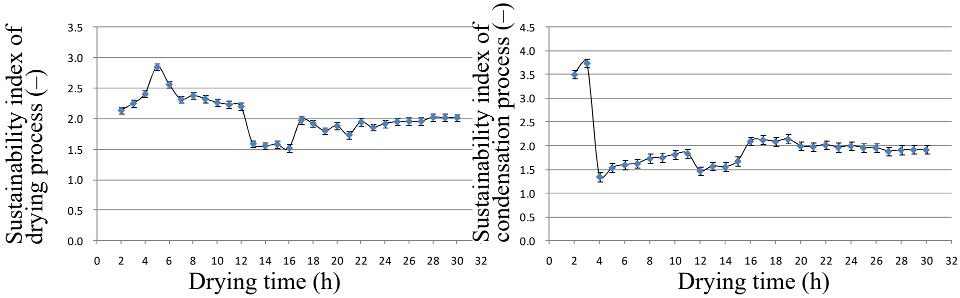
Similarly, the change in sustainability index of the condensation process with drying time was similar to that of the exergy efficiency; its value was 1.3–2.1 under the test conditions, as shown in Figure 5(b). In particular, after the condensation process had stabilised, the sustainability index was 1.9–2.1, which was relatively high and had less impact on the environment.

Figure 4 Changes in the improvement potential rate of drying and condensation process with drying time (standard error bars), (a) improvement potential rate of drying process (b) improvement potential rate of condensation process (see online version for colours)



(a) (b)

Figure 5 Changes in the sustainability index of drying and condensation process with drying time (standard error bars), (a) sustainability index of drying process (b) sustainability index of condensation process (see online version for colours)

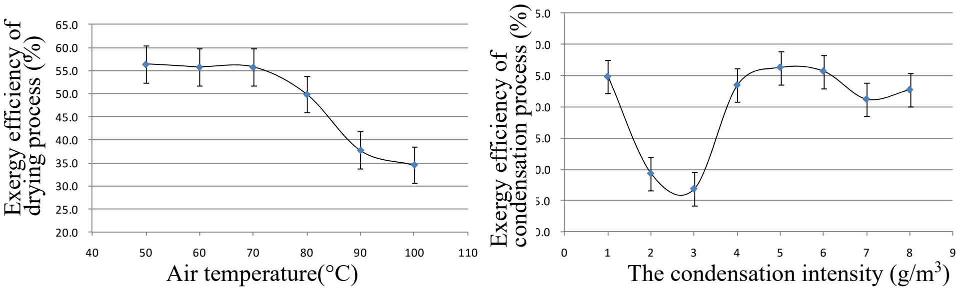


(a) (b)

3.3 *Influence of the drying and condensation conditions on the exergy efficiency of the system*

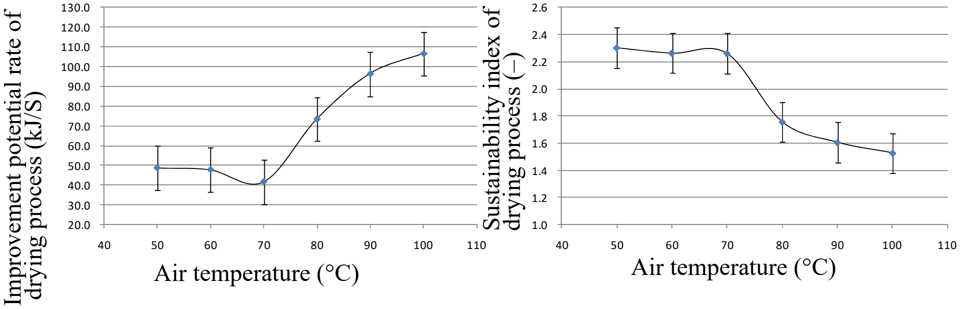
Figure 6(a) shows that the exergy efficiency of the drying process of the system decreased with increasing drying air temperature. The exergy efficiency slowly decreased within 50–70°C and subsequently significantly decreased from 80°C. The drying air temperature was an important factor that affected the exergy efficiency. The exergy efficiency in this study varied with air temperature, whereas Mondal et al. (2019) found that the exergy efficiency increased with the increase in air temperature in the range of 40–80°C in their study of corn drying with a mixed flow dryer. This difference mainly occurred because of the exhaust air recirculation in this system and the increase in inlet enthalpy. However, the result was identical to that of Afzali et al. (2019), who studied an infrared hot air dryer with an air recycling system, where the exergy efficiency decreased with increasing drying air temperature.

Figure 6 Changes in the exergy efficiency of drying process with air temperature and that of condensation process with the condensation intensity(standard error bars), (a) exergy efficiency of drying process (b) exergy efficiency of condensation process (see online version for colours)



(a) (b)

Figure 7 Changes in the improvement potential rate and sustainability index of drying process with air temperature (standard error bars), (a) improvement potential rate of drying process (b) sustainability index of drying process



(a) (b)

For this drying system, the condensation process was an auxiliary process, and it was necessary to appropriately condense the drying medium according to the requirements of the drying process. Figure 6(b) shows that the exergy efficiency of the condensation process was high when the condensation intensity was 4–6 g/m^3; therefore, the working process of the drying system could be considered to control the condensation intensity within this range to ensure that the condensation process maximises the exergy efficiency.

Figure 7(a) shows that the improvement potential rate of the drying process increased with increasing drying air temperature, especially for a drying medium temperature over 70°C. The reason is that the exergy was lost into the environment, and the exergy destruction increased with increasing drying air temperature; therefore, the improvement rate of the drying process also increased. This conclusion is consistent with those of Mondal et al. (2019) and Khanali et al. (2013).

Figure 7(b) shows that when the drying air temperature was below 70°C, the sustainability index did not significantly change with the drying air temperature, but when the drying air temperature exceeded 70°C, the sustainability index of the drying process decreased with the increase in drying air temperature. This change was identical to that described by Khanali et al. (2013): within the range of 50–70°C, the sustainability index of rough rice drying of the fluidised bed dryer (1.04–1.13) decreased with the increase in drying air temperature. However, the result did not agree with that described by Mondal et al. (2019): the sustainability index of maise drying of the mixed flow dryer (1.09–1.26) increased with an increase in drying temperature at air velocities of 3.0 and 6.0 m/s and drying air temperatures of 40–80°C. The result also did not agree with that described by Begi et al. (2017), who found that the sustainability index of rough rice drying of the convective dryer (1.05–1.42) increased with increasing drying air temperature. These results show that the sustainability index is also greatly affected by other process parameters.

4 Conclusions

In this study, an exergy analysis was used to evaluate the performance of a newly designed electric grain drying system with full recirculation of exhaust air. The exergy efficiency, improvement potential rates and sustainability indices of the drying process and condensation process were analysed. The variation in these parameters of the drying process with the air temperature and exergy efficiency of the condensation process with the condensation intensity were also analysed. The following conclusions were drawn:

1. Exhaust air circulation can improve the exergy efficiency and sustainability index of the drying process and achieve the goals of energy savings and environmental protection.
2. The grain drying system with full recirculation of exhaust air can dry grain at gradually increasing air temperature and humidity, and the corn drying process can obtain an optimal comprehensive drying goal, which includes energy savings and corn quality indices.
3. For grain drying systems with full recirculation of exhaust air, moderate condensation should be performed according to the requirements of the drying process. The condensation process is an auxiliary process, and the exergy analysis of the system should focus on the drying process.
4. The exergy efficiency and sustainability index of the drying process of the system were 34.03–64.90% and 1.5–2.8, respectively, which decreased with increasing drying air temperature and decreased faster when the drying air temperature exceeded 80°C.
5. The improvement potential rate was 37–52 kJ/s; when the drying air temperature was 90–100°C, the improvement potential rate was 109–115 kJ/s and increased with increasing drying air temperature.
6. The exergy efficiency of the condensation process fluctuated within a range. As a result, the best intensity of the condensation range was 4–6 g/m^3, where the exergy efficiency was maximal.

Further research should be performed on the relationship among the condensation intensity, drying rate and influence of drying process parameters (such as the air velocity and condensation intensity) on the exergy efficiency, sustainability index and other exergy parameters of grain drying systems with full recirculation of exhaust air. This study provides technical support for the development of a real-time control system for a grain drying system with full recirculation of exhaust air based on exergy optimisation, and it provides basic technological guidance to improve the energy savings and environmental protection in drying equipment.

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Nomenclature

C	Specific heat, kJ/kg·°C
$\dot{E}\chi$	Exergy rate, kJ/s
$I\dot{P}$	Improvement potential rate, kJ/s
$\dot{m}$	Mass flow rate, kg/s
M	Moisture content, %
$\dot{Q}$	Heat transfer rate, kJ/s
R	Gas constant, kJ/kg·°C

SI	Sustainability index
T	Temperature, °C.

Subscripts

$_{a}$	Air
$_{c}$	Condensation
$_{d}$	Drying
e	Evaporation
$_{fin}$	Final
$_{g}$	Grain
$_{in}$	Input
$_{ini}$	Initial
$_{out}$	Output
$_{v}$	Water vapour
$_{w}$	Water
$_{0}$	Reference state
$_{da,\ in}$	Air input during drying process, other subscripts like this, and so on.

Greek letters

ω	Humidity ratio (kg H_2O/kg dry air)
ψ	Exergy efficiency (%)
θ	Drying rate (% (wb)/h).