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Exploratory Testing of Energy-Saving Characteristics of Large-Scale Freeze-Drying Equipment

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Abstract: The advantages of continuous freeze-drying are increasingly being emphasized, including energy saving, high production efficiency, and superior quality. In this context, an innovative continuous production process and cold trap structure for large-scale freeze-drying equipment is proposed. Built-in alternating cold traps are adopted instead of the stationary type to reduce the defrosting downtime, significantly improving the energy efficiency of the refrigeration and heat pump heating units. In the freeze-drying production of shiitake, comparisons between the built-in alternating cold traps and the stationary type indicate a reduction in energy consumption of approximately 24% for the full production process when the alternating cold traps with tube coils are used, that is, from 1937 kW·h for the stationary type to 1471 kW·h. In addition, the energy consumption for the built-in alternating cold traps with finned tube coils could be further reduced by about 8%. Finally, through the implementation of the new continuous production process and built-in alternating cold traps in industrial large-scale freeze-drying equipment, the systematic energy consumption per unit of food dehydration (kg) is reduced by approximately 40%, i.e., from 1.31 kW·h in the intermittent production process to 0.79 kW·h in the new continuous production process.

Keywords: freeze-drying; frosting/defrosting; production process; energy-saving

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1. Introduction

During the processing, storage, and distribution of food, various changes might occur in the physical, chemical, and biological properties, and the quality of food becomes increasingly important in influencing consumer choice [1]. For traditional drying technologies, water evaporation in food generally occurs through heat absorption in the liquid state but not under a vacuum environment below the triple point. However, the moisture of foods in the solid state must be sublimed by absorbing heat in an environment below 610.75 Pa, which is a typical vacuum environment. As a good example, for freeze-drying, foods are first frozen below their eutectic point temperature, heated in a vacuum environment, and dehydrated through ice crystal sublimation [2]. Compared with traditional food drying using hot air, freeze-drying has minimal effects on the biological activity, and the nutrition, volume, and color of foods are effectively maintained [3], particularly the volume without deformation. It can preserve heat-sensitive substances in food better and is considered the best technology for maintaining the original quality of food [4]. As a result, freeze-dried foods, which are superior to other drying products in terms of shape, color, flavor, and rehydration capacity, have become increasingly popular among consumers worldwide [5–7]. Unfortunately, the high energy consumption of the freeze-drying process severely limits its large-scale application in plain foods [8].

As the porous structure of foods remains unchanged during the freeze-drying process, heat transfer downgrades, and drying time becomes longer [9,10]. In particular, due to frosting at low temperatures, heat transfer greatly deteriorates, which necessitates the consideration of the defrosting process. Conventionally, an intermittent production process is adopted, which results not only in a long production period, low productivity, and high costs, but also in great energy consumption [11–13].

During the processes of freeze-drying, approximately 70% of the total energy consumption is attributed to dehydration. The refrigeration unit, which includes the refrigeration compressor, condenser, and evaporator, provides cooling capacity for a cold trap. The energy consumption of the refrigeration unit accounts for 80% of the energy consumption for dehydration, which means that the energy consumption related to the cold trap accounts for about half of the total process energy consumption [14–16].

Due to the limitations of the intermittent production process, for intermittent freeze-drying equipment with a stationary cold trap, the energy consumption greatly fluctuates in production. Additionally, the equipment has to face severe idling problems. It becomes an important challenge to reduce energy consumption and lift production efficiency.

In recent years, with the continuous development of the economy and the improvement of living standards, people's perception of consumption changes day by day. Freeze-drying technologies have become increasingly popular for producing high-quality foods, which are delicious and have natural additives and excellent nutrition. Consequently, freeze-drying technologies are gaining wider recognition and appreciation in society.

Although freeze-drying is a recognized technique for producing high-quality products, its long drying time, high energy consumption, and high processing costs have restricted its large-scale application [17]. Combining microwave, pulsed electric field, explosion puff, and infrared as pretreatments for freeze-drying could improve the drying rate, reduce energy consumption, and preserve nutritional content and colors [18]. Cao et al. used microwave heating at 1, 1.5, and 2 W/g to process barley grass, observing that MFD (microwave freeze-drying) preserved chlorophyll, flavonoid, color, and odor, while reducing energy usage during freeze-drying [19]. Fauster et al. studied the impacts of pulsed electric field pretreatment on the physical characteristics of bell peppers and strawberries, noting reduced shrinkage compared to untreated samples [20]. Yi et al. combined FD-DIC (freeze-drying and the instant controlled pressure drop process) for restructured carrot–potato chips and its processing conditions were optimized using RSM (response surface methodology) with the purpose of improving the quality of products and reducing energy consumption [21]. Colucci et al. studied the ultrasound-assisted freeze-drying process and proposed an in silico method to optimize the industrial process. The URIF (uniformly retreating ice front) model is broadly used to determine kinetic parameters. Although power ultrasound increased tunnel dryer productivity by four to five times on an industrial scale, practical limitations remain despite the anticipated benefits from simulation [22]. Khampakool et al. conducted experiments on FD (freeze-drying), IRAFD (infrared assist-freeze-drying), and continuous IRAFD, respectively, and continuous IRAFD showed a reduction in drying time up to 210 min, with 70% time saving [10].

Furthermore, in the last decade, great efforts have been made by pharmaceutical companies in the development of new technologies for continuous freeze-drying [23,24]. Continuous freeze-drying is a process with applications in both the pharmaceutical and food industries, with the aim of extending the shelf life of products and increasing yields. Notable distinctions exist between the two sectors; in the pharmaceutical industry, such a technique is primarily employed to enhance the stability of drugs, thereby ensuring their effectiveness; in the food industry, it is utilized to preserve flavor and nutritional value. It is imperative to highlight that the stringent regulatory standards for continuous freeze-drying are upheld by the pharmaceutical industry due to its critical impacts on the quality and stability of pharmaceuticals. In contrast, although the food industry prioritizes safety and quality, its standards are comparatively less stringent. Therefore, greater emphasis should be placed on the development of a continuous freeze-drying process in the food industry for its numerous advantages in terms of energy saving, process efficiency, and product quality. Through further research focused on streamlining and optimizing operations, these techniques could be integrated into commercial processes [17].

The performance and dependability of freeze-drying equipment could be enhanced by the integration of built-in cold traps, which effectively manage the discharge of condensed water, thereby ensuring product quality and stability. The proliferation of large-scale freeze-drying equipment is facilitated by this advancement, and substantial quantities of freeze-drying products could be efficiently processed, thus boosting production efficiency and reducing costs. The implementation of built-in cold traps has facilitated the scaling and automation of freeze-drying equipment, optimizing the overall freeze-drying food production process in terms of effectiveness, reliability, and cost-effectiveness [25]. Additionally, the risk associated with difficult-to-clean areas is reduced by the absence of pipelines and valves connected to the drying chamber in built-in cold traps, and the large opening at the top of the cold traps facilitates easier cleaning, meeting food hygiene standards.

In this context, a new continuous freeze-drying method with built-in alternating cold traps is proposed as an innovation in the production process and cold trap structure for large-scale freeze-drying equipment [26,27]. Industrial experiments are conducted to evaluate the effects of heat transfer enhancement during the frosting/defrosting processes of the cold traps on the reduction of energy consumption, with a capacity to capture 1500 tons of water per year. Furthermore, a comparative study of the characteristics of systematic energy consumption is carried out, utilizing an innovative continuous production process.

2. Manufacture and Testing of Large-Scale Freeze-Drying Equipment

As large-scale freeze-drying equipment with alternating cold traps for the continuous production process, the equipment is coupled with an integrated energy system in which the refrigeration unit, heat pump heating unit, and drying bins simultaneously exchange energy through the heat exchangers under stable conditions. The main processes of large-scale food freeze-drying production are shown in Figure 1.

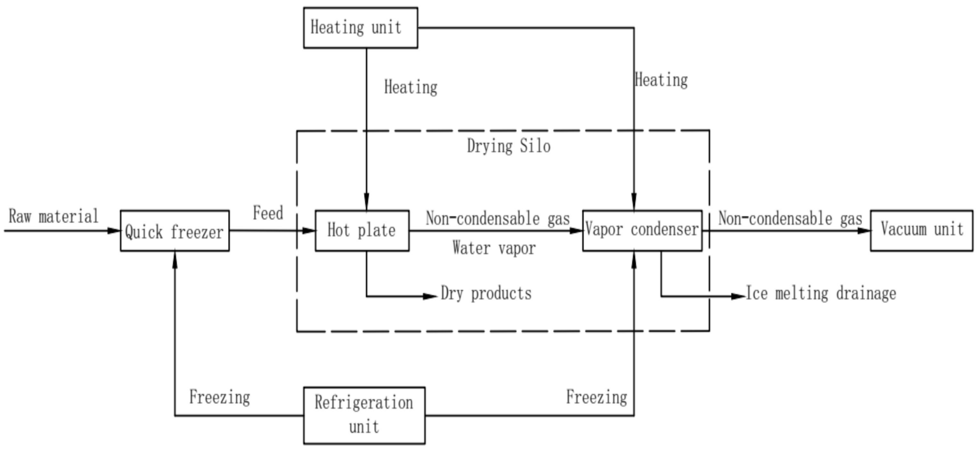

Figure 1. Main processes of large-scale food freeze-drying production.

The workflow of the refrigeration unit is as follows. The refrigerant gas at low-temperatures and low-pressures enters the low-pressure circulation barrel from the freeze-drying bin for gas–liquid separation; the refrigerant liquid remains in the barrel and the gas enters the compressor for compression. After compression, the high-temperature and high-pressure gas is formed and enters the condensing evaporator (heat is exchanged with the heat pump heating unit and the heat is taken away by the heat pump heating unit). The refrigerant liquid, after condensation, passes through the refrigeration unit and enters the barrel pump unit. The refrigerant liquid at the evaporating temperatures is pumped to the end of the freeze-drying bin. After heat transfer occurs in the freeze-drying bin, the gas–liquid two-phase refrigerant returns to the barrel pump unit and circulates again.

The processes of the heat pump heating unit are as follows. The refrigerant on the high-temperature side exchanges heat with the refrigerant on the cooling side in the condensing evaporator, forming a gaseous refrigerant fluid, which is compressed by the heat pump heating unit to form a high-temperature and high-pressure refrigerant gas entering the water-cooled condenser for heat exchange with water to produce hot water. The refrigerant liquid, after condensation, passes through the throttling device into the condensing evaporator for heat transfer (heat extraction), forming a gaseous refrigerant fluid and circulating again.

An experimental comparison is adopted using an intermittent freeze-dryer with a stationary trap, which was manufactured by True Cold-chain Co., Ltd. (Yantai, China). The others are all designed and manufactured by Zhejiang Tongking FD Technology Co., Ltd. (Quzhou, China), including the intermittent freeze-dryer with built-in alternating traps and the continuous freeze-dryer with built-in alternating traps. The energy consumption of the dryer with alternating cold traps (continuous process) or stationary type (intermittent process) is collected and recorded by means of an electric power meter, and the relevant instrument parameters are shown in Table 1. For the alternating cold traps (continuous process), the power includes compressors in the refrigeration unit, a compressor in heat pump heating unit, circulation pumps, and vacuum pumps.

Table 1. Main instruments and parameters in testing.

Instrument Name	Model	Accuracy	Range	Measuring Parameter
Vacuum gauge	CDG025D	±0.2%	0–1333 mbar	Vacuum level in drying bin
Vortex flowmeter	Focvor4102	1.5%	/	Flow of hot steam
Platinum resistance thermometer	Pt100	±0.5 °C	−50–150 °C	Temperature of food and fluids
Electric power meter	LD-C83TH-5A01	1%	/	Power of a compressor for refrigeration unit and heat pump unit in the continuous process
Electric power meter	DTSU666	1%	/	Power consumption of a vacuum pump and circulation pump
Electric power meter	PM215CDI2RO	1%	/	Power of a compressor for refrigeration unit in intermittent process
Electronic balance	TCS-200	50 g	1–200 kg	Weighing captured water

The captured water in the alternating cold traps (continuous process) is measured by weighing the defrosted water discharged by the drainage pump during the defrosting phase and by using an electronic weighing scale (TCS-200). In the stationary type (intermittent process), the amount of captured water is calculated by weighing the total amount of the defrosting water at the end of a freeze-drying process. In addition, the amount of captured water is related to the thickness of the frost layer, the heat transfer area of the cold trap, and the density, and the thickness and the density of the frost layer interact with each other. Assuming that the frost density produced by the condensation process is uniform, then the following applies:

$$G = \rho_c \cdot A_k \cdot \delta_c, \quad (1)$$

where G is the weight of captured water, kg; ρ_c is the density of frost, kg/m^3; A_k is the surface area of the cold trap, m^2; and δ_c is the thickness of frost, m.

The frost thickness obtained from the cold traps is used as a calibration parameter for accuracy in the amount of water captured by the aforementioned weighing method, and it is also an important auxiliary parameter for the control of the operation processes in testing. In order to accurately obtain the frost layer thickness at the cold traps, an innovative design of the frost thickness measurement module is proposed, which is installed on the cold trap coil. The measurement module and the cold trap coil are clamped with adiabatic material, held tightly between the measurement module, and a gradient of steps (each step of 1 mm) is equipped with a different color marking to facilitate the identification of video images to read, as shown in Figure 2.

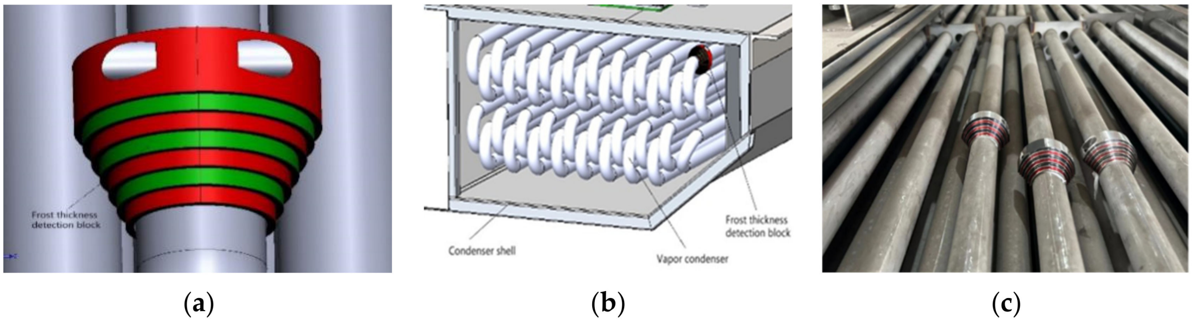

Figure 2. Schematic diagram of the measuring module for the frost thickness: (**a**) Schematic of the structure of the module; (**b**) schematic of the installation; (**c**) photo of the installed module in the cold trap coils.

The main testing processes for large-scale freeze-drying production are carried out as follows.

(a) The food raw materials are evenly placed on the tray according to certain requirements, and two to three of the trays are selected for inserting a thermometer into the center of the material. After that, the tray is loaded into the carriage and pushed into the quick-freezing tunnel for quick-freezing treatment, usually being frozen to below −40 °C in about 4 h.
(b) After rapid freezing, the raw food materials are moved into the vacuum freeze-drying bin by the carriage system and the guide rail system. At this time, the tray containing the raw food materials is placed above the hot plate, and the vacuum freeze-drying bin door is covered.
(c) The vacuum freeze-drying bin is evacuated by the vacuum unit, and the vacuum pipe of the vacuum unit is connected to the vacuum freeze-drying bin through the cold traps. The vacuum process is pumped to about 80 Pa within 10 to 30 min. At the same time, the refrigeration unit begins to pre-cool the cold trap; the general pre-cooling is below −35 °C.
(d) After the vacuum reaches the required value, the heat pump heating unit heats the hot plate, while the raw food materials absorb heat and begin an intense sublimation process. Sublimation starts from the surface ice crystal of the material, and the sublimation interface gradually migrates to the inner layer during the process. The migration speed is determined by the actual working conditions, generally 0.3–2 mm per hour. A large amount of water vapor and a small amount of non-condensing gas is produced during the sublimation process of raw food materials.
(e) After reaching the set value, the temperature is maintained by the hot plate, and the raw food materials are continuously heated. During this period of continuous heating of the hot plate, a balance is reached, which is reflected in the vacuum degree remaining unchanged and the temperature displayed by the thermocouple in the material becoming basically constant.
(f) With the sublimation process, the water content of the food material is gradually reduced. As the sublimation interface becomes gradually deeper, the escape of water vapor gradually becomes more difficult, resulting in a gradual reduction of the captured water. The temperature displayed by the food material's thermocouple begins to rise and slowly approaches the hot plate temperature. When the temperature displayed is almost consistent with that of the hot plate, it indicates that the free water in the food material has been sublimated. It is necessary to continue heating for 2 to 3 h as analytical treatment after this stage.
(g) Upon completion of the analytical processing, the vacuum freeze-drying processes are completed, and the raw materials are transformed into dry products. The processes of vacuuming, heating, and cooling are stopped, the vacuum freeze-drying bin is opened to break the vacuum, and the food materials are removed.

3. Results and Discussion

3.1. Energy Analysis on the Built-In Alternating Cold Trap

The capturing of water vapor in freeze-drying equipment is essential, with most of the vapor from food dehydration captured by the cold trap. And then, the captured vapor becomes liquid and is discharged from the equipment. In this context, an innovative structure of built-in alternating cold traps is proposed for the large-scale freeze-drying bin, as shown in Figure 3. The alternating cold traps are located at the bottom of the drying bin. And the heat transfer coils, which are installed in the cold trap shell, are divided into two sets. When one set of coils operates to capture water vapor, the other set is in a state of defrosting by the heating unit until it completes defrosting, and then the two sets of coils operate interchangeably.

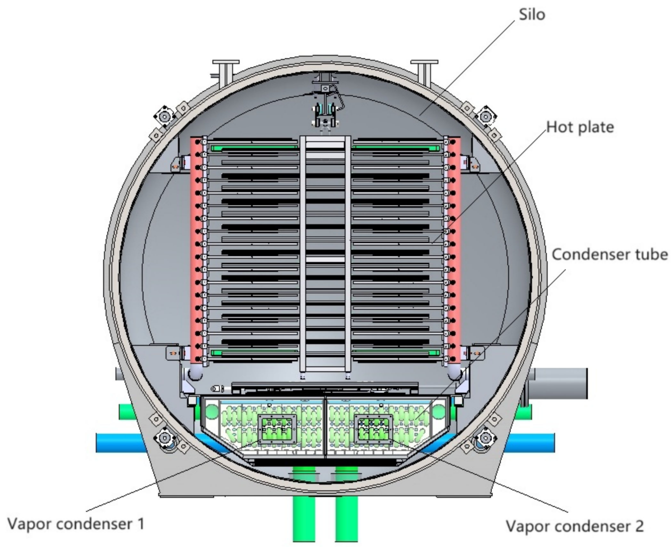

Figure 3. Alternating cold traps of the freeze-drying bin.

From the basic calculation, the footprint might be doubled by adding a new or external cold trap. Although the built-in structure with alternating cold traps might be more complex than simply adding a new trap, the footprint by built-in alternating cold traps might only increase by 20–25%., and it has a lower investment cost. Certainly, it may have a higher failure rate during production and require more maintenance.

First, comparative testing is conducted between the intermittent freeze-drying equipment using alternating cold traps with tube coils and the stationary type with tube coils for the production of shiitake. The relationships between the amount of captured water and the energy consumption of the cold trap are shown in Figure 4. A total of 360 kg of water vapor is captured in the first hour of the operation, with the captured water vapor exceeding 300 kg/h only at the first 3 h. The amount of captured water by the cold traps gradually decreases. The energy consumption of the refrigeration unit is basically synchronized with the gradual decline, but the rates of decline are not obvious, despite the decline in the amount of trapped water vapor.

The aforementioned method in Section 2 is used to record the frost thickness and dehydration data for analysis during the operation with the alternating cold traps or the stationary type. During the operation of the vacuum freeze-drying bin with alternating cold traps, the cold traps melt frost alternately once every 25 min in the early stage. Observing the operation over the first 3 h, the maximum thickness of the cold trap frost is 2.8 mm. Subsequently, the maximum thickness reduces to 2 mm and gradually thins.

Simultaneously, the change in the weight of the tray in the vacuum freeze-drying bin and the thickness of frost in the measuring block are analyzed. The water removal and captured water increase at a constant rate during the first 3 h of operation. When the maximum thickness of the frost in the cold trap is 2.8 mm, 180 kg of water is removed, and the frost density is calculated at about 918 kg/m^3.

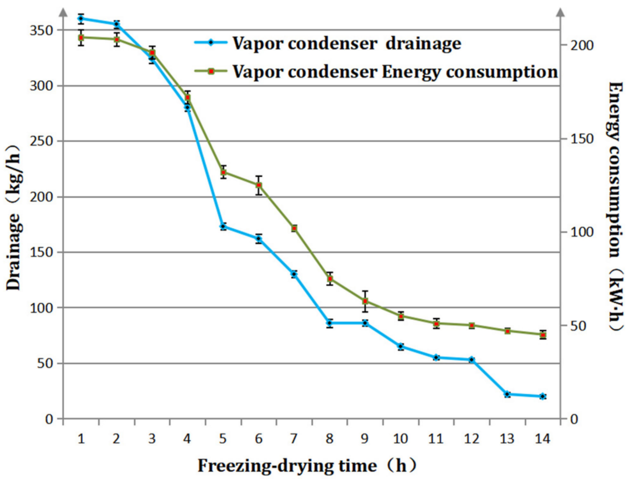

Figure 4. The relationships between the amount of captured water and the energy consumption in the cold traps during the freeze-drying process over time.

The energy consumption per hour for those with the stationary type and alternating one is shown in Figure 5. During the first hour of the freeze-drying process, the energy consumption of the alternating cold traps is 198 kW·h, when the stationary type is 171 kW·h. In the second hour, the energy consumption is close to about 195 kW·h. In the third hour, while the stationary type is 189 kW·h, the alternating cold traps consume slightly less at 186 kW·h. Similarly, in the fourth hour, the alternating cold traps are 165 kW·h, compared with 174 kW·h in the stationary type. From the data in the fourth hour, the energy consumption of the alternating cold traps is about 5% less than 174 kW·h of the stationary type. In the fifth hour, the energy consumption of the alternating cold traps becomes 135 kW·h, which is about 20% less than 162 kW·h of the stationary type, and in the last hour, the energy consumption of the alternating cold traps is over 50% less than that of the stationary type. From the viewpoint of the full production process, the alternating cold traps consume 1471 kW·h, compared to 1937 kW·h for the stationary type, showing a reduction of about 24%. The energy consumption of the alternating cold traps is tested by replacing the tube coils with finned-tube ones in the freeze-drying bin. The results show that the energy consumption of the cold traps can be further reduced from 1471 kW·h to 1346 kW·h, which is a reduction of about 8%.

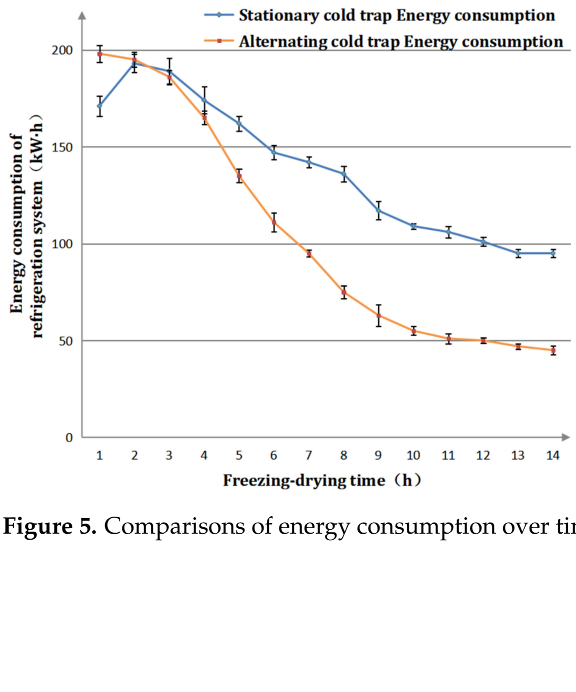

Figure 5. Comparisons of energy consumption over time for stationary type and alternating type.

3.2. Systematic Energy Testing of the Continuous Production Process

The structure of the large-scale freeze-drying equipment with alternating cold traps for a continuous production process is shown in Figure 6. In comparison to the large-scale freeze-drying equipment with stationary type for an intermittent production process, the main differences include the following:

(a) The vertical freezer is used instead of the quick-freezing tunnel, and the vertical freezer could be synchronized with the freeze-drying silo for continuous operation;
(b) The materials (foods) under atmospheric pressure could be continuously moved in and out of the drying silo under the vacuum environments by the pressure difference transition silo;
(c) When the foods enter into the drying silo, the materials are put into continuous propulsion through the automatic tray divider device;
(d) When the foods enter into the drying bin, the materials are put into the continuous pushing hot plate by the automatic tray separating device. The material tray is then slowly pushed forward by the non-powered continuous pushing hot plate.

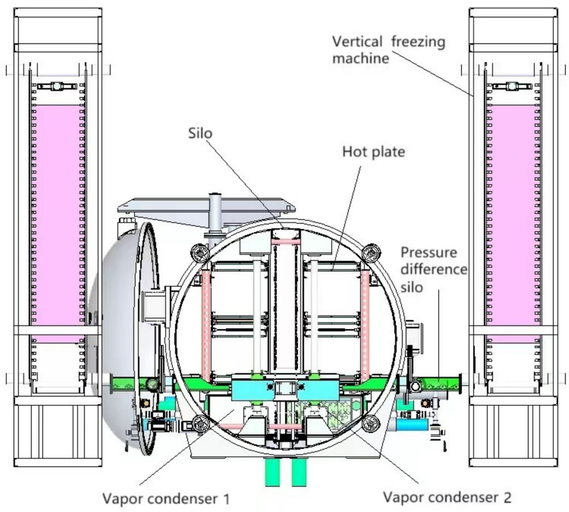

Figure 6. Schematic diagram of large-scale freeze-drying equipment for the continuous production process.

The systematic energy consumption per unit of dehydration (kg) of freeze-drying shiitake via the continuous production process and the intermittent one is shown in Figure 7. From the production process, the systematic energy consumption of the continuous freeze-drying equipment is 11.06 kW·h, and the systematic energy consumption at any time is relatively stable, basically remaining in the vicinity of 0.79 kW·h. The systematic energy consumption of the intermittent freeze-drying equipment is 18.3 kW·h, and the systematic energy consumption per unit of dewatering (kg) is 1.31 kW·h.

Due to high efficiency in utilizing the equipment, lower energy consumption is observed during the initial stage of freeze-drying in intermittent freeze-drying. However, the dehydration rate gradually decreases as the freeze-drying process progresses. The minimum operating condition of the refrigeration compressor cannot fully match the dehydration rate, resulting in a significant increase in the energy consumption per unit of dehydration (kg) towards the end of the drying process [25].

As seen in Figure 7, the systematic energy consumption of the intermittent production process fluctuates considerably; the systematic energy consumption is 1.1 kW·h in the 1st hour and gradually increases to 1.65 kW·h in the 14th hour. Experimental data on continuous freeze-drying equipment show that optimizing the match between the refrigeration unit and the heat pump heating unit could result in smoother system energy consumption and better feasibility. The industrial testing data also show that the systematic energy consumption of freeze-drying could be significantly reduced through the comprehensive utilization of energy between the refrigeration unit and the heat pump heating unit.

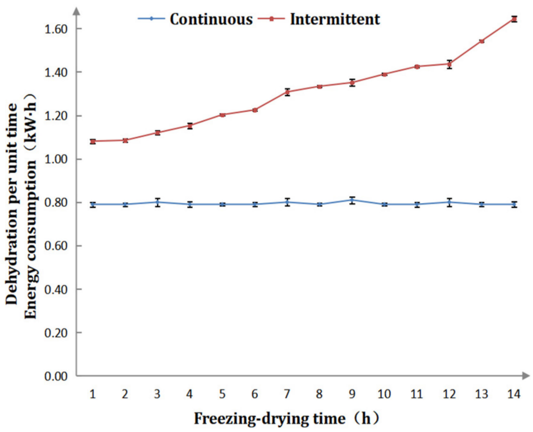

Figure 7. Comparisons of systematic energy consumption between the continuous production process and the intermittent one for freeze-drying shiitake.

In consideration of the improvement of energy efficiency, systematic energy consumption could be saved more than 15% through the use of continuous freeze-drying with built-in alternating cold traps. For instance, assuming an average power consumption of 150 kW·h with an industrial electricity price of 1 RMB/(kW·h), the annual energy savings might amount to approximately RMB 110,000 (or USD 15,000) under a 5000 h operation of the freeze-dryer per year. These experimental investigations under industrial levels offer valuable insights into the implementation of continuous freeze-drying technology in the food industry.

4. Conclusions

To overcome the challenges of high systematic energy consumption and low productivity per unit of food dehydration (kg) in conventional large-scale freeze-drying equipment with a stationary cold trap and an intermittent production process, in this context, with the innovation of a continuous production process and cold trap structure, exploratory experiments on industrial freeze-drying equipment are conducted. The energy consumption characteristics of the novel continuous process and cold trap structure are analyzed, and the following main conclusions are obtained:

(1) Continuous freeze-drying equipment with built-in alternating cold traps could effectively alleviate the heat transfer deterioration caused by frost in the cold traps, reducing the defrosting time and energy consumption. And the energy consumption of the novel cold traps, supported by the refrigeration and heat pump heating units, could be reduced by more than 20%.
(2) The structure of the coils in the cold traps has an important impact on the energy consumption of the alternating cold traps. Compared to the tube coils, finned-tube coils reduce energy consumption by approximately 8%.
(3) The systematic energy consumption and productivity of large-scale freeze-drying equipment are greatly influenced by the advanced production process. The use of a continuous production process and built-in alternating cold traps enhances matching energy consumption characteristics across different units, resulting in a 40% reduction in systematic energy consumption and significant productivity improvement.

The investigations in this context have mainly focused on the energy-saving characteristics of food vacuum freeze-drying. Detailed studies on the differences between food freeze-drying processes and equipment are expected in the future, given that industries such as biotechnology, pharmaceuticals, and chemical engineering have different labeling and specification requirements for freeze-drying processes and equipment.

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