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Analysis Energy of Freeze Vacuum Drying System with Thermal Energy Storage and Reverse Valve of 4kg Capacity

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ABSTRACT

This research evaluates the energy efficiency of the Aloe vera drying process using a Freeze Vacuum Drying (FVD) system, focusing on the thermal performance and the role of a Thermal Energy Storage (TES) unit with paraffin wax as the storage medium. Experiments were conducted with Aloe vera samples of 2 kg, 3 kg, and 4 kg to assess their effects on energy usage, Coefficient of Performance (COP), and moisture removal efficiency. The highest Specific Moisture Extraction Rate (SMER) was 0.132 kg.water/kWh for the 4 kg sample, with a Specific Energy Consumption (SEC) of 7.223 kWh/kg.water and a COP of 5.4. The energy efficiency peaked at 10.80%, achieved by incorporating TES. The results demonstrate that TES improves COP and reduces the specific energy demand, leading to a more energy-efficient drying process.

KEYWORDS: *Freeze vacuum drying, Energy efficiency, Thermal energy storage, SMER, Aloe vera.*

1. INTRODUCTION

Maintaining low temperatures, minimizing product damage from high temperatures, and creating goods with acceptable physical quality are all benefits of vacuum freeze dryers. This approach offers improved moisture content drying and can return the product to its initial state once it has dried [1]. Nevertheless, maintaining product quality while reducing energy consumption remains a challenge. One potential solution is to utilize the waste heat from the condenser to accelerate the sublimation process and minimize energy usage [2].

Although effective, freeze vacuum drying suffers from the drawback of substantial energy consumption due to the long drying duration, especially during the sublimation phase below the triple point condition. To reduce the drying time, the temperature can be increased or the pressure within the chamber can be lowered [3].The refrigeration machine, which incorporates a compressor, condenser, expansion valve, and evaporator as its primary components, is an essential component in the vacuum freeze-drying process. It plays a significant role in the operation of this method [4].

The freeze vacuum dryer will convert the product's water content into ice, after which the ice crystals will undergo sublimation at pressures and temperatures below the triple point in the water phase diagram. The separation process in the vacuum freeze dryer comprises three stages as shown on Figure 1: (a) the freezing stage, (b) the main drying stage, and (c) the secondary drying stage. During the freezing phase, the product will be cooled to a temperature at which it attains a completely frozen state. The freezing rate influences the dimensions of the ice crystals produced, mass transfer resistance, and the sublimation rate during the subsequent drying phase. A gradual cooling pace will produce larger ice crystals, hence expediting the sublimation process [5].

Currently, the development of vacuum freeze drying technology still faces two primary challenges is, maintaining product quality and mitigating energy consumption during the process. One viable strategy to reduce energy requirements is by accelerating the sublimation rate through the utilization of waste heat from the condenser [7]. Energy efficiency in the freeze vacuum drying system is a critical element in process optimization, particularly in the reutilization of generated heat.

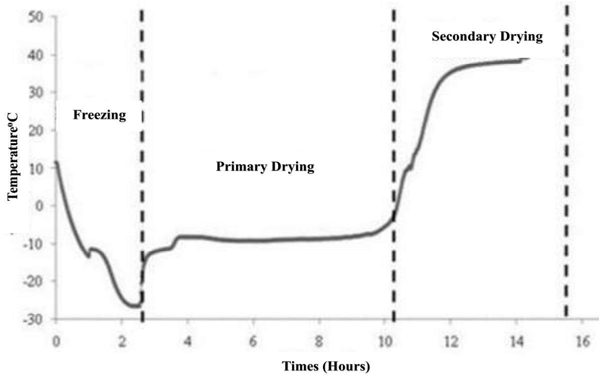

Figure 1: Freeze vacuum drying process [6]

This study conducts an energy assessment of the Aloe vera drying process through a Freeze Vacuum Drying (FVD) system. It examines the thermal efficiency and performance of the main FVD components, while also emphasizing the role of a Thermal Energy Storage (TES) system that employs paraffin wax as the storage material.

2. THEORICAL BACKGROUND

The energy balance is calculated based on the principle of energy conservation, which states that the change in the total energy of the system during the process is equivalent to the difference between the total energy input and the total energy output, as outlined in Equation 1 [8].

$$E_{\text{output}} - E_{\text{input}} = \Delta E_{\text{system}} \quad (1)$$

$$\dot{Q} - \dot{W} = \sum_{out} \dot{m}\, h - \sum_{in} \dot{m}\, h \quad (2)$$

In the freeze vacuum drying process, the energy supply comes from electricity, which is used to operate the vacuum pump, reverse valve, fan, and compressor.

$$W_{\text{total}} = W_{\text{compressor}} + W_{\text{fan}} + W_{\text{reversevalve}} + W_{\text{vacuum pump}} \quad (3)$$

The freeze vacuum drying system comprises many primary components that systematically facilitate cooling and heating and consist of compressor, expansion valve, condenser, evaporator.

The Coefficient of Performance (COP) serves as a parameter to evaluate system efficiency, particularly in refrigeration cycles. In cooling or refrigeration systems, COP is defined as the ratio of the cooling effect produced in the evaporator to the energy consumed by the compressor, the coefficient of performance (COP) is defined as:

$$COP = \frac{\dot{Q}l}{\dot{W}_{in}} \quad (4)$$

The dryer's performance is often evaluated using the Specific Moisture Extraction Rate (SMER), which can be calculated based on the following equation.

$$\text{SMER} = \frac{\text{Moisture remove from product}}{\text{Energy consumption}} \quad (5)$$

In freeze vacuum drying, Specific Energy Consumption (SEC) refers to the amount of electrical energy required to remove a unit mass of water from the material being dried. This parameter is generally expressed in kWh per kilogram of evaporated water;

$$\text{SEC} = \frac{\text{Energy consumption}}{\text{Moisture remove from product}} \quad (6)$$

Energy efficiency in a freeze vacuum drier denotes the ratio of the effective energy employed for sublimation and moisture extraction from the product to the total energy input expended by the system throughout the drying process. This metric quantifies the efficiency with which the system converts thermal or electrical energy into productive drying work.

$$\eta_{energy} = \frac{\dot{m_{air}}\ x\ \dot{h_{Sub}}}{\dot{E_{in}}} \times 100\% \quad (7)$$

3. METHODS

The freeze vacuum drying of Aloe vera focuses on energy analysis involving intensive cooling and heating processes. In this approach, a novel system is developed by integrating thermal energy storage, which functions to retain heat and redistribute it within the system. This integration ensures uniform product heating while simultaneously lowering energy consumption [10][11].

3.1.Experimental set-up

The fundamental principle of vacuum freeze-drying involves the removal of liquid from a solid material via evaporation. In this technique, the heat source does not directly interact with the material, a process commonly referred to as indirect-heat drying. The operation of a vacuum freeze dryer take place at pressures lower than atmospheric pressure but above the triple point of water.

In the freeze-drying process, Aloe vera was first solidified in the drying chamber at approximately –5 °C to preserve its physical structure. Drying occurs in two phases: primary drying, where sublimation was induced under vacuum heating and secondary drying, which removes bound water molecules [12]. Experimental variations were conducted using sample masses of 2 kg, 3 kg, and 4 kg with an initial moisture content of about 95%.

3.2. Experimental Procedure

The freeze vacuum dryer functions through two fundamental thermodynamic cycles in food preservation. The refrigeration cycle is responsible for lowering the product temperature below its freezing point, thereby facilitating the sublimation of ice under vacuum conditions. Meanwhile, the heating cycle provides controlled thermal energy required to sustain sublimation and ensure complete moisture removal from the material [13].

After the system reaches the targeted cooling temperature, the operational mode was transitions into the heating cycle. This stage plays a crucial role in supplying the necessary thermal energy to initiate and sustain the sublimation process, thereby ensuring effective moisture removal from the product. The progression of this phase, along with its interaction with the preceding cooling process, is illustrated in Figure 4, which provides a clearer representation of the overall freeze vacuum drying mechanism.

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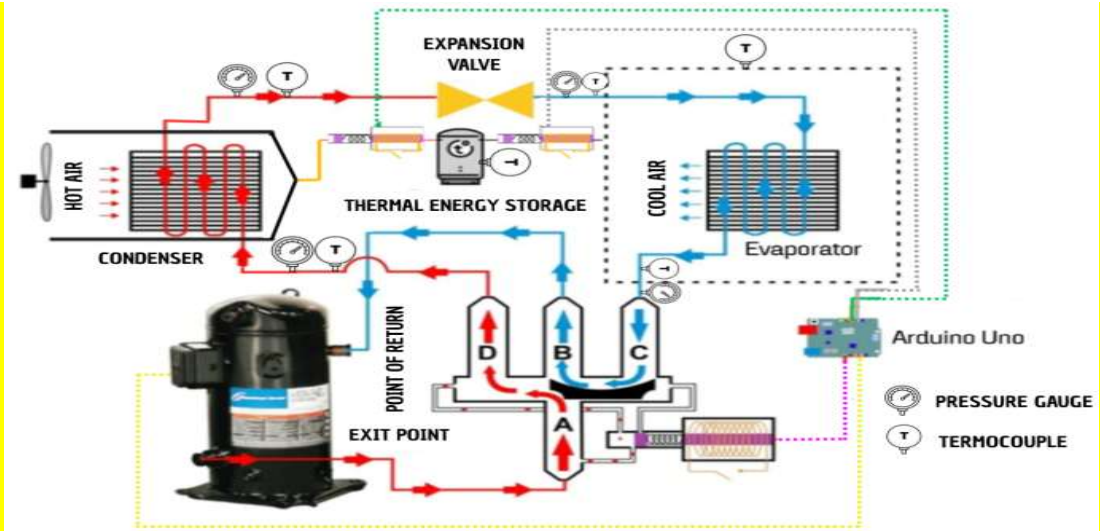

Figure 2: Schematic cooling system and charging thermal energy storage; -selenoid valve 1-arduino; -selenoid valve 2-arduino; -reverse valve 2-arduino [13]

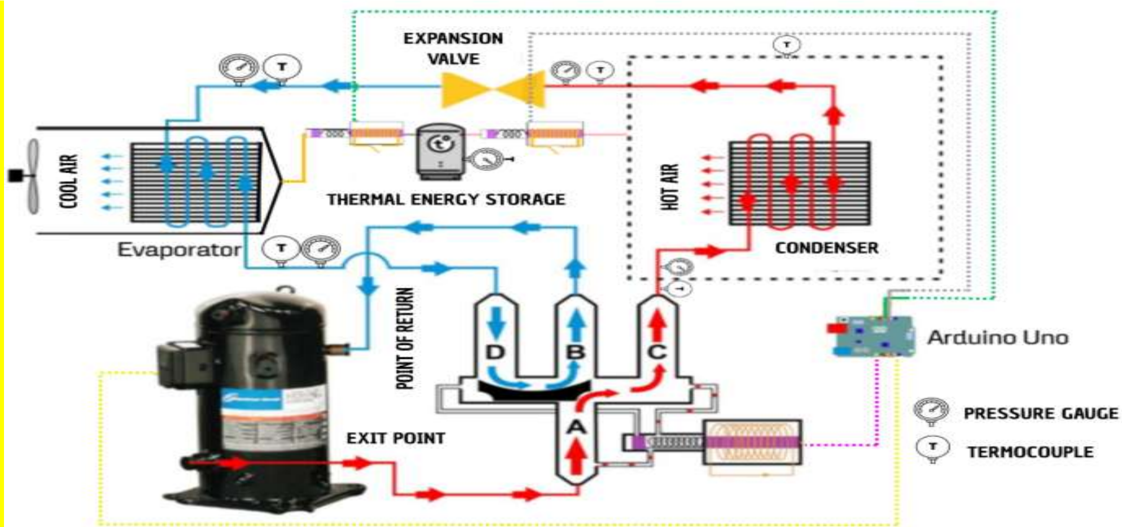

Figure 3: Schematic heating system and discharging thermal energy storage; -selenoid valve 1-arduino; -selenoid valve 2-arduino; -reverse valve 2-arduino [13]

4. RESULTS AND DISCUSSION

This study monitored the temperature profile of Aloe vera products during a drying period of 12 to 14 hours. Temperature measurements were taken at regular intervals to capture fluctuations occurring throughout the process. The collected data were subsequently analyzed to evaluate temperature reduction patterns, drying duration, and the influencing factors, such as the application of thermal energy storage and variations in product mass [14][15]. To support analysis and interpretation, the measurement results are presented in both tabular and graphical form.

4.1 Energy Analysis

A freeze vacuum drying system was designed to evaluate energy consumption by measuring the power usage of the compressor, condenser fan, and vacuum pump throughout the drying process and the corresponding results are presented in Figure 4. Graphical analysis reveals that the freezing stage demands the greatest energy input, while the heating stage requires the least. In general, higher drying temperatures reduce the energy consumption of the vacuum pump, compressor, and condenser fan. Furthermore, as chamber pressure and temperature increase, the power demand of the vacuum pump decreases.

Energy analysis is performed to assess the entire system performance during each cycle, specifically the freezing cycle and the heating cycle. The analysis is predicated on the real energy balance of the equipment, and the findings are as follows.The energy balance equation is founded on the first law of thermodynamics, which pertains to the conservation of energy. In the freeze vacuum drying system, the energy input must equal the energy output [16][17].

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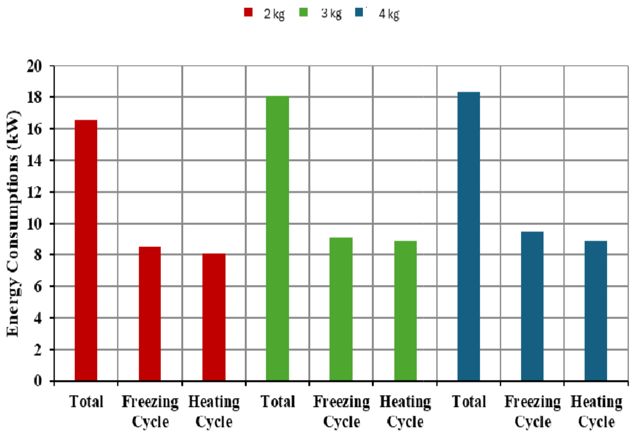

Figure 4: Vacuum freeze dryer energy consumption at different masses

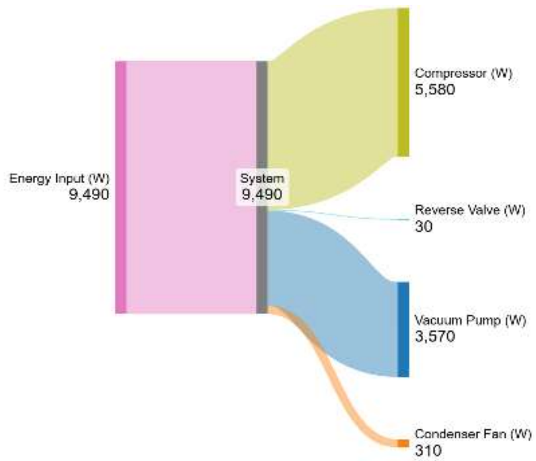

Figure 5: Sankey diagram of freeze vacuum Drying

4.2 The Effect of Mass on Energy Consumption

The energy consumption observed during the freeze vacuum drying experiments demonstrated a clear correlation with variations in the mass of Aloe vera flesh. Increasing drying loads of 2 kg, 3 kg, and 4 kg resulted in higher energy usage during both the cooling and heating cycles. The total energy consumption recorded was 16.562 kW for the 2 kg load, 18.052 kW for the 3 kg load, and 18.369 kW for the 4 kg load.

Throughout the drying process, the compressor and vacuum pump were identified as the primary contributors to energy consumption. As shown in Table 1, energy use during the heating cycle was lower compared to the freezing cycle. Moreover, an increase in drying temperature led to a reduction in energy demand, while a decrease in drying temperature caused a significant rise in consumption. These trends were particularly evident in the compressor and vacuum pump, which account for the majority of energy usage in freeze vacuum drying[18] [19].

The energy consumption results as shown in Table 1. It was based on the producing energy in each cycle. It provides a picture that aligns with the studies conducted by Kovaci, 2020 and Hasbullah, 2020 [9, 20]. Whereas in the cooling cycle, there will be a significant increase in energy consumption compared to the drying cycle. And in Figure 5, an illustration of the energy balance provided to the system and utilized as work in the drying process at a mass variation of 4 kg.

Table 1: Energy consumptions of vacuum freeze dryer at different masses and cycle

Variant	Cycle	Equipment				Total (kW)	Total Power (kW)
		Reverse Valve (kW)	Compressor (kW)	Vacuum Pump (kW)	Fan Condenser (kW)		
2 kg	Freezing	0.03	5.39	2.79	0.31	8.51	—
	Heating	0.03	5.11	2.60	0.31	9.05	16.56
3 kg	Freezing	0.03	5.72	3.10	0.31	9.16	—
	Heating	0.03	5.55	3.00	0.31	8.89	18.05
4 kg	Freezing	0.03	5.58	3.57	0.31	9.49	—

4.3 The Effect of Product Mass on the Actual COP and the Carnot COP

The Coefficient of Performance (COP) in the freeze vacuum drying experiments was calculated using the previously stated equation. As illustrated in Figure 6, the COP of the refrigeration cycle in freeze vacuum drying with thermal energy storage increases with higher loading, a trend also observed for the Carnot COP. The COP serves as an indicator of thermal system efficiency, defined as the ratio between useful energy applied for drying and the total energy consumed [21].

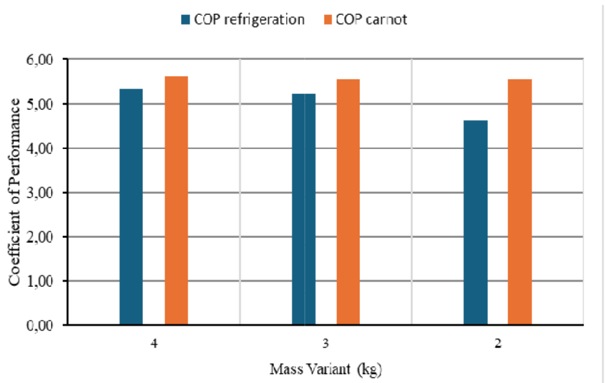

Figure 6: Coefficient of performance refrigeration and carnot of vacuum freeze dryer at different masses

The refrigeration COP of the system demonstrates an increasing trend with the addition of Aloe vera mass. Specifically, the value rose from 4.63 at 2 kg to 5.22 at 3 kg. However, the refrigeration COP remains lower than the Carnot COP.

4.4 The Effect of Mass Product on the Energy Efficiency

As presented in Figure 7, the energy efficiency of freeze vacuum drying is evaluated by calculating the ratio of the mass of water evaporated to the energy consumed during the cooling and heating cycles. Energy consumption is directly influenced by the drying load, thereby exerting a proportional effect on the overall energy efficiency of the process.

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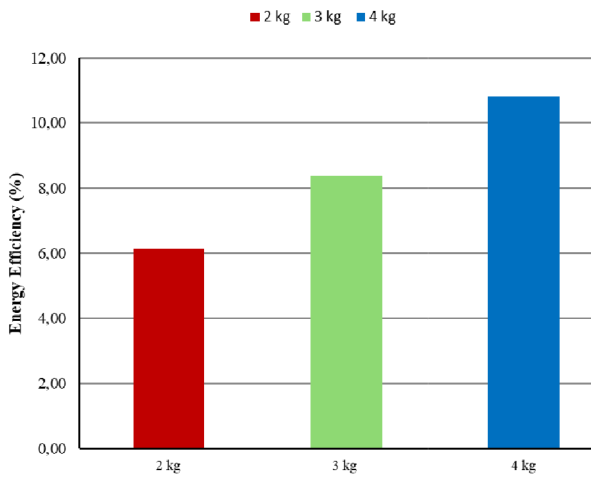

Figure 7: Energy efficiency of vacuum freeze dryer at different masses

Efficiency improved with increasing sample mass, reaching 6.06% for 2 kg and 8.68% for 3 kg, while the highest efficiency of 10.8% was achieved at 4 kg. Energy efficiency varies throughout the drying process due to fluctuations in drying conditions. The Specific Moisture Extraction Rate (SMER) is used to measure the volume of water removed per unit of energy consumed, thereby serving as an indicator of dryer performance. A higher SMER value reflects lower operating costs and a faster return on investment. As shown in Table 2, the highest SMER value of 0.132 was obtained at a 4 kg sample mass, with corresponding SEC and MER values of 7.223 and 0.182, respectively. These findings are consistent with the energy efficiency results illustrated in Figure 7, which indicate that the 4 kg sample mass with TES achieved the maximum efficiency of 10.8% [22].

Table 2: Performance of vacuum freeze dryer at different masses

Mass (kg)	Drying Rate (%)	Drying Time (hours)	SMER (kg water/kWh)	SEC (kWh/kg water)
2	68.42	12.75	0.078	12.740
3	68.00	13.58	0.107	9.315
4	66.92	14.00	0.132	7.223

5. CONCLUSIONS

The experimental results confirmed that the target temperatures were achieved, namely –5 °C during the freezing cycle and 40 °C during the heating cycle, with the drying process lasting 14 hours for the 4 kg Aloe vera sample. A higher Specific Moisture Extraction Rate (SMER) reflects lower operational costs in the drying process. For the 4 kg mass, the maximum SMER obtained was 0.132 kg.water/kWh, with a Specific Energy Consumption (SEC) of 7.223 kWh/kg.water. Energy consumption was observed to increase proportionally with drying load, and energy efficiency followed a similar trend. At 4 kg, the system achieved an efficiency of 10.8% with TES, compared to 8.37% at 3 kg. These results demonstrate the effectiveness of TES integration, with the 4 kg sample achieving the highest energy efficiency.

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