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Enhancing evaporation in vacuum freeze drying: Optimizing airflow in horizontally-connected chambers

Indra Buana [a], Engkos Achmad Kosasih [a,*], Muhsin Kilic [b], Ahmad Zikri [b,c], Ari Satmoko [a,d], M. Burhanuddin Fauzi [a]

[a] Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus Baru UI, Depok, 16424, West Java, Indonesia
[b] Department of Mechanical Engineering, Faculty of Engineering, Bursa Uludag University, Bursa, 16059, Turkiye
[c] Department of Mechanical Engineering, Faculty of Engineering, Universitas Sumatera Utara, Medan, 20155, Indonesia
[d] Research Center for Nuclear Beam Analysis-National Research and Innovation Agency (BRIN), Serpong, Banten, Indonesia

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ABSTRACT

Efforts to enhance the evaporation rate in a vacuum freeze-drying system were carried out by adding a fan between the drying chamber and the cold trap, which are horizontally connected. The fan was installed to accelerate the vapor movement from the drying chamber to the cold trap. In this study, distilled water was used as a test material, placed in a container inside a horizontally configured drying chamber. A low-power axial fan was installed in the connecting pipe to induce forced vapor flow, and the system employed electric heaters mounted on the chamber walls to provide convective heating. The experimental setup tested four different drying chamber temperatures (20 °C, 25 °C, 30 °C, and 35 °C), with each condition repeated under fan-on and fan-off states. The experimental results showed that the use of a fan in the drying chamber significantly enhanced the sublimation rate compared to the tests without the fan. The highest evaporation rate increased by up to 42.9 % was achieved at 35 °C with the fan, reaching 27.47×10^{-7} kg/s. On average, the evaporation rate with the fan increased by 27.3 %. The average specific energy consumption of vacuum freeze drying decreased when using a fan proportionally with the 20.8 %. This research confirmed that the fan significantly improved the evaporation rate. The obtained evaporation rate data using the convective heating method with electric heaters can serve as a preliminary reference for those seeking a simpler alternative in operational complexity and initial investment compared to microwave or infrared vacuum freeze-drying systems.

Nomenclature

A container area (m^2)
E energy (kWh)
hr time (hour)
h heat transfer coefficient ($W/m^2.K$)
k coefficient of conduction rate (W/m.K)
m mass (kg)
P_o triple point pressure of water (611.657 Pa)
μ dynamic viscosity (Pa·s),
c_p specific heat capacity at constant pressure (J/kg·K)
k thermal conductivity of the fluid (W/m·K).

Subscripts
a aquadest
c convection

(*continued on next page*)

* Corresponding author.
E-mail address: kosri@eng.ui.ac.id (E.A. Kosasih).

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Nomenclature	
P pressure (Pa)	d diffusion
Q heat rate (W)	dc drying chamber
t time (second)	i initial
T temperature (^{o}C)	f final
T_o triple point temperature of water (0.01 °C)	r radiation
y height from the top of the container to the top surface of the aquadest (m)	s specific
	σ Stefan-Boltzmann constant 5,67 $\times$ 10^{-8} (W/m^2.K^4)
ρ fluid density (kg/m^3)	ϵ emissivity
u free stream flow velocity (m/s)	∞ environment
L characteristic length (m),	

1. Introduction

Vacuum Freeze Drying (VFD) has demonstrated significant applications in the preservation of food and pharmaceutical products [1]. In the food sector, VFD is used to dry a variety of fruits, vegetables, and meats while maintaining the nutritional integrity, color, and original texture of the products [2,3]. In the medical field, VFD is employed in the processing and storage of biological products such as blood plasma, vaccines, and biological tissues for transplantation [4]. The dried products obtained through the VFD method exhibit high quality due to the sublimation-based evaporation process, which preserves the cellular structure of the dried material [5]. One of the primary objectives of the drying process is to reduce moisture content and extend shelf life [6]. Vacuum freeze drying is a reliable method for carrying out the drying process while preserving product quality.

One of the main challenges in using vacuum freeze drying technology is its relatively high energy consumption compared to other drying methods [7]. The high energy demand of the VFD primarily results from the prolonged drying times, which are due to the inherently low evaporation rate. Various strategies have been explored to increase the evaporation rate, including the pre-treatment of the material before drying. Such pre-treatment methods include ultrasonic exposure, which enhances the porosity and facilitates vapor release during the sublimation phase, thereby shortening the overall drying time [8]. Another approach to reducing the VFD energy consumption involves optimizing the mode of heat transfer to the material within the drying chamber, with the aim of improving the operational efficiency and lowering the energy usage.

The evaporation rate of the materials is influenced by several variables, including temperature and pressure [9,10]. Previous studies have shown that the shelf temperature and chamber pressure significantly affect both the drying time and the energy consumption [11,12]. The temperature difference between the drying chamber and the cold trap creates a thermal gradient, as the cold trap is maintained at a significantly lower temperature than the drying chamber. The temperature difference between the drying chamber and the cold trap creates a thermal gradient because the cold trap is maintained at a significantly lower temperature than the drying chamber. This temperature differential results in a pressure gradient between the drying chamber and the cold trap, which in turn induces a passive, natural vapor flow from the drying chamber to the cold trap. However, this slow-moving vapor flow can contribute to extended drying times [13]. This occurs because the humidity within the drying chamber increases due to the continuous release of water vapor from the material being dried. As a result, the difference between the material's moisture content and the relative humidity of the air inside the drying chamber becomes smaller. Simulations conducted under these conditions have shown that the evaporation rate decreases accordingly. [14]. The reduction in the evaporation rate during the vacuum freeze-drying process is undesirable, as it increases the overall drying time. The application of fans to enhance vapor flow in vacuum freeze drying systems remains underexplored in current literature. Nevertheless, existing studies suggest that improved vapor transport toward the cold trap can significantly influence the overall evaporation rate. For instance, research conducted by Masahiro Kitamura demonstrated that the integration of a heater and blower directed into the drying chamber effectively enhanced vapor movement, resulting in a drying time reduction of up to 50 %. This finding highlights the potential impact of forced convection mechanisms on drying efficiency and warrants further investigation into fan-assisted systems [15].

Material heating in a vacuum freeze dryer can be performed via conduction or non-conduction modes. In conduction heating, the container holding the material—such as a crucible or bottle made of stainless steel, polymer glass, or other materials—is heated using an electric heating element or steam [16]. The primary advantage of conduction heating is that the heat from the electric heating element is rapidly transferred to the material container, enabling the target material temperature to be achieved quickly. Since the material placed in the container is in direct contact with the heat source, this method ensures efficient thermal transfer. Additionally, conduction heating systems are relatively simple to operate, making them a cost-effective choice for small-to medium-scale industrial applications.

However, localized overheating can occur at the contact area between the material and the container, leading to inconsistent drying [17]. There is also a risk of thermal degradation in heat-sensitive products due to direct exposure to the heat source [18]. To mitigate these drawbacks, non-conduction heating methods can be employed. Two known non-conduction heating techniques in VFD are microwave freeze drying and infrared freeze drying [19]. Studies have demonstrated that microwave freeze drying can significantly accelerate the drying process while reducing energy consumption compared to conventional vacuum freeze drying [20]. Similarly, the application of infrared heating has shown potential in reducing the processing time during VFD operations [21]. However, both microwave and infrared freeze-drying systems require more complex operational controls, thereby increasing the

system complexity. In addition, these systems demand higher initial investments compared to conventional conduction-based VFD systems.

In this study, we implemented a non-conduction heating approach using an electric heating system. This method offers simpler control mechanisms and lower capital costs than microwave or infrared freeze-drying systems. The primary objective of this research was to enhance the evaporation rates by incorporating a fan in the connecting duct between the drying chamber and the cold trap. This modification aims to improve the energy efficiency and reduce operational costs, thereby enhancing the feasibility of vacuum freeze-drying systems and supporting sustainable energy use practices.

The data obtained from this simplified non-conduction heating system serve as a preliminary reference for evaporation rates in non-conduction heating applications, providing a more accessible alternative to the more complex microwave and infrared freeze-drying systems. Although various studies have explored the use of advanced heating methods such as microwave and infrared in VFD systems, few have examined airflow modification as a means of improving sublimation performance using simpler heating modes. This study introduces a novel approach by integrating a low-power axial fan in the connecting pipe between a horizontally aligned drying chamber and cold trap, enabling enhanced vapor flow and forced convection. To the best of our knowledge, this specific system configuration and its effect on evaporation and energy consumption have not been previously reported.

2. Materials and methods

The vacuum freeze-drying setup in this study consists of a drying chamber positioned horizontally in line with the cold trap. A fan is installed at the beginning of the connecting pipe between the drying chamber and the cold trap (Fig. 1a). When activated, the fan facilitates the flow of vapor from the drying chamber toward the cold trap. The cooling coil captures the vapor entering the cold trap, which causes most of the vapor to condense and form ice crystals.

The drying chamber is cylindrical, with a diameter of 0.3 m and a height of 0.3 m. The cold trap is also cylindrical, with a diameter of 0.3 m and a height of 0.35 m. The drying chamber is connected to the cold trap in a horizontal configuration via a pipe with a diameter of 0.019 m. The fan is placed inside the drying chamber and positioned directly in front of the pipe connecting the drying chamber to the cold trap (Fig. 1b).

2.1. Material

The material used for testing in this study was distilled water (aquadest). The aquadest was placed in a container with a volume of 2.8×10^{-4} m^3. The cross-sectional area (A) of the container was 7×10^{-3} m^2. Aquadest was selected to characterize the vacuum freeze drying system. By using aquadest as the test material, the evaporation observed can be attributed solely to the operational parameters and the performance of the vacuum freeze-drying system, thereby minimizing the influence of material-specific factors such as water-cell binding commonly found in plant-based or biological materials.

A sealed copper pipe with a diameter of 6.5×10^{-3} m was inserted into the container. This pipe served as a housing for a type-K thermocouple cable, which was inserted during data acquisition to measure the temperature of the aquadest throughout the drying process. The data obtained from the thermocouple, measured at the inner wall of the copper pipe, were used to represent the temperature of the aquadest (see Fig. 2).

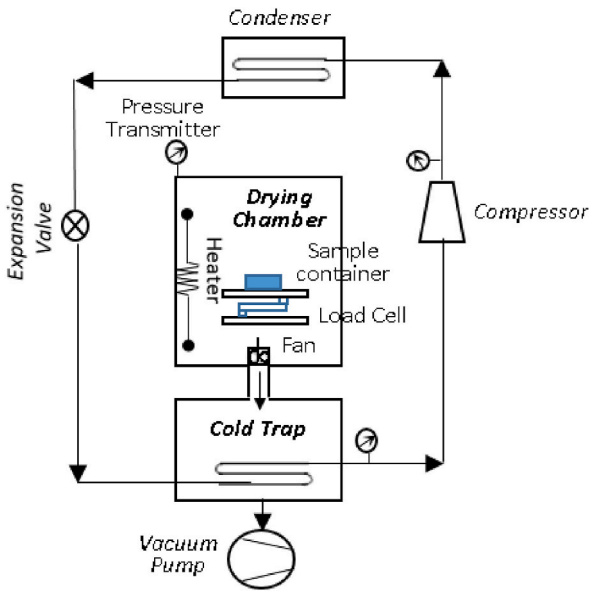


Fig. 1a. Schematic diagram of the vacuum freeze drying system.

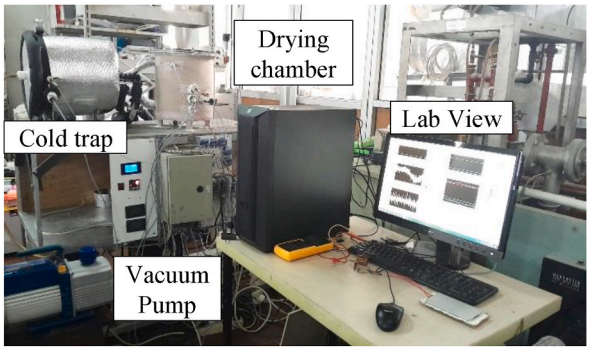


Fig. 1b. Vacuum freeze drying system for experiment.

2.2. Method

All tests were carried out under room temperature conditions, with the average temperature (T_∞) maintained around 27 °C. The aquadest was placed in an open plastic container, with each side of the container coated with heat-resistant paint and aluminum foil. The aquadest was placed in a container with a volume of 2.8×10^{-4} m^3. The cross-sectional area (A) of the container was 7×10^{-3} m^2. Liquid aquadest with a mass of 0.15 kg was first frozen in a freezer. Once the aquadest reached a temperature of $T_a = -8$ °C, it was transferred to the drying chamber. The pressure in the drying chamber was then reduced to below the triple point pressure of water (P_o). When the pressure reached the target value and the aquadest temperature remained at −8 °C, the electric heater was activated (Fig. 3). The experimental setup in this study can be seen more clearly in (Fig. 4).

The drying chamber temperature was set according to the experimental parameters (see Table 1). The ambient temperature of the drying chamber (T_{dc}) was measured using a type-K thermocouple (± 1.5 °C) positioned above the container holding the aquadest. The temperature data from the drying chamber, which served as the test variable, were recorded using a National Instruments DAQ system (NI9213). The drying chamber temperature was controlled using an Autonics TC4S temperature controller. The evaporation rate was measured sequentially at chamber temperatures ranging from 20 °C to 35 °C. For each temperature setting, the evaporation rate was measured over a duration of 1200 s.

The pressure inside the drying chamber was measured using a pressure transmitter (± 0.25 % F.S) connected to a National Instruments data acquisition system (NI9207). Before activating the heater, the chamber pressure was targeted at 100 Pa. As the heater was activated and the drying chamber temperature increased, the chamber pressure also increased. During data acquisition, it was essential to maintain the pressure below the triple point of water. The pressure inside the drying chamber must be maintained below the triple point pressure of water to ensure that evaporation occurs through sublimation. To calculate the evaporation rate, the mass of the aquadest was measured in real time using a load cell (± 0.001 gr) connected to a National Instruments DAQ system (NI9201). Data collection was repeated three times, and the values used were the average of these repetitions. The testing parameters employed in this study are summarized in Table 1.

In this study, the researchers powered the fan with a 8-W DC motor and used a blade diameter of 3.5×10^{-2} m. They installed the fan inside the drying chamber, placing it directly in front of the pipe that connects the chamber to the cold trap. The fan facilitated the movement of the water vapor resulting from aquadest evaporation, accelerating its flow toward the cold trap. Additionally, the presence of the fan increased the vapor flow within the drying chamber, enabling forced convective heat transfer to occur at the surface of the aquadest.

The electric heaters were mounted on the inner walls of the drying chamber, positioned higher than the material container. The heater is positioned slightly above the container vessel to ensure that the dominant heat transfer mechanisms during fan-off are radiation and diffusion. Three low-power plate heaters were used, each with a power rating of 10 W. These heaters were connected in



Fig. 2. Aquadest container.

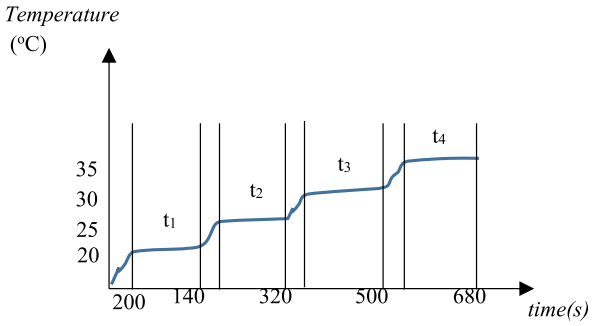


Fig. 3. Data collection, $t_1 = t_2 = t_3 = t_4 = 1200$ s.

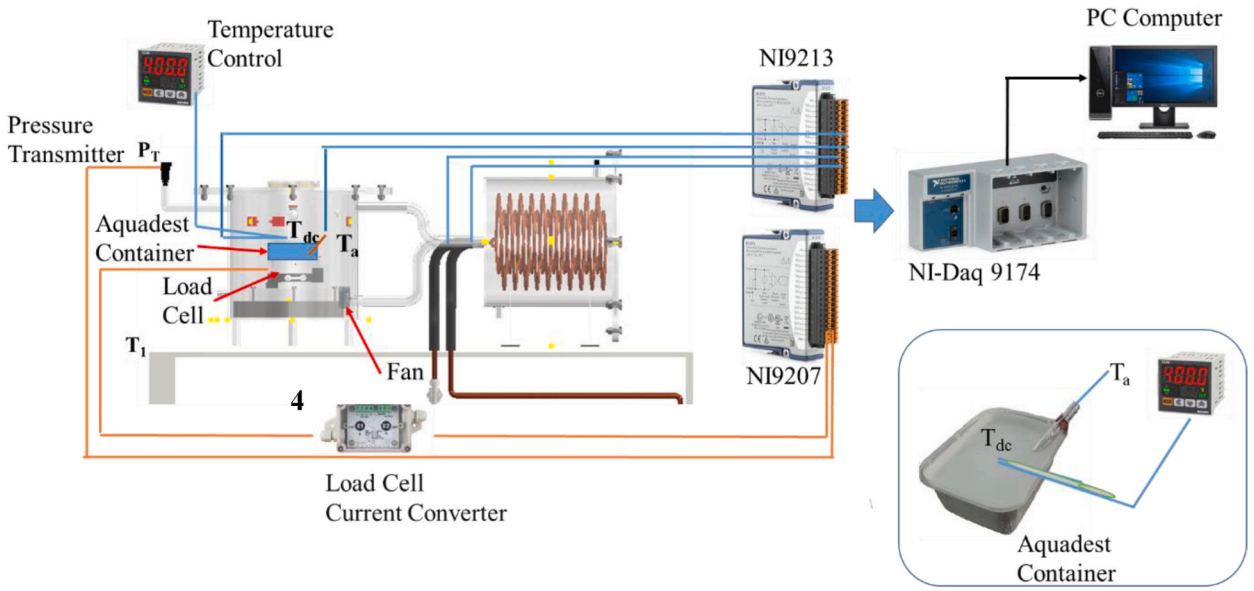


Fig. 4. Experiment setup.

Table 1
Experimental parameters.

Temperature T_{dc} (°C)	Time (s)	Fan (on/off)	
		Condition 1	*Condition 2*
20	1200	Off	On
25	1200	Off	On
30	1200	Off	On
35	1200	Off	On

parallel, resulting in a total power consumption of 30 W when the heaters were operating.

The vacuum freeze-drying process (see Fig. 5) can generally be divided into three stages: a) freezing, in which the temperature of water is reduced below its freezing point; b) vacuuming, in which the pressure in the drying chamber is lowered below the triple point pressure of water; c) sublimation, in which the frozen water undergoes a direct phase change from solid to vapor until the desired moisture content is achieved. Drying process divided into primary and secondary drying. Primary drying is the sublimation of ice directly into vapor under reduced pressure below triple point of water. Secondary drying follows primary drying and targets the removal of bound water by desorption [22,23].

The freezing process of aquadest was carried out using a freezer until the temperature of the aquadest (T_a) reached −8 °C. The frozen aquadest was then transferred to the drying chamber. During the experiment, the cold trap temperature initially reached −20 °C and gradually increased as the overall system temperature increased. The use of distilled water (aquadest) as the drying material indicates that the evaporation occurring in this experiment corresponds to the primary drying stage. To determine the evaporation rate of aquadest the calculation was based on the change in mass between the initial and final measurements divided by the duration of the observation period [25]. The equation used to calculate the mass change is as follows:

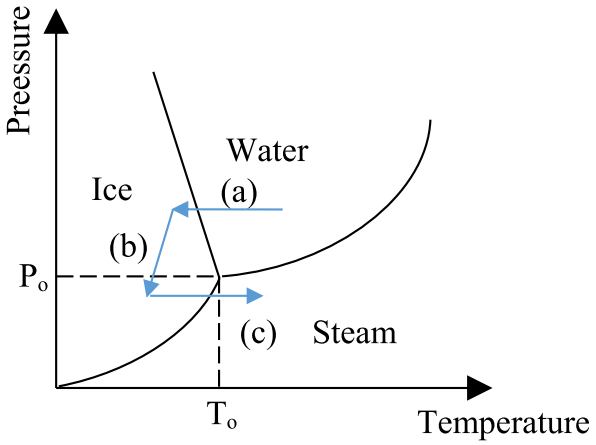


Fig. 5. Water Phase Diagram and VFD steps [24].

$$\dot{m} = \frac{(m_i - m_f)}{t_{i-f}} \quad 1)$$

There is a difference in the heat transfer modes between the operation with and without the use of a fan. In Condition 1, when the fan is turned off, the dominant modes of heat transfer during the operation of the vacuum freeze dryer are radiation and diffusion. In this study, for Condition 1, convective heat transfer is negligible because the heater is positioned slightly above the aquades container, minimizing conditions that would induce natural convection. Instead, heat transfer occurs primarily through diffusion in this configuration. Radiation heat transfer is one of the heat transfer modes that occurs during vacuum freeze-drying, primarily because the process takes place under vacuum conditions [26]. The radiative heat transfer can be calculated using the following equation:

$$Q_r = h_r.A.(T_{dc} - T_a) \quad 2)$$

Coefficient of the radiation heat transfer is obtained from

$$h_r = \epsilon.\sigma\ (T_{dc}^2 + T_a^2).(T_{dc} + T_a) \quad 3)$$

The magnitude of the diffusion heat transfer mode can be calculated from the equation

$$Q_d = k.A\ \frac{\delta T}{\delta y} \quad 4)$$

Height from the top of the container to the top surface of the aquadest (y) influences the diffusion energy that occurs [14]. In conditions where the vacuum freeze dryer operates with a fan, convective heat transfer can occur. The magnitude of the convective heat transfer can be calculated using the Newton law of cooling equation:

$$Q_c = h_c.A.(T_{dc} - T_a) \quad 5)$$

Understanding the mechanisms of heat transfer, using the equations described by Newton's Law of Cooling, is critical to optimizing drying techniques [27,28]. When the surface area of the evaporating aquadest (A) and the temperatures (T_∞, T_a) are held constant, the amount of heat transferred is primarily influenced by the convective heat transfer coefficient h_c. In this study, although the convective heat transfer coefficient h_c was not directly calculated, its theoretical relevance is acknowledged through the concept of the Nusselt number *Nu*. The Nusselt number is a dimensionless quantity that expresses the ratio of convective to conductive heat transfer in a fluid. Under forced convection conditions, *Nu* is typically represented as a function of the Reynolds number Re and the Prandtl number Pr, which describe, respectively, the ratio of inertial to viscous forces and the ratio of momentum diffusivity to thermal diffusivity. These parameters are defined as:

$$Re = \frac{\rho.u.L}{\gamma} \quad 6a)$$

$$Pr = \frac{\gamma c_p}{k} \quad 7)$$

Empirical correlations often express the Nusselt number as:

$$Nu = C.Re^m.Pr^n \quad 8)$$

where *C, m,* and *n* are constants dependent on geometry and flow regime.

This theoretical background supports the assumption that introducing a fan enhances convective transport by increasing the free-

stream velocity, thereby raising the Reynolds number, and consequently the Nusselt number and h_c. Although the airflow velocity from the fan was not measured in this work, the convective enhancement is conceptually addressed using this framework.

To measure energy consumption in the freeze-drying system, a power meter is used. All equipment that consumes electrical energy is connected to the power meter. The energy used can be measured and recorded during the experimental process. The schematic diagram can be seen in Fig. 6.

Specific energy, which is the energy required to evaporate 1×10^{-3} kg of dry matter mass, is obtained from the mass of distilled water evaporated and the total energy (E_t) required to run the VFD system. The total energy required to operate the entire cycle, including the cooling and evaporation stages, affects the specific energy calculation [29].

$$E_s = \frac{E_t}{m_{in} - m_f} \tag{6b}$$

The Two-Way ANOVA statistical method was employed to analyze the effects of two independent variables drying chamber temperature and the use of a fan on the evaporation rate of distilled water. The analysis was conducted at a 95 % confidence level ($\alpha = 0.05$) to determine whether the observed differences were statistically significant. This approach was used to evaluate the individual and interactive effects of each factor in order to assess the effectiveness of fan addition in accelerating the evaporation rate.

3. Result and discussion

Unlike vacuum freeze-drying systems that utilize conductive heating where heat is directly transferred to the material through contact this study employed a non-conductive heating method, which requires time to alter the drying chamber temperature, as shown in Fig. 6. For instance, increasing the drying chamber temperature by 5 °C takes approximately 10 min. This time delay is influenced by factors such as the material of the inner wall of the drying chamber, the chamber volume, and the presence of objects within the chamber. This phenomenon does not occur in systems using conductive heating, where the heat source is in direct contact with the trays or containers holding the material. This limitation of non-conductive heating using electric heating plates was anticipated in the system design. However, this drawback can be minimized in drying operations where frequent temperature adjustments in the drying chamber are not required. Moreover, the time needed to reach the desired drying chamber temperature becomes relatively insignificant when compared to the total operating time of the vacuum freeze-drying process necessary to dry the material.

The drying chamber temperature (T_{dc}) significantly influences the evaporation rate. As T_{dc} increases, the evaporation rate also increases. Fig. 7 illustrate the evaporation rates at the target testing temperatures. Across all graphs, it is evident that when the fan is turned on, the evaporation rate is higher compared to when the fan is off (see Fig. 8).

Based on heat transfer equations, assuming constant cross-sectional area (A) and temperature difference ($T_{dc} - T_a$), the rate of heat transfer increases when the heat transfer coefficient increases. Under conditions where temperature and pressure are assumed to be

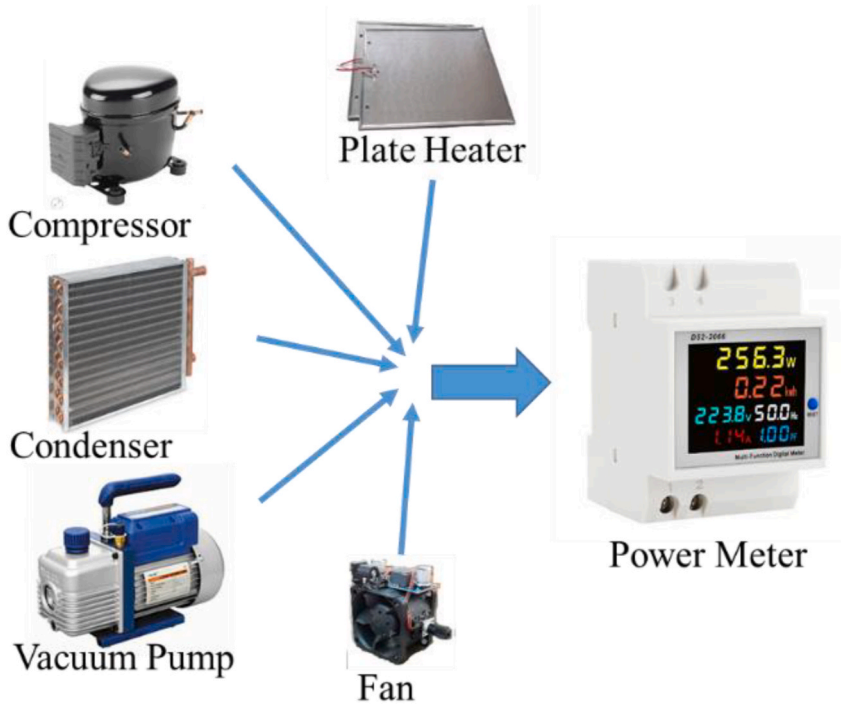


Fig. 6. Schematic diagram of energy measurement using a power meter.

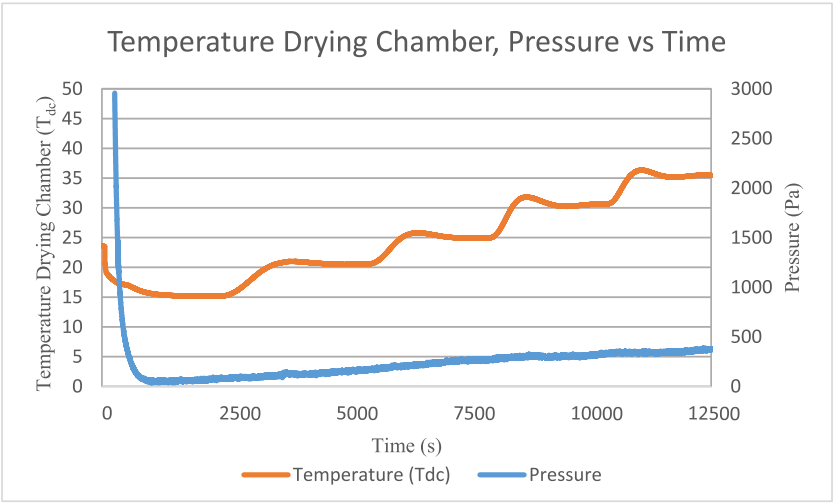


Fig. 7. Temperature, Pressure vs Time.

constant, the heat transfer coefficient becomes the primary factor affecting the amount of transferred heat.

This study demonstrates that the addition of a fan has the potential to increase the heat transfer coefficient compared to conditions without a fan. An increase in heat transfer indicates that more energy is delivered to the aquadest as sublimation energy. Consequently, the energy required for sublimation increases, leading to a higher evaporation rate when the fan is on compared to when it is off.

The use of a fan to enhance evaporation rate suggests a promising strategy to improve vacuum freeze drying performance, even when different heating methods are employed. By altering the heat transfer coefficient within the drying chamber, the application of a fan could potentially increase the evaporation rate in various types of vacuum freeze drying systems (Table 2).

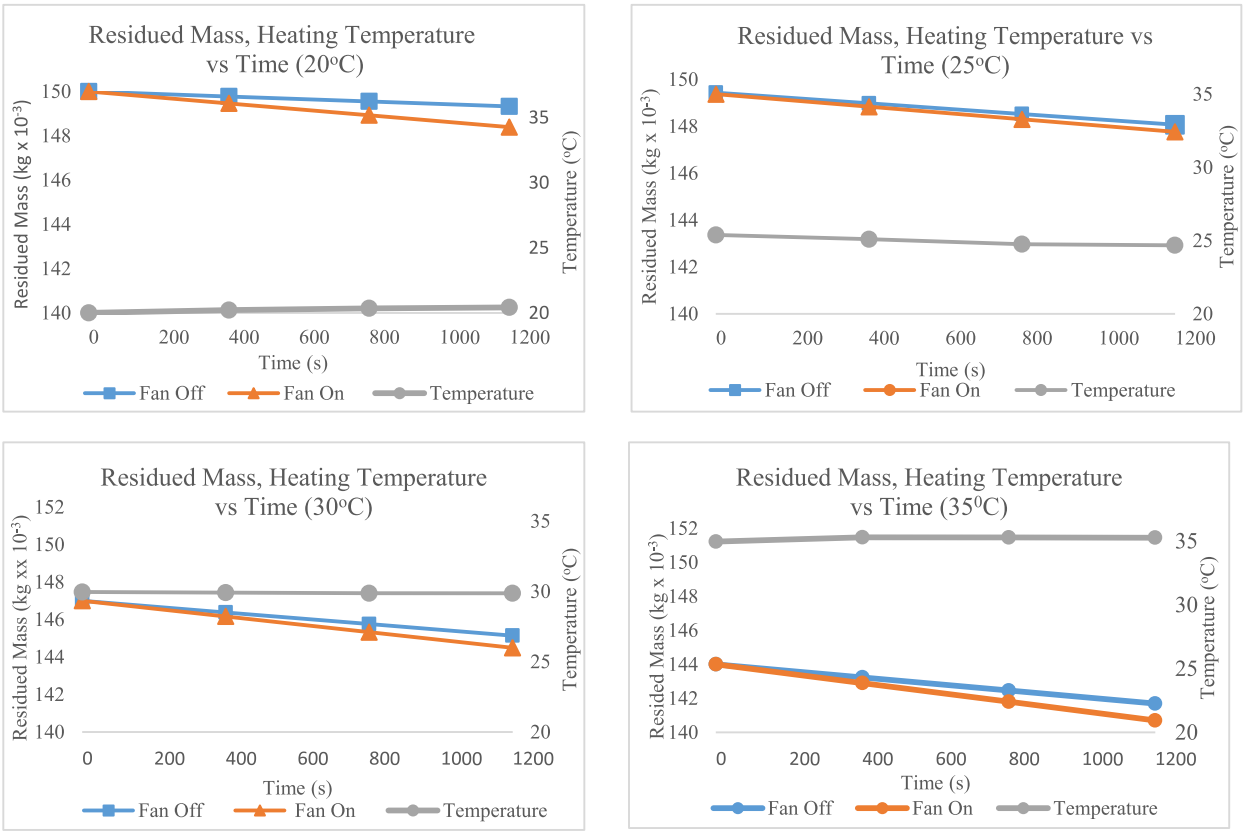


Fig. 8. Residued Mass, Heating Temperature vs Time (20 °C, 25 °C, 30 °C, 35 °C).

Table 2
Evaporation rate.

Temperature (°C)	Evaporation Rate (kg/s x 10^{-7})		Evaporation Rate Improvement (%)
	(Fan Off)	(Fan On)	(Fan On vs Fan Off)
20	5.63	6.43	14.2 %
25	11.43	13.43	17.5 %
30	15.53	20.90	34.5 %
35	19.22	27.47	42.9 %
		Average	27.3 %

Under fan-off conditions, the highest evaporation rate was observed at a drying chamber temperature of 35 °C, reaching 19.22 × 10^{-4} kg/s. At similar average chamber pressure and temperature conditions, turning the fan on increased the evaporation rate to 27.47 × 10^{-4} kg/s. This represents a 42.9 % increase, the highest observed in this study, occurring at 35 °C. The lowest increase in evaporation rate was recorded at 20 °C, with an improvement of 14.2 %. On average, the increase in evaporation rate when using a fan compared to without a fan in this study was 27.3 %. This result was obtained under a horizontal installation configuration of the drying chamber and cold trap in the vacuum freeze drying (VFD) system. Fig. 9 presents a comparison of the evaporation rates at 20 °C, 25 °C, 30 °C, and 35 °C between the VFD system operating with fan-on and fan-off. The heat movement inside the system is delineated in equation (2) through 8. The primary mechanism of heat transfer when the fan is activated is forced convection. Radiative heat transmission remains constant at a uniform temperature. When the fan is activated, diffusion heat transfer transitions to forced convection heat transfer. The distinction when the fan is inactive is the heightened steam flow velocity. When the temperature of distilled water (Ta) and the temperature of the drying chamber (Tdc) are identical, variations in steam flow velocity affect the Reynolds number (Re). The qualities in question remain unchanged, hence it can be presumed that the Prandtl number is constant. An elevation in the Reynolds number leads to an augmented Nusselt number (*Nu*). Consequently, the convection coefficient hk increases, resulting in a larger energy absorption by aquadest when the fan is activated and utilized for sublimation energy. Fig. 9 illustrates that as temperature increases, the disparity in evaporation rates between fan-on and fan-off circumstances becomes more pronounced. As the temperature rises, the evaporation rate of water increases, necessitating a consistent channel capacity or flow rate for steam flow. The fan facilitates the steam flow to the cold trap. The graph indicates that the fan maintains a consistent steam flow and substantially enhances the evaporation rate when operational, in contrast to when it is inactive.

The results of the Two-Way ANOVA statistical analysis on the evaporation rate data indicate that the use of a fan has a statistically significant effect on the evaporation rate at a 95 % confidence level (p-value <0.05), demonstrating that the addition of a fan accelerates the evaporation process. The drying chamber temperature also has a significant effect on the evaporation rate. However, the interaction between fan usage and temperature is not statistically significant (p-value >0.05), suggesting that each factor independently influences the evaporation rate. The effect of the fan remains consistent across different temperature levels without specific dependency.

The increased evaporation rate observed during fan-on operation is attributed to enhanced convective heat transfer and evaporation rate. Under fan-off conditions, vapor movement relies solely on passive diffusion driven by the pressure gradient between the drying chamber and the cold trap. This vapor movement is inherently slow due to the low-pressure environment.

The fan operation alters the boundary layer conditions at the aquadest surface, reducing mass transfer resistance and promoting faster sublimation. This aligns with Newton's Law of Cooling (Equation (5)), where the convective heat transfer coefficient is enhanced by forced vapor flow. The fan reduces humidity near the aquadest surface, creating a steeper vapor concentration gradient—a critical factor influencing sublimation rate.

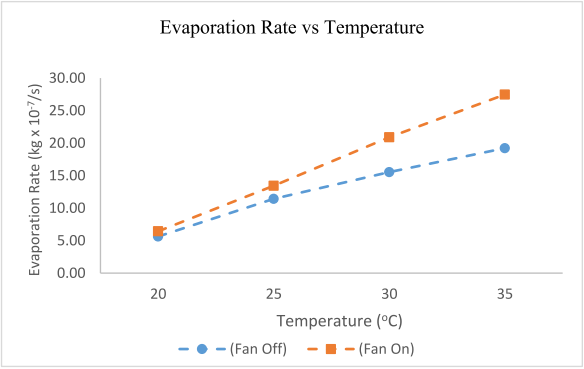


Fig. 9. Evaporation rate at temperatures of 20 °C, 25 °C, 30 °C, 35 °C (fan on/off).

Table 3
Spesific energy consumption.

Temperature (°C)	Evaporated Mass (kg x10^{-4})		Energy Consumption (kWh)		Spesific Energy (kWh/kg x10^{4})		Improvement (%)
	Fan Off	Fan On	Fan Off	Fan On	Fan Off	Fan On	FanOn vs FanOff
20	6.76	7.72	0.127	0.127	0.019	0.016	12.44 %
25	13.71	16.12	0.129	0.129	0.009	0.008	14.94 %
30	18.64	25.08	0.121	0.121	0.006	0.005	25.68 %
35	23.06	32.96	0.123	0.123	0.005	0.004	30.04 %
					Average		20.8 %

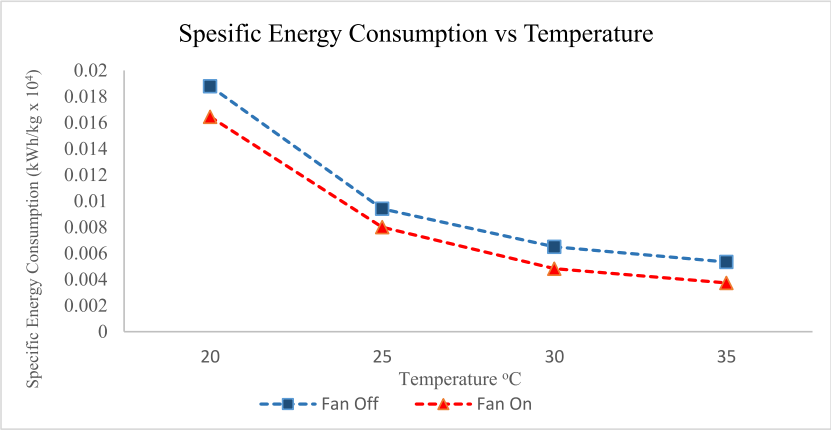


Fig. 10. Spesific Energy Consumption vs Temperature.

Statistical analysis indicating no significant interaction effect between fan usage and temperature ($p > 0.05$) suggests that the fan's impact is primarily mechanical (flow-induced) rather than thermal. Temperature independently affects the magnitude of energy input.

Under fan-on conditions, the total energy consumption of the heater and fan was slightly lower than the energy consumption of the heater alone under fan-off conditions. However, the energy consumed by the heater and fan in the vacuum freeze drying system was significantly lower than the energy demand of the overall system. The energy consumption of the cooling system and the vacuum pump was substantially higher. As a result, the total system energy consumption (E_t) was measured to be similar under both fan-on and fan-off conditions, as shown in Table 3

A key advantage of operating the vacuum freeze drying system with a fan is the increased evaporation rate (see Table 2). Consequently, the system's specific energy consumption is lower when the fan is used. In this study, the average reduction in specific energy was 20.8 % under fan-on conditions. The greatest reduction in specific energy consumption was observed at a drying chamber temperature of 35 °C, with a decrease of 30.04 % compared to the fan-off condition. The graph depicting the relationship between specific energy consumption and each temperature variable is presented in Fig. 10.

The uncertainty analysis was conducted separately for both operating conditions (fan-off and fan-on), as each experimental condition produced distinct evaporation rates and energy usage. Despite using identical measurement instruments, the resulting uncertainty in evaporation rate and specific energy was calculated independently for each case using propagation of error methods. The uncertainty analysis of the fan-off condition reveals that measurement errors are more influential at lower temperatures, where the evaporated mass is small. The propagated uncertainties in evaporation rate and specific energy were calculated using the standard error propagation method, taking into account the sensor specifications. These results emphasize the need for caution when interpreting drying efficiency under low thermal input conditions (Tables 4 and 5).

Table 4
Fan-off uncertainty analysis.

Temperature (°C)	Evaporated Mass (kg x10^{-4})	Evaporation Rate (kg/s x10^{-7})	Specific Energy (kWh/kg x10^{4})	Mass Uncertainty (kg x10^{-4})	Evaporation Rate Uncertainty (10 x $^{-4}$ kg/s)	Specific Energy Consumption Uncertainty (kWh/kg)
20	6.76	5.63	0.019	±5	±7	±0.01
25	13.71	11.43	0.009	±5	±7	±0.01
30	18.64	15.53	0.006	±5	±7	±0.01
35	23.06	19.22	0.005	±5	±7	±0.01

Table 5
Fan-on uncertainty analysis.

Temperature (°C)	Evaporated Mass (kg x10^{-4})	Evaporation Rate (kg/s x10^{-7})	Specific Energy (kWh/kg)	Mass Uncertainty (10 x $^{-7}$ kg)	Evaporation Rate Uncertainty (10 x $^{-4}$ kg/s)	Specific Energy Consumption Uncertainty (kWh/kg)
20	7.72	6.43	164.51	±5	±7	±0.01
25	16.12	13.43	80.12	±5	±7	±0.01
30	25.08	20.9	48.25	±5	±7	±0.01
35	32.96	27.47	37.32	±5	±7	±0.01

The uncertainty analysis for the fan-on mode indicates that both the evaporation rate and the specific energy are subject to considerable variation, particularly at lower temperatures. The uncertainty in the evaporation rate remains consistent across temperatures due to the fixed time interval and measurement precision, while the uncertainty in specific energy decreases at higher temperatures due to larger mass differences. These results support the conclusion that operating the fan improves drying performance, particularly under elevated temperatures.

4. Conclusion

From the results of the experiment in this study, the evaporation rate increased for the use of fans in the vacuum freeze-drying system with the installation of a drying chamber parallel to the cold trap. The highest increase in evaporation rate when the fan was on was obtained at a drying chamber temperature of 35 °C. The evaporation rate at a temperature of 35 °C without using a fan was 19.22×10^{-7} kg/s compared to the evaporation rate of 27.47×10^{-7} kg/s when the fan was on. The evaporation rate increased by 42.9 % by using a fan. In this study, an average increase in evaporation rate was obtained using a fan of 27.3 %.

The system shows lower specific energy consumption when the fan is on. The average specific energy consumption of vacuum freeze drying decreased when using a fan proportionally with the 20.8 %. The highest increase in specific energy consumption occurs when the fan was on at a temperature of 35 °C by 30 %. Although the system energy consumption is comparable at the same operating time duration between fan-on or off, the evaporation rate is higher when the fan is operating resulting in lower specific energy consumption. This indicates an increase in system efficiency.

The fan assists the movement of vapor from the drying chamber to the cold trap, increasing the convective heat transfer coefficient in the drying chamber which increases the evaporation rate and reduces the overall drying time.

To help identify the optimal configuration to maximize drying efficiency, testing of fan usage at various power levels can be performed. This is done to evaluate the impact of fan speed and vapor flow design on drying performance as an area for further research. The potential for increasing drying rates using fans is worth testing in vacuum freeze dryers with different material heating modes. Testing with different materials and heating methods could provide further insight into the applicability of vacuum freeze drying systems with the addition of fans.

The configuration and location of heaters in the drying chamber could be explored to increase the effectiveness of using non-conducting electric heaters. This can be minimized if the system does not require significant temperature variations during operation.

In conclusion, the application of a fan optimizes vapor flow in the vacuum freeze drying system, significantly improves the evaporation rate, and enhances the system's specific energy efficiency. The findings of this study demonstrate that enhancing vapor flow using a strategically placed fan within a horizontally connected VFD system significantly improves evaporation performance and energy efficiency. This represents a novel and practical enhancement to conventional VFD designs, particularly for systems relying on conduction-free heating methods. The proposed configuration offers a low-cost and scalable solution for improving drying efficiency in various applications, especially in settings where advanced heating technologies may be impractica

CRediT authorship contribution statement

Indra Buana: Writing – original draft, Supervision, Methodology, Data curation. **Engkos Achmad Kosasih:** Resources, Investigation, Funding acquisition, Conceptualization. **Muhsin Kilic:** Validation, Data curation. **Ahmad Zikri:** Visualization, Project administration. **Ari Satmoko:** Software, Formal analysis. **M. Burhanuddin Fauzi:** Validation, Project administration, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Achmad Engkos Kosasih reports financial support was provided by University of Indonesia. Achmad Engkos Kosasih reports a relationship with University of Indonesia that includes: board membership and funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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