Performance of Exergetic, Energetic and Techno-Economic Analyses on a Gas-Type Industrial Drying System of Black Tea

Zhiheng Zeng 1, Bin Li 2, Chongyang Han 1, Weibin Wu 1,*, Tianci Chen 1, Chengju Dong 1, Changlun Gao 1, Zhaokai He 1 and Fangren Zhang 1

1 College of Engineering, South China Agricultural University, Guangzhou 510642, China
2 School of Intelligent Manufacturing Engineering, Chongqing University of Arts and Sciences, Chongqing 404100, China
* Correspondence: wuweibin@scau.edu.cn; Tel.: +86-20-85282269

Abstract: The purpose of this research work is to perform detailed exergetic, energetic and techno-economic analysis of the black tea drying process in the gas-type industrial dryer. Exergy–energy and techno-economic methodology was applied to investigate the heat loss, exergetic and energetic performance, exergy efficiency, improvement potential rate, sustainability index and techno-economic performance of a drying system. The results showed that the heat loss of exhaust air in the late drying process played a main contributing role in the heat loss and exergy loss of the whole drying system. Therefore, the exergy efficiency of the initial drying period and the redrying period varied from 38.08% to 65.09% and 24.76% to 26.97%, respectively. In addition, the improvement potential rate and sustainability index of the whole system varied from 6.93 kW to 12.94 kW and 1.33 to 2.86, respectively. The improvement potential obtained in the present work indicated that the drying operation is greatly in need of exergy performance improvement. Finally, the net present value and payback period obtained from techno-economic analysis were 179,442.03 USD and 5.3 years, the result is useful for investors or contractors to refer to and make investment decisions.

Keywords: exergetic; energetic; techno-economic; drying; tea; industrial

1. Introduction

Drying is a traditional method which is widely used to extend the preservation of agricultural or marine products such as grains, bananas, cassava and rough rice [1–4]. Traditionally, drying is a high-energy-consumption operation that removes water from material with high moisture content by externally supplying energy [5]. The original drying method is natural drying, and the current large-scale industrial production drying involves burning a large amount of fossil fuels, as found from the literature reporting that the energy consumed by the drying industry accounts for about 15% of the country’s total energy consumption, and the drying cost in particular is close to 60–70% of the total cost [6,7]. Considering the global energy shortage and sustainable development strategies, it is necessary to reveal the overall energy matching structure and the transfer mechanism of the drying system, and clarify the evaluation indicators, such as energy efficiency and sustainability of the drying system. Therefore, it is of great significance to improve the overall efficiency of the drying system and develop the drying theory for the energy conservation and sustainability of the drying industry.

The drying process of material is a dewatering process based on the supply of heat. From the perspective of thermodynamics, the drying of materials is due to the heat transfer which increases the activation energy of water molecules to form a temperature field and a humidity field, which promotes the evaporation and dehydration of the moisture inside the material [8,9]. As mentioned above, the drying processes is a highly energy-intensive operation and the kinetic process of mass transfer and heat transfer. Application of the first
and second laws of thermodynamics to reveal the energy structure and transfer mechanism
of the agricultural product drying system or industrial production drying system is a
method commonly used by researchers in recent decades [10–12]. For example, Silva
et al. designed and tested a solar dryer of corn grains and evaluated the performance of
energy and exergy of the dryer based on the first and second laws of the thermodynamics,
identified that the average thermal efficiency was 21% and the exergy efficiency ranged
between 10–66% [13]. Not only that, there are many such research studies on the evaluation
and analysis of agricultural product drying system by the exergy analysis method, such
as bananas [14] and medicinal plants [15]. The drying systems mentioned above are
laboratory-scale drying systems, and there are also a few studies in the literature which
reported industrial-scale drying systems [16–18]. Sarker et al. and Li et al. employ the
method of energy–exergy to estimate the energetic and exergetic performance of a novel
industrial multi-field synergistic dryer, and carried out the influence of the crackle ratio,
generation potential, and generation rate for the quality of the dried paddy [16]. Moreover,
energy is a quantitative indicator which is defined as the amount of external work applied
by a system. Different to energy, exergy is a qualitative indicator which is defined as the
maximum useful work supplied by a system externally [19–21]. The method of energy–
exergy analysis not only enables the energy efficiency of the drying system to be evaluated
in terms of energy quantity, but also the exergy of different components of the system
can be evaluated in terms of energy quality to help make informed design decisions [22].
Therefore, obtaining energy (exergy) efficiency based on the energy–exergy analysis method
can not only evaluate the sustainability of the drying system, but also facilitate the guidance
of the design of efficient dryers [23].

For a drying system, the evaluation of energy and efficiency is essential. Similarly,
the overall economics of drying production are also a considerable indicator that should
be fully considered for producers or farmers. The economic estimation of the drying
system consists of the investment cost and the production cost of the drying system.
However, the production cost may be controversial, as the comprehensive availability
of local raw materials, the cost of local manufacturing, and the cost of power sources
deviate between places [24]. Currently, economics evaluation is the primary and most
common method for drying systems, while the techno-economic method is among the most
common and popular economic analysis methods for studying thermodynamic systems,
such as the traditional energy system [25,26] and emerging energy system [27,28]. The
main advantages of the techno-economic method are that the cost flow and the energy
flow of the system can be combined to identify the energy–exergy destruction rate of
each component, indicate the improvement direction, and obtain the unit cost of the
final product of the system [29]. The evaluation factor which is carried out based on
the thermodynamic–economic considerations mentioned above cannot fully meet the
requirements of economic evaluation of a drying system which undertakes the large task
of high-production drying quantities every year. For investors or contractors, the economic
rationality of the equipment and operating costs required for the drying system should
receive more attention. Therefore, a few relevant studies in the literature [10,30–32] have
reported a method which applied a techno-economics indicator, such as capital cost \( C_c \),
payback period \( PP \), and net present value \( NPV \), etc., to evaluate the performance of
the techno-economics of a drying system. For instance, Yahya et al. applied the techno-
economic analysis method to obtain the payback period and net present value of the
solar heat pump fluidized bed dryer with the value of 1.6 years and 8563.82 dollars,
respectively [33]. Nadiya et al. have reported detailed economic analysis through the
annualized cost, life cycle saving and payback period method [34]. Moreover, economic
estimation used the macroeconomics indicator mentioned above to provide a simple
method for investors or contractors to deal with simple economic issues and make the
correct choice for the selection and use of drying systems [35,36]. Therefore, investors or
contractors can determine the overall rate of return and payback period of the drying system.
and evaluate various technical options to meet the system based on the overall capital cost, the whole revenue and profit of the drying system obtained by economic analysis.

To summarize, in the last few decades, evaluation of the exergy–energy and techno-economic indicators was widely applied to evaluating the performance of the drying system. In the present work, we pay attention to a gas-type industrial drying system of black tea, which is currently the most widely used tea dryer [37], whereas relevant research studies have carried out research on the thin-layer drying model of tea, the prediction of drying time, and the heat and mass transfer model for the tea dryer [38–41], knowledge of performance analysis on exergy–energy and the techno-economics of the gas-type industrial drying system of black tea seems to be scarce in the existing scientific research literature. Therefore, the objective of the present study is not only concerning performance analysis of exergetic and energetic factors for a gas-type industrial drying system of black tea based on the first and second law of thermodynamics, which to reveal the energy loss in the drying system and to guide to design more efficient thermal systems, but also evaluating indicators such as net present value (NPV) and payback period (PP) to assess the economic performance of the drying system from the techno-economic perspective. This will generate insight into the drying system performance, benefitting the whole revenue stream by increasing energy utilization and commercialization of the drying system for an investor or contractor.

2. Materials and Methods

2.1. Materials

The experimental material shown in Figure 1 was freshly tea leaves (variety: Yinghong NO. 9) with an average initial moisture content 58.33% (w.b.), harvest from a local farm at Yangshan County, Guangdong Province.

![Figure 1. The freshly tea leaves for the experiment.](image-url)

2.2. Operation Principle of Experimental

A gas-type industrial drying system of black tea was installed in a tea enterprise in Yangshan County, Guangdong Province. The photograph of a gas-type industrial drying system of black tea was shown in Figure 2, which consisted of five principal components, including an air blower, furnace, drying chamber, hoist and chain plate motor.
Experiments were carried out in a tea enterprise in Yangshan County, Guangdong Province. The schematic diagram of a gas-type industrial drying system of black tea is shown in Figure 3. Tea farmers freshly harvested tea in tea garden, and turned it into approximately 180 kg of fermented tea leaves, which were placed into the drying chamber for the drying process. The working principle of the gas-type industrial drying system of black tea is that the air blower sends the air into the furnace for heating and then sends the heated air into the drying chamber from the bottom of the left side of the drying chamber to dry the fermented tea leaves which enter the conveyor chain network from the top feed port. The drying leaf reciprocates with the chain mesh layer to send the material to the discharge port. The hot-air-dried the fermented tea leaves are discharged from the exhaust pipe at the top of the drying chamber. Generally, the operation of drying was divided into two periods, the initial drying period and the redrying period. The detailed operation process is shown in Table 1.
Table 1. Detailing operation process in the present work.

| Materials                | Drying Period (Air Temperature) | Duration (min) | Mian Function   | Product                  |
|--------------------------|---------------------------------|----------------|-----------------|--------------------------|
| Fresh tea leaves         | Initial drying (120 °C)         | 90 min         | Initial drying tea | Dry tea (Approximately 45 kg) |
|                          | Redrying (100 °C)              | 60 min         | Redrying tea    |                          |

The temperature of the hot air at the inlet of the drying chamber is measured by a temperature sensor inserted into the hot air inlet and displayed in the control cabinet of the combustion chamber. Air temperature in the drying chamber was measured by using a PT100 thermal resistance. During the overall drying operation, the temperatures of the four layers of the drying chamber (\(T_i\), \(i = 1, 2, 3\) and 4, acquiescent \(T_4 = T_{\text{outlet}}\) especially) were measured by thermal resistance sensors inserted into the corresponding components. The air velocity and pressure were measured by using a wind speed and air volume measuring instrument. The details of the relevant measuring instruments are listed in Table 2.

Table 2. Details of the experimental instruments.

| Instrument                      | Type                  | Measurement          | Instrument |
|---------------------------------|-----------------------|----------------------|------------|
| Thermal resistance              | PT100                 | \(-200–450 °C\)      | ±0.1 °C    |
| Temperature and humidity sensors| AM2301                | \(0–100\%/-40–80 °C\) | ±3%/±0.5 °C |
| Electronic scale                | ABJ 320-4NM           | \(0–380 g\)          | ±0.01 g    |
| Constant-temperature drying box | DGG-9070A             | \(105 °C\)           | ±0.1 °C    |
| Data acquisition system         | Self-developed        | -                    | -          |
| Intelligent anemometer          | DP2000                | \(0–100 m/s, 0–\infty\ m\) | \(±0.1 m/s, ±0.5 m^3/h, ±0.5 KPa\) |

| Instrument                      | Type                  | Measurement          | Instrument |
|---------------------------------|-----------------------|----------------------|------------|
|                                 |                       |                      |            |

Measurement equipment error, data collection operation error and data accuracy will all have a certain impact on the accuracy of the overall work \([42]\). Therefore, the ascertainment of uncertainty analysis is necessary, and the calculation formula is as follows:

\[
W = \left[ \left( \frac{\partial y}{\partial x_1} w_1 \right)^2 + \left( \frac{\partial y}{\partial x_2} w_2 \right)^2 + \ldots + \left( \frac{\partial y}{\partial x_n} w_n \right)^2 \right]^{1/2}
\]  

(1)

where \(W\) is total uncertainty in result measurement, \(w_1, w_2, \ldots w_n\) are uncertainties in independent variables and \(x_1, x_2, \ldots x_n\) are independent variables.

2.3. Energy–Exergy Analysis

In this work, the mass and energy balance equation were applied to analyze the performance of the energy and exergy in a gas-type industrial drying system of black tea which were defaulted to be a steady state and steady flow drying system, the relevant calculation formula is as follows \([43]\):

\[
\sum m_{iin}h_{in} = \sum m_{out}h_{out}
\]

(2)

The energy conversation of the whole system can be expressed as the following calculation \([40]\):

\[
\sum Q + \sum m_{iin}h_{in} = \sum W + \sum P + \sum m_{out}h_{out}
\]

(3)

In the present work, the total heat (\(Q_{\text{gas}}\)) supplied by natural gas to the drying system, the heat (\(Q_a\)) used for heating the natural air, the useful energy (\(E_{\text{gas}}\)) to heat the air,
the power for the air blower ($P_{\text{blower}}$), the chain plate motor ($P_{\text{motor}}$), the hoist ($P_{\text{hoist}}$), the specific energy consumption (SEC), the specific thermal energy consumption (STEC), the exergy efficiency for the drying chamber ($\eta_{\text{ex}}$), the improvement potential (IP), and the sustainability index (SI) of the drying system can be calculated using Equations (4)–(19) tabulated in Table 3 [44–46].

### Table 3. Energy–exergy analysis of black tea drying system.

| Energy–Exergy Analysis                           | Equation                                                                 | Eq. No. |
|------------------------------------------------|--------------------------------------------------------------------------|---------|
| Total heat applied from gas                     | $Q_{\text{gas}} = V_{\text{gas}} \times q_{\text{gas}}$                 | (4)     |
| Energy for heating air                          | $Q_a = m_{a,c}c_{p,a}(T_1 - T_0)$                                       | (5)     |
| Heat loss of exhaust air outlet                 | $Q_{\text{loss,air}} = m_{a,c}c_{p,a}(T_4 - T_0)$                       | (6)     |
| Heat loss of the wall heat transfer             | $Q_{\text{loss,wall}} = \frac{1}{4}\sum_{i=1}^{4} (T_{\text{wall},i} - T_0)$ | (7)     |
| Exergy for heating air                          | $E_{\text{gas}} = m_{a,c}c_{p,a}\left[(T_1 - T_0) - T_0\ln\left(\frac{T_1}{T_0}\right)\right]$ | (8)     |
| Exergy of air blower                           | $E_{\text{blower}} = W_{\text{blower}} = P_{\text{blower}}t$           | (9)     |
| Exergy of chain plate motor                     | $E_{\text{motor}} = W_{\text{motor}} = P_{\text{motor}}t$              | (10)    |
| Exergy of hoist                                 | $E_{\text{hoist}} = W_{\text{hoist}} = P_{\text{hoist}}t$             | (11)    |
| Total exergy entering the drying system         | $E_{\text{gas}} + E_{\text{blower}} + E_{\text{motor}} + E_{\text{hoist}}$ | (12)    |
| Total exergy outlet the drying system           | $E_{\text{DC,in}} = \frac{E_{\text{DC,IN}}}{E_{\text{DC,OUT}}}$       | (13)    |
| The specific energy consumption                 | $\text{SEC} = \frac{Q_{\text{DC}}}{E_{\text{DC,in}}}$                 | (14)    |
| The specific thermal energy consumption         | $\text{STEC} = \frac{Q_{\text{DC}}}{T_{\text{DC}}}$                   | (15)    |
| Exergy of drying chamber                        | $E_{\text{DC}} = E_{\text{DC,IN}} - E_{\text{DC,OUT}}$                | (16)    |
| Exergy efficiency for drying chamber            | $\eta_{\text{ex}} = \frac{E_{\text{DC}}}{E_{\text{DC,IN}}}$           | (17)    |
| The improvement potential                       | $\text{IP} = (1 - \eta_{\text{ex}})E_{\text{DC}}$                     | (18)    |
| The sustainability index                        | $\text{SI} = \frac{1 - \eta_{\text{SI}}}{\eta_{\text{ex}}}$          | (19)    |

### Table 4. Economic analysis of black tea drying system.

| Economic Index      | Equation                                  | Eq. No. |
|---------------------|-------------------------------------------|---------|
| Production cost     | $C_P = C_{el} + C_{gas} + C_{la} + C_m + C_{dp}$ | (20)    |
| Profit              | $PR = TS - C_C - C_P$                      | (21)    |
| Return of capital   | $ROR = \frac{PR}{C_C}$                    | (22)    |
| Payback period      | $PP = \frac{C_C}{PR}$                     | (23)    |
| Net present value   | $NPV = \sum_{n=1}^{N} P_n(1 + i)^{-n} - C_C$ | (24)    |
|                     | $P_n = S(1 + i)^{-n}$                     | (25)    |

Where in the table, $C_{el}$, $C_{gas}$, $C_{la}$, $C_m$ and $C_{dp}$ are the cost of electricity, gas, labor, maintenance and depreciation; $P_n$ is the discounted present value ($S$) of the investment to be invested in the next $n$ years.
3. Results and Discussion

3.1. Energy Matching Structure of the Drying System

The uncertainty analysis of the parameters in the drying process are shown in Table 5. Compared with the previous studies [48,49], uncertainties regarding the experimental data were within a reasonable range, indicated that the dependability of the data used for calculating the indicators adopted in the present work.

Table 5. Detail parameters of the related equipment applied in this work.

| Parameters                     | Unit          | Uncertainty Value |
|--------------------------------|---------------|-------------------|
| Moisture content               | gwater/gwet mateer | ±0.012           |
| Air temperature                | °C            | ±0.299            |
| Mass of the product            | kg            | ±0.113            |
| Specific energy consumption    | kJ/g          | ±4.36%            |
| Specific thermal energy        | kJ/g          | ±4.391%           |
| consumption                    |               |                   |
| Time measurement               | min           | ±0.124            |

In the present work, drying operation consumption mainly include the energy of electricity and natural gas. The heat required to dry the material of the drying system supplied by the natural gas, the whole drying machine is provided by electricity. Detailed parameters of the related equipment applied in the present study are listed in Table 6. Furthermore, Figure 4 describes the proportion of the initial drying period, the redrying period energy, as well as the whole energy consumption of the drying system and energy consumption, including gas, induced fan and hoist. In the initial drying period, energy consumption by gas, fan, motor and hoist account for 94.32%, 4.56%, 0.56% and 0.56% in the initial drying system, in the redrying system account for 90.77%, 7.40%, 0.91% and 0.91%, respectively.

Table 6. Detailed parameters of the related equipment applied in this work.

| Equipment                | Power      |
|--------------------------|------------|
| Induced fan              | 3 kw       |
| Chain plate motor        | 0.37 kw    |
| Hoist                    | 0.37 kw    |

Figure 4. Total energy consumption ratios of the whole system: (a) energy consumption ratios in initial drying period; (b) energy consumption ratios in redrying period.

3.2. Heat Loss Characteristics of the Drying System

Heat loss is an important indicator to give reasons for the high energy consumption of drying systems. To clear energy consumption and energy efficiency of the system, the heat
loss characteristics of the drying system were investigated. In the present study, the heat loss of the drying system mainly considers the heat loss caused by the exhaust air outlet ($Q_{\text{loss,air}}$) and the heat loss of wall heat transfer ($Q_{\text{loss,wall}}$), the relevant calculation results shown in Table 7. As can be seen from Table 7, whatever in the initial drying period or redrying period, the heat loss of the exhaust air outlet played a main contributing role in the heat loss of the drying system. The value of the variation of the heat loss of exhaust air is 14.89–52.42 kW in the initial drying period and 49.55–51.27 kW in the redrying period; the value of the heat loss of wall heat transfer is 0.946–1.421 kW in the initial drying period and 1.227–1.420 kW in the redrying period. In addition, the variation interval of the whole heat loss is 15.84–53.84 kW in the initial drying period and 50.78–52.51 kW in the redrying period. The change trend of heat loss during the drying period of the whole drying system is that the heat loss of the exhaust gas and wall heat transfer in the initial drying period increases with the increase in drying time, and then tends to be stable until the redrying period and the end of drying. In the beginning of the drying process, the evaporation of the water of the fresh tea required the consumption of a lot of heat, and instability of the drying chamber temperature leads to the lower heat loss. As the drying process progresses, the variation curve of heat loss tends to be constant, which may be the result of the drying chamber temperature tending towards stability and the outlet temperature being higher than the temperature of the tea. The situation of the heat loss of the whole drying system tending to be steady in the latter period of the drying has been reported in relevant literature [50–52]. Thus, efforts should be made to recover and reuse the heat of the exhaust gas to improve the energy efficiency of the whole drying system.

| Period             | Initial Drying Period | Redrying Period |
|--------------------|-----------------------|-----------------|
| Time (min)         | 0  10  20  30  40  50  60  70  80  90  100  110  120  130  140  150  160 |
| Heat loss of exhaust air (kW) | 14.89 23.49 33.42 41.91 47.64 50.22 50.98 51.84 52.42 52.32 51.27 49.55 49.84 49.55 50.32 50.22 |
| Heat loss of wall heat transfer (kW) | 0.946 1.127 1.214 1.315 1.375 1.378 1.398 1.415 1.420 1.421 1.240 1.227 1.231 1.227 1.230 1.230 1.229 |
| Percentage of total heat loss to total heat (%) | 14.38 22.34 31.44 39.24 44.49 46.84 47.55 48.34 48.87 48.78 57.20 55.31 55.63 55.31 55.63 56.15 56.04 |

3.3. Analysis the Exergy Flow of the Drying System

The corresponding change trend curve of exergy flow is shown in Figure 5. Figure 5 describes the trend of the curve of the exergy inflow and exergy outflow increasing with the increase in time, and then tending to stability until to end of the drying. In the initial drying period, the value of the exergy inflow, exergy outflow and exergy of the drying chamber varied between 36.94–44.18 kW, 3.23–24.24 kW and 19.72–33.70 kW, respectively; and in the redrying period varied between 31.99–32.67 kW, 22.50–22.76 kW and 9.21–10.03 kW, respectively. Comparing with Table 7, we can see that the trend of the exergy flow is similar to the trend of the heat loss flow. In the beginning of the drying process, the temperature of the tea entering the drying chamber is lower, which results in huge amounts of exergy consumed to increase the temperature of the tea and remove moisture. Furthermore, the increase in the average temperature of the whole drying chamber results in the increase in the exergy outflow. A similar investigation has been made by Beigi for rice in a deep-bed convective dryer [53]. In general, exergy loss of the outflow played a contributing role in the exergy loss of the whole drying system, hence, a few studies in the literature have indicated that the exergy loss from the exergy outflow to the surroundings is one of the thermodynamic inefficiencies of drying systems [54,55]. Therefore, the focus of effort is not
only on the heat recovery of exhaust air, but also on the exergy loss of the exergy outflow to further optimize the structure of the drying system.

### 3.3. Analysis the Exergy Flow of the Drying System

The corresponding change trend curve of exergy flow is shown in Figure 5. Figure 5 describes the trend of the curve of the exergy inflow and exergy outflow increasing with the increase in time, and then tending to stability until the end of the drying. In the initial drying period, the value of the exergy inflow, exergy outflow and exergy of the drying chamber varied between 36.94–44.18 kW, 3.23–24.24 kW and 19.72–33.70 kW, respectively; and in the redrying period varied between 31.99–32.67 kW, 22.50–22.76 kW and 9.21–10.03 kW, respectively. Comparing with Table 7, we can see that the trend of the exergy flow is similar to the trend of the heat loss flow. In the beginning of the drying process, the temperature of the tea entering the drying chamber is lower, which results in huge amounts of exergy consumed to increase the temperature of the tea and remove moisture. Furthermore, the increase in the average temperature of the whole drying chamber results in the increase in the exergy outflow. A similar investigation has been made by Beigi for rice in a deep-bed convective dryer [53]. In general, exergy loss of the outflow played a contributing role in the exergy loss of the whole drying system, hence, a few studies in the literature have indicated that the exergy loss from the exergy outflow to the surroundings is one of the thermodynamic inefficiencies of drying systems [54,55]. Therefore, the focus of effort is not only on the heat recovery of exhaust air, but also on the exergy loss of the exergy outflow to further optimize the structure of the drying system.

Figure 5. Variation in the exergy inflow, exergy outflow and exergy of the chamber vs. drying time: (a) variation of exergy in the initial drying period; (b) variation of exergy in the redrying period.

### 3.4. Exergetic Performance of the Drying System

In the present study, evaluation of the indicators, including exergy efficiency ($\eta_{ex}$), improvement potential (IP), sustainability index (SI), specific energy consumption (SEC) and specific thermal energy consumption (STEC), was carried out to investigate the exergetic performance of the drying system. The variations in the evaluation indicators mentioned above are shown in Table 8 during the whole drying period.

#### Table 8. Variations in the evaluation indicators of the drying system.

| Drying Process | Drying Time (min) | $\eta_{ex}$ | IP (kW) | SI (-) | SEC (kJ/g) | STEC (kJ/g) |
|----------------|------------------|------------|--------|-------|-----------|----------|
| Initial drying period | 0 | 65.09% | 11.77 | 2.86 | 18.09 | 16.43 |
| | 10 | 64.34% | 11.88 | 2.80 | 19.58 | 17.91 |
| | 20 | 55.23% | 12.80 | 2.23 | 19.83 | 18.17 |
| | 30 | 48.97% | 12.94 | 1.96 | 20.67 | 19.00 |
| | 40 | 43.12% | 12.70 | 1.76 | 20.96 | 19.29 |
| | 50 | 38.28% | 12.23 | 1.62 | 20.60 | 18.94 |
| | 60 | 38.69% | 12.28 | 1.63 | 20.92 | 19.26 |
| | 70 | 37.85% | 12.18 | 1.61 | 20.99 | 19.32 |
| | 80 | 38.08% | 12.21 | 1.62 | 21.21 | 19.55 |
| | 90 | 38.63% | 12.28 | 1.63 | 21.31 | 19.65 |
| Redrying period | 100 | 24.76% | 6.93 | 1.33 | 129.58 | 116.27 |
| | 110 | 26.00% | 7.16 | 1.35 | 127.13 | 113.82 |
| | 120 | 26.60% | 7.26 | 1.36 | 128.60 | 115.29 |
| | 130 | 26.56% | 7.26 | 1.36 | 127.87 | 114.56 |
| | 140 | 26.97% | 7.33 | 1.37 | 129.09 | 115.78 |
| | 150 | 25.55% | 7.08 | 1.34 | 128.36 | 115.05 |
| | 160 | 26.28% | 7.21 | 1.36 | 129.09 | 115.78 |
As shown in Table 8, $\eta_{ex}$ and $SI$ decrease with the increase in the drying time; conversely, $IP$ increased with the increase in the drying time. In the present work, exergy efficiency values varied from 37.85% to 65.09% in the initial drying period and 24.76% to 26.97% in the redrying period. According to the previous analysis of the change trend of heat loss and exergy flow, the exergy efficiency increased with the decrease in the heat loss and exergy outflow. It can be clearly seen from Table 8 that the improvement potential ($IP$) values change from 11.77 kW to 12.94 kW in the initial drying period, and from 6.93–7.33 kW in the redrying period. Additionally, corresponding to the initial and redrying period, the value of the sustainability index of the present study varied from 1.61 to 2.96 and from 1.33 to 1.37. Previous studies have indicated that the higher exergy efficiency resulted the higher sustainability index and the lower effect on the environment [56]. Accordingly, efforts should be made to ameliorate the exergy efficiency of the present drying system to reduce the effective on the environment. Furthermore, as can be clearly seen from Table 8, the value of $SEC$ and $STEC$ varied from 18.09 kJ/g to 21.31 kJ/g and 16.43 kJ/g to 21.21 kJ/g in the initial drying period; but in the redrying period, the value of $SEC$ and $STEC$ varied from 127.13 kJ/g to 129.58 kJ/g and 113.82 kJ/g to 116.27 kJ/g, respectively. The phenomenon that $SEC$ and $STEC$ increases rapidly in the redrying period due to the existence of the binding energy, and a similar conclusion was found by Xiong et al. [57] and Yıldırım et al. [58].

3.5. Techno-Economic Analysis of the Drying System

In this section, the techno-economic analysis mainly includes the capital cost of the drying system, the net present value, the net cash flow and the payback period; the following Tables 9–13 record the economic analysis results of the whole drying system of the present work. The discount factor, maintenance costs, depreciation rate and expected life of the dryer were performed with an assumed value of 10%, 2%, 9.5% and 10 years, respectively. As can been seen from Table 9, the cost of infrastructure and tea garden construction and management constitute the main component of the whole capital cost. Based on the capital costs mentioned above and the parameters shown in Table 10, the product costs include the cost of fresh tea (30,731.04 USD/Year), labor (21,865.89 USD/Year), electricity (139.97 USD/year), natural gas (8388.06 USD/year), maintenance (3147.01 USD/year) and depreciation (14,948.32 USD/year). Table 11 has tabulated annual operation cost, annual revenue and the net cash flow were 64,271.97 USD/year, 94,413.60 USD/year and 30,141.63 USD/year, respectively. As can be shown in Tables 12 and 13, the economic analysis of the drying system in the present work calculated and demonstrated that the net present value and the payback period had values of 179,442.03 USD and 5.3 Years, respectively.

Table 9. The capital costs of the drying system.

| Item                      | Cost USD   |
|---------------------------|------------|
| Furnace                   | 1025.94    |
| Blower                    | 180.47     |
| Drying chamber            | 6414.00    |
| Hoist                     | 1676.38    |
| Chain plate motor         | 94.75      |
| Transportation and installation costs | 728.86 |
| Infrastructure cost       | 72,886.30  |
| Tea garden construction and management costs | 74,344.02 |
| Whole capital cost        | 157,350.72 |

Currency exchange rate: 6.86 CNY = 1 USD
Table 10. Parameters used in the calculation of the net present value (NPV) and payback period (PP) of the drying system.

| Parameter                                         | Unit   | Value  |
|---------------------------------------------------|--------|--------|
| Initial weight of tea                             | kg     | 180    |
| Final weight of tea                               | kg     | 45     |
| Initial moisture content of tea (wet basis)       | %      | 58.33  |
| Final moisture content of tea (wet basis)         | %      | 4.63   |
| Drying time                                       | min    | 162    |
| Price of the fresh tea                            | USD/kg | 0.67   |
| Factory price of dried tea                        | USD/kg | 14.57  |
| Price of natural gas                              | USD/kg | 3.12   |
| Price of electricity                              | USD/kWh| 0.10   |
| Tea harvest and management costs                  | USD/day| 213.41 |
| Discount factor                                   | %      | 10     |
| Maintenance costs                                 | %      | 2      |
| Depreciation                                      | %      | 9.5    |
| Expected life of the dryer                        | Year   | 10     |
| Net present value (NPV)                           | USD    | 179,442.03 |
| Payback Period (PP)                               | Years  | 5.3    |

Currency exchange rate: 6.86 CNY = 1 USD

Table 11. Cash flow statement of the drying system.

| Years | Capital costs (USD) | Production costs (USD) | Total production costs (USD) | Revenue (USD) | Net cash flow (USD) |
|-------|---------------------|------------------------|-------------------------------|---------------|---------------------|
| 0     | 157,350.72          |                        |                               |               |                     |
| 1     |                     | Fresh tea              | 21,865.89                     |               |                     |
| 2     |                     | Labor                  | 30,731.04                     |               |                     |
| 3     |                     | Electrical             | 139.97                        |               |                     |
| 4     |                     | Natural gas            | 8388.06                       |               |                     |
| 5     |                     | Maintenance            | 3147.01                       |               |                     |
| 6     |                     | Depreciation           | 14,240.24                     |               |                     |
| 7     |                     |                        | 64,271.97                     | 94,413.60     | 30,141.63           |
| 8     |                     |                        |                               |               |                     |
| 9     |                     |                        |                               |               |                     |
| 10    |                     |                        |                               |               |                     |

Currency exchange rate: 6.86 CNY = 1 USD

Table 12. NPV of the drying system (NPV = 179,442.03 USD).

| Years | Capital Costs (CC) (USD) | Net Cash Flow (USD) | Discount Factor (i = 10%) | Present Value (USD) |
|-------|--------------------------|---------------------|---------------------------|---------------------|
| 0     | 157,350.72               |                     | 1                         | 27,401.76           |
| 1     | 30,141.63                | 0.9091              | 24,909.04                 |
| 2     | 30,141.63                | 0.8264              | 22,645.41                 |
| 3     | 30,141.63                | 0.7513              | 20,586.73                 |
| 4     | 30,141.63                | 0.6830              | 18,714.94                 |
| 5     | 30,141.63                | 0.6209              | 17,014.95                 |
| 6     | 30,141.63                | 0.5645              | 15,468.68                 |
| 7     | 30,141.63                | 0.5132              | 14,061.07                 |
| 8     | 30,141.63                | 0.4665              | 12,783.07                 |
| 9     | 30,141.63                | 0.4241              | 11,619.60                 |
| 10    | 30,141.63                | 0.3855              | 10,545.25                 |

The final depreciation value = 14,948.32 USD
The final present value = 5763.22 USD

Currency exchange rate: 6.86 CNY = 1 USD
Table 13. Payback Period of drying system ($PP = 5.3$ years).

| Years | Capital Costs (CC) (USD) | Annual Benefit (USD) | Benefit Cumulative (USD) |
|-------|--------------------------|----------------------|--------------------------|
| 0     | 157,350.72               | 0                    | 0                        |
| 1     | 30,141.63                | 30,141.63            | 30,141.63                |
| 2     | 30,141.63                | 60,283.26            | 90,424.89                |
| 3     | 30,141.63                | 90,424.89            | 150,708.15               |
| 4     | 30,141.63                | 120,566.52           | 241,274.67               |
| 5     | 30,141.63                | 150,708.15           | 392,982.82               |
| 6     | 30,141.63                | 180,849.78           | 573,832.57               |

Currency exchange rate: $6.86 \text{ CNY} = 1 \text{ USD}$

4. Conclusions

In the present work, black tea was dried through the use of a gas-type industrial dryer. In the aspect of energy efficiency evaluation of the drying system, the exergetic and energetic performance of the dryer were investigated; in the aspect of economic analysis of the whole system, the net present value and payback period of the system were considered in the investigation. The main conclusion to be drawn are as follows:

1. In approximately the first 50 min of the whole drying process, both the heat loss and exergy outflow increase with the increase in drying time, and then become stable as a result of the influence of the binding energy between the dry matter and water molecules until to end of drying process.

2. The heat loss of the exhaust air makes an important contribution to the heat loss and exergy loss of the whole drying system, especially in the redrying period. Therefore, it is recommended that a device be designed to recover heat from the exhaust air so as to improve the energy efficiency and reduce the exergy loss rate of the whole drying system.

3. In the drying process, the improvement potential rate varied from 6.93 kW to 12.94 kW and the value of the sustainability index ranged from 1.33 to 2.86 of the drying system, indicating that the exergy efficiency should be improved so as to improve the environmental sustainability.

4. According to the techno-economic method’s calculations, the net present value and payback period are 179,442.03 USD and 5.3 years, respectively.

Finally, further studies are advised to investigate the influence of factors such as ventilation temperature and speed on the drying efficiency, optimize the drying process parameters, and further improve the sustainability and efficiency of the drying system.

Author Contributions: Conceptualization, Z.Z. and B.L.; methodology, Z.Z. and B.L.; software, Z.Z., C.H. and C.D.; validation, Z.Z., C.H. and Z.H.; formal analysis, Z.Z. and T.C.; investigation, Z.H., C.G. and F.Z.; resources, C.H., T.C. and C.G.; data curation, C.H. and F.Z.; writing—original draft preparation, Z.Z. and B.L.; writing—review and editing, Z.Z. and B.L.; visualization, Z.Z. and B.L.; supervision, W.W.; project administration, W.W.; funding acquisition, W.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the development and application demonstration of transportation and spraying equipment for Jiexi alpine tea gardens (Dzxnny004); Guangdong Provincial Special Fund for Modern Agriculture Industry Technology Innovation Teams (2022KJ120); Guangdong Agricultural Scientific and Technology research project (2020-440000-02100200-8418); Guangdong Province Special fund for scientific and technological innovation strategy (“Climbing Plan” Special fund: pdjh2022a0072).

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank to the editors and reviewers for their valuable and constructive comments.
Conflicts of Interest: The authors declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature

\( m \) Mass flow rate (kg s\(^{-1}\))
\( E_x \) Exergy rate (kW)
\( h \) Specific enthalpy (kJ kg\(^{-1}\))
\( Q_{\text{gas}} \) Heat of gas (J)
\( V_{\text{gas}} \) Unit volume of natural gas (m\(^3\))
\( Q_a \) Heat of heating air (J)
\( m_g \) Mass flow of air (kg s\(^{-1}\))
\( c_p \) Specific heat of air (J kg\(^{-1}\) °C\(^{-1}\))
\( T_1 \) Temperature of inlet (°C)
\( T_4 \) Temperature of outlet (°C)
\( T_0 \) Temperature of ambient (°C)
\( T_{\text{wall}} \) Temperature of wall (°C)
\( Q_{\text{loss,air}} \) Heat loss of exhaust air (kW)
\( Q_{\text{loss,wall}} \) Heat loss of the wall heat transfer (kW)
\( A_0 \) Heat transfer area of the drying chamber (m\(^2\))
\( E_{x_{\text{gas}}} \) Exergy of gas (kW)
\( E_{x_{\text{blower}}} \) Exergy of blower (kW)
\( E_{x_{\text{motor}}} \) Exergy of chain plate motor (kW)
\( E_{x_{\text{hoist}}} \) Exergy of hoist (kW)
\( E_{x_{\text{dc,in}}} \) Total exergy entering the drying system (kW)
\( E_{x_{\text{dc,out}}} \) Total exergy outlet the drying system (kW)
\( E_{x_{\text{dc}}} \) Exergy of drying chamber (kW)
\( W_{\text{blower}} \) Work rate of blower (kW)
\( W_{\text{motor}} \) Work rate of chain plate motor (kW)
\( W_{\text{hoist}} \) Work rate of hoist (kW)
\( P_{\text{blower}} \) Power rate of blower (kW)
\( P_{\text{motor}} \) Power rate of chain plate motor (kW)
\( P_{\text{hoist}} \) Power rate of hoist (kW)

Abbreviations

DR Drying rate (g\(_{\text{water}}\)/g\(_{\text{wet matter}}\) h)
SEC Specific Energy Consumption (kJ/g)
STEC Specific Thermal Energy Consumption (kJ/g)
SI Sustainability index
IP Improvement potential rate (kW)
NPV Net present value
PP Payback period

Subscripts

\( a \) Air
\( in \) Inlet
\( out \) Outlet

Greek symbols

\( \eta_{\text{ex}} \) Exergy efficiency (%)
\( \delta \) Thickness (m)
\( \gamma \) Thermal conductivity (W m\(^{-1}\) °K\(^{-1}\))

References

1. Li, B.; Li, C.; Li, T.; Zeng, Z.; Ou, W.; Li, C. Exergetic, Energetic, and Quality Performance Evaluation of Paddy Drying in a Novel Industrial Multi-Field Synergistic Dryer. *Energies* 2019, 12, 4588. [CrossRef]
2. Lingayat, A.; Chandramohan, V.P.; Raju, V.R.K. Energy and Exergy Analysis on Drying of Banana Using Indirect Type Natural Convection Solar Dryer. *Heat Transf. Eng.* 2019, 41, 551–561. [CrossRef]
3. Aviara, N.A.; Onuoha, L.N.; Falola, O.E.; Igbeka, J.C. Energy and exergy analyses of native cassava starch drying in a tray dryer. *Energy* 2014, 73, 809–817. [CrossRef]
35. McGarity, A.E. Solar Heating and Cooling, An Economic Assessment; National Science Foundation, U.S. Govt Printing Office: Washington, DC, USA, 1977.

36. Riva, G.; Mazzetto, F. Comparative Analysis of the Results Obtained by the Country Teams Applying the Procedure on Barriers Evaluation; REUR Technical Series; FAO: Rome, Italy, 1988.

37. Wang, W.M.; Xiao, H.R.; Song, Z.Y.; Han, Y.; Ding, W.Q. Research status and prospect of mechanization technology in the whole process of tea production. Chin. J. Agric. Mach. 2020, 41, 226–236.

38. Dong, S.L.; Sun, C. Mathematical model of heat transfer of green tea cyanogens. Tea Sci. 1988, 2, 81–82.

39. Panchyariya, P.C.; Popovic, D.; Sharma, A.L. Thin-layer modelling of black tea drying process. J. Food Eng. 2002, 52, 349–357. [CrossRef]

40. Temple, S.J.; van Boxtel, A.J.B. Thin Layer Drying of Black Tea. J. Agric. Eng. Res. 1999, 74, 167–176. [CrossRef]

41. Yin, H.F. Engineering principle of tea drying time prediction. Chin. Tea 1987, 6, 3–5.

42. Sević, S. Experimental investigation of a new design solar-heat pump dryer under the different climatic conditions and drying behavior of selected products. Sol. Energy 2014, 105, 190–205. [CrossRef]

43. De Fraeye, T. Advanced computational modelling for drying processes—A review. Appl. Energy 2014, 131, 323–344. [CrossRef]

44. Akpinar, E.K.; Midilli, A.; Bicer, Y. The first and second law analyses of thermodynamic of pumpkin drying process. J. Food Eng. 2006, 72, 320–331. [CrossRef]

45. Yahya, M.; Fudholi, A.; Hafizh, H.; Sopian, K. Comparison of solar dryer and solar-assisted heat pump dryer for cassava. Sol. Energy 2016, 136, 606–613. [CrossRef]

46. Fudholi, A.; Sopian, K.; Bakhtyar, B.; Gabbasa, M.; Othman, M.Y.; Ruslan, M.H. Review of solar drying systems with air-based solar collectors in Malaysia. Renew. Sustain. Energy Rev. 2015, 51, 1191–1204. [CrossRef]

47. Ibrahim, M.N.; Sarker, A.; Aziz, N.A.B.; Salleh, M. Drying performance and overall energy requisite of industrial inclined bed paddy drying in Malaysia. J. Eng. Sci. Technol. 2014, 9, 398–409.

48. Aghbashlo, M.; Tabatabaei, M.; Jazini, H. Exergoeconomic and exergoenvironmental co-optimization of continuous fuel additives (acetins) synthesis from glycerol esterification with acetic acid using Amberlyst 36 catalyst. Energy Convers. Manag. 2018, 65, 183–194. [CrossRef]

49. Khanlari, A.; Güler, H.O.; Tuncer, A.D.; Şirin, C.; Bilge, Y.C.; Yılmaz, Y.; Güngör, A. Experimental and numerical study of the effect of integrating plus-shaped perforated baffles to solar air collector in drying application. Renew. Energy 2020, 145, 1677–1692. [CrossRef]

50. Yahya, M. Sistem Penyahlembapan Terbantu Suria Untuk Herba Perubatan. Ph.D. Thesis, Universitas Kebangsaan Malaysia, Selangor, Malaysia, 2007.

51. Ma, X.; Fang, Z.; Li, C. Energy efficiency evaluation and experiment on grain counter-flow drying system based on exergy analysis. Trans. Chin. Soc. Agric. Eng. 2017, 33, 285–291.

52. Shiun, L.J.; Haslenda, H.; Zainuddin, A.M.; Shariafah, R.A. Optimal design of a rice mill utility system with rice husk logistic network. Ind. Eng. Chem. 2012, 51, 362–373. [CrossRef]

53. Beigi, M.; Tohidi, M.; Torki-Harchegani, M. Exergetic analysis of deep-bed drying of rough rice in a convective dryer. Energy 2017, 140, 374–382. [CrossRef]

54. Kuzgunkaya, E.H.; Hepbasli, A. Exergetic evaluation of drying of laurel leaves in a vertical ground-source heat pump drying cabinet. Int. J. Energy Res. 2007, 31, 245–258. [CrossRef]

55. Aghbashlo, M.; Mobli, H.; Madaoulou, A.; Rafiee, S. Influence of spray dryer parameters on exergetic performance of microencapsulation process. Int. J. Exergy 2012, 10, 267–289. [CrossRef]

56. Rosen, M.A.; Dincer, I. Exergy as the confluence of energy, environment and sustainable development. Int. J. Exergy 2001, 1, 3–3. [CrossRef]

57. Xiong, S.; Sun, W.; Zhao, L.; Lu, Z.; He, X.; Mao, J.; Zhou, Q. Optimization of three-stage drying of paddy. Food Sci. 2017, 38, 274–281.

58. Yildirim, N.; Genc, S. Energy and exergy analysis of a milk powder production system. Energy Convers. Manag. 2017, 149, 698–705. [CrossRef]