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# Simulation of the Effect of Air Humidity Ratio in the Drying Room on the Rate of Material Evaporation in Vacuum Freeze Drying

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**ABSTRACT**

In the drying process there are several parameters that influence the evaporation rate. Apart from pressure and temperature, air humidity in the drying room has been shown to influence the evaporation rate. To find out how much influence air humidity has on the evaporation rate in a Vacuum Freeze Dryer (VFD) system, calculations and simulations need to be carried out. Evaporation in a VFD occurs by sublimation at evaporation conditions below the triple point of water. Ice weighing $2x10^{-2}$ kg was used as dry material to characterize the VFD process at a temperature of -10$^{o}$C. The ice temperature and operating pressure are selected at conditions below the triple point so that sublimation evaporation occurs. The temperature of the drying room for heating was varied, namely (20, 25, 30)($^{o}$C) and pressure (0.5, 0.4, 0.3)(kPa). Air humidity ratio, varies at (300, 200, 100, 10, 1, 0.1, 0.01, 0.001) (kg $H_2O$/kg dry air). The simulation is carried out in a drying room, the ice receives heat due to the temperature difference with room temperature, heat transfer occurs by radiation and diffusion. Heat is used to evaporate the ice through sublimation. The temperature of the ice upon sublimation is close to the wet bulb temperature and remains constant until the ice has completely evaporated. From the simulation it is known that changing the air humidity ratio in the drying room from 300 (kg $H_2O$/kg dry air) to 0.001 (kg $H_2O$/kg dry air) will increase the evaporation rate between 6.2% - 9.5%. The evaporation rate increased by 6.2% was obtained at $P\infty$=0.3kPa, $T\infty$=30$^{o}$C. This increase in evaporation rate shortened the drying time by 0.42 hours. The evaporation rate increased by 9.5% at a pressure of $P\infty$=0.5kPA, $T\infty$=20$^{o}$C thereby shortening the drying time by 1.03 hours. Simulations show that increasing the evaporation rate and shortening the drying time has the potential to increase the energy efficiency of the VFD. The increase in evaporation rate is influenced by operating temperature and pressure. Simulations confirmed that the evaporation rate increased when the drying chamber temperature was increased and the air pressure was decreased.

## 1. Introduction

Drying is a method used to reduce product humidity with the aim of, among other things, extending shelf life, ease of storage, ease of transportation and other processes [1]. Vacuum freeze drying (VFD) is a drying method that operates under conditions below the triple point of water

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(Po=611.657Pa; To=0.01°C), the process takes place at low pressure and temperature and evaporation occurs by sublimation [2]. There are three processes that occur in vacuum freeze drying, refer to Figure 1(a): freezing, namely lowering the water temperature to below its freezing point; Figure 1(b): vacuum, namely a decrease in pressure until it reaches a pressure below the triple point pressure; Figure 1(c): drying, namely evaporation until it reaches the target water content [2].

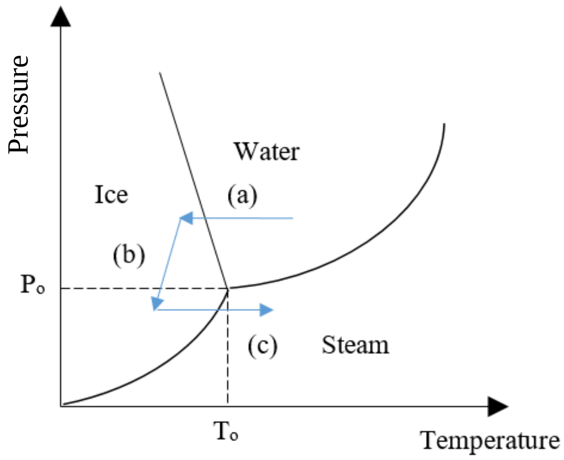


**Fig. 1.** Water Phase Diagram and VFD steps; (a) freezing, (b) vacuum, (c) drying

The sublimation evaporation process at low temperatures has been proven to produce good quality products that are able to maintain the physical and chemical properties of dry products so that it is widely applied in the pharmaceutical and food industries [3,4]. The drying process in vacuum freeze drying apart from sublimation in the first stage of drying also involves a desorption process, especially in the second stage of drying. The desorption process can involve the release of gases or volatile compounds that were initially adsorbed or absorbed by the material [5,6]. However, vacuum freeze dryers consume higher energy than other drying methods. The high energy consumption of VFDs causes high operational costs [7]. Various methods are used to increase the evaporation rate of vacuum freeze dryers to reduce their energy consumption.

Methods used to increase the efficiency of vacuum freeze dryers include treating the material before drying. The treatment of the material before drying has been proven to have an effect on the evaporation rate when dried. For example, Zhang *et al.,* [8] tested the effect of longitudinal and transverse cutting on drying time and the quality of drying results. Apart from that, the heating method in the drying chamber also affects the evaporation rate. Heating materials using infrared rays, microwaves, utilizing condenser waste heat and a combination of heating methods has an effect on the evaporation rate and energy consumption [9-12]. For example, Jia *et al.,* [13] which compared the evaporation rate using the hot air heating method, hot air-microwave combination and vacuum freezing for drying persimmons including analysis of the physical-chemical properties of the dried product. From various efforts made to increase the efficiency of vacuum freeze dryers, it is known that the evaporation rate is influenced by temperature and pressure. The pressure and temperature in the drying chamber can be designed using equipment tailored to the desired needs. From experiments by Ju *et al.,* [14] and Xu *et al.,* [15], it is known that differences in the relative humidity of the material being dried and the environment affect the drying rate. The steam produced from evaporation of materials causes the air humidity in the drying room to increase and reach a saturated condition. When air humidity reaches saturated conditions, the evaporation rate decreases. This is an unavoidable condition when the vacuum freeze dryer is operated. By introducing air into the drying chamber to condition the air humidity in the drying chamber to a small value, it is hoped that the evaporation rate of the material can be increased. For this reason, it is necessary to simulate the effect of changes in the humidity ratio on the evaporation rate of the material. Process simulations on vacuum freeze dryers have been carried out for different case studies. For example, Ganguly and Alexeenko [16], computational modeling for vapor flow and ice layer analysis. Tachiwaki *et al.,* [17] simulating the sublimation rate of thin cylindrical ice using a heating method with a plate at the base ice. Numerical and experimental analysis studies on the heat transfer that occurs during vacuum freeze drying of kiwi fruit have been carried out by Chen *et al.,* [18]. Analytical study of convective heat and mass transfer by volumetric heating. The results of convective heat and mass transfer studies with volumetric heating show that the sublimation rate increases with volumetric heating sources [19]. Chaurasiya *et al.,* [20] conducted research in the case of non-linear porous sublimation where thermal conductivity depends on temperature and mass diffusivity depends on concentration. The research results provide a complete theoretical and mathematical understanding. Analytical studies for the case of moving boundaries related to heat and mass transfer by convection show that the presence of heat transfer by convection will increase the drying rate in vacuum freeze dryers [21]. This paper simulates the effect of humidity ratio on material evaporation rate in a vacuum freeze dryer. The material used for process characterization is ice. Ice sublimes at a constant rate of evaporation, the temperature of the ice when subliming is close to the temperature of the wet bulb in the drying chamber.

This paper examines the effect of introducing air into the drying chamber to reduce humidity in the drying chamber to increase the evaporation rate in a vacuum freeze dryer. Increasing the evaporation rate means shortening the drying time and lowering the energy consumption of the vacuum freeze dryer. Reducing energy consumption means lower operating costs and can expand vacuum freeze dryer applications and support sustainable energy. The main aim of this paper is to determine the effect of drying room humidity on the evaporation rate by simulating changes in the ratio of air humidity to the evaporation rate. The air humidity ratio in the drying chamber is varied, where the evaporation rate is calculated to occur at the specified pressure and temperature.

## 2. Methodology

### *2.1 Case Study*

The simulation was carried out on frozen water weighing $2x10^{-2}$ kg put into a container (A=0.01 $m^2$) in drying chamber at a temperature $T_i$ = -10°C, as shown in Figure 2. The temperature of -10°C was chosen to be below the triple point temperature (To=0.01°C), thus the evaporation occurs by sublimation in vacuum freeze drying [2]. The distance from the ice surface to the top of the container is $2x10^{-2}$ m.

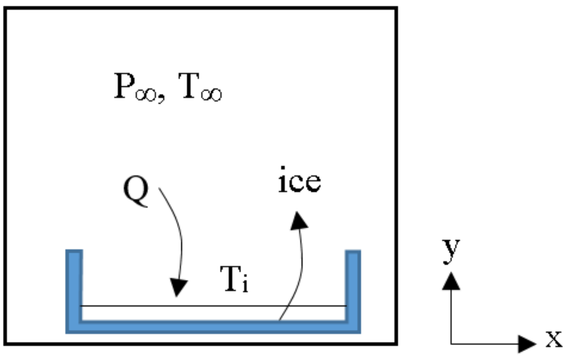


**Fig. 2.** Ice in a container in the drying chamber

The pressure and temperature of the drying chamber are $P_\infty$ and $T_\infty$. Heat (Q) is the total heat received by the ice, the amount is obtained from the sum of the heat flowing by radiation ($Q_r$) and diffusion ($Q_d$). The assumptions used in the calculations are as follows

(a) The drying chamber temperature $T\infty$ is constant and uniform.
(b) Most of heat enters from the y-axis direction. The x and z axis directions are ignored.
(c) The ice is completely sublimated at a constant temperature equal to the wet bulb temperature of the drying chamber.
(d) The surface area of the ice ($1x10^{-2}$ $m^2$) is much larger than its thickness ($2x10^{-4}$ m), the position of the heater is above the ice. Heat transfer calculations are approached by assuming a 1-dimensional vertical y-axis direction.

To simulate the effect of the air humidity ratio in the drying chamber at a certain pressure and temperature, the parameters are determined as in Table 1.

**Table 1**
Simulation parameters

| Pressure (kPa) | Temperature (°C) | Humidity Ratio (ω) (kg $H_2O$/kg dry air) |
|---|---|---|
| 0.5 | 20, 25, 30 | 300, 200, 100, 10, 1, 0.1, 0.01, 0.001 |
| 0.4 | 20, 25, 30 | 300, 200, 100, 10, 1, 0.1, 0.01, 0.001 |
| 0.3 | 20, 25, 30 | 300, 200, 100, 10, 1, 0.1, 0.01, 0.001 |

Thermodynamic properties of air and ice required in calculations such as conduction coefficient (W/m.K), sublimation heating value (J/kg) are obtained based on Liley [22].

*2.2 Saturated Vapor Pressure*

By using pressure and temperature references at the triple point of water (Po, To) to obtain the saturated steam temperature if the room pressure $P\infty$ is known, you can use the Claysius Clapeyron equation [23].

$$\ln\frac{Po}{Psv} = -\frac{L}{R}\left(\frac{1}{To} - \frac{1}{T\infty}\right) \quad (1)$$

*2.3 Psychrometrics Equations*

There is a mixture of air and water vapor in the drying chamber, the ratio of humidity, partial pressure and total pressure of water vapor is obtained from equations [24].

The humidity ratio is calculated:

$$\omega = 0.622\frac{Pv}{P-Pv} \quad (2)$$

Relative humidity is calculated [24]:

$$\phi = \frac{Pv}{Psat} \quad (3)$$

### *2.4 Wet Bulb Temperature*

The time required for ice to evaporate completely starts when the ice reaches wet bulb temperature, which is the sublimation temperature of the ice and the temperature of the ice remains constant until it is completely used up.

When the vacuum freeze dryer is operating, the material evaporation process occurs in the drying chamber, the water vapour will reach a saturated condition. This condition occurs at a certain pressure and the temperature that occurs on the surface of the material is close to the wet bulb temperature ($T_{wb}$). The equilibrium equation for calculating the temperature of the sphere follows Sadeghi *et al.,* [25]

$$\lambda . T_{wb}^2 + \varphi . T_{wb} + \psi = 0 \quad (4)$$

To obtain the wet bulb temperature, calculate some necessary constants

$$\Delta = \varphi^2 - 4\lambda\psi \quad (5)$$

$$\varphi = \xi(T_\infty) + \gamma P_\infty \quad (6)$$

$$\gamma = 0{,}4\ (\frac{gwater}{kgair}.K)$$

$$\psi = a - \lambda P_\infty T_\infty - P_v \quad (7)$$

$$a = 0.611$$

$$\lambda = 0{,}0014 * EXP(0{,}027 * T_\infty) \quad (8)$$

$$\xi(T_\infty) = (-3x10^{-7})T_\infty^3 - (10^{-5})T_\infty^2 + (2x10^{-5})T_\infty \quad (9)$$

The wet bulb temperature is

$$T_{wb} \cong \frac{-\varphi + \sqrt{\Delta}}{2\lambda}\ (^{\circ}\mathrm{C}) \quad (10)$$

### *2.5 Heat Transfer Calculations*

Ice in the drying chamber receives heat through radiation and diffusion [26]. The amount of heat gained by the ice through radiation is calculated:

$$Q_r = h_r.A.(T_\infty - T_{wb}) \quad \text{(Watt)} \quad (11)$$

The radiation heat transfer constant is obtained from Wang and Sun [27] using equation

$$h_r = \epsilon.\ \sigma.(T_\infty^2 - T_{wb}^2).(T_\infty - T_{wb}) \quad (\mathrm{W.m^{-2}.K^{-1}}) \quad (12)$$

Diffusion heat transfer is calculated

$$\frac{\delta^2 T}{\delta^2 y} = 0 \quad (13)$$

$$\frac{\delta T}{\delta y} = C_1 \tag{14}$$

$$T = C_1 y + C_2 \tag{15}$$

Boundary conditions

y = *0*, $T = T_{wb}$

y = $2 \times 10^{-2}$ m, $T = T_\infty$

The amount of heat obtained through the diffusion process

$$Q_d = k.A \frac{\delta T}{\delta y} \tag{16}$$

$$Q_d = k.A.C_1 \quad \text{(Watt)} \tag{17}$$

*2.6 Evaporation Rate and Drying Time*

The ice evaporation rate is calculated,

$$\dot{m} = \frac{(Qr + Qd)}{h_{sg}} \quad (\text{kg.s}^{-1}) \tag{18}$$

The drying time required for the ice to completely run out can be calculated from the weight of the ice divided by the evaporation rate,

$$t = \frac{m}{\dot{m}} \qquad (sec) \tag{19}$$

*2.7 Validate the Simulation with Experiments*

To compare the simulation calculations with experiments, secondary data of the vacuum freeze drying system were used. The heating method was chosen with a standard heater rather than using an infrared heater or microwave. Selection of secondary data for drying materials with the greatest water composition or materials mixed with water with a water content of more than ninety-five percent (>95%). The data taken is the first stage of evaporation rate data where the water in the form of ice on the surface of the material sublimes and has no bonds with the material as shown in Figure 3. Meanwhile, in the second stage of drying, the drying rate will decrease because water has a hydroscopic bond with the material as shown in Figure 4. More energy is required to maintain the evaporation rate in the second stage of drying, depending on the type of material being dried.

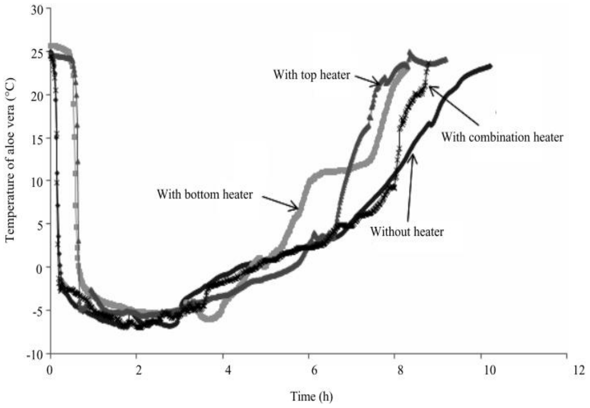

**Fig. 3.** Temperature vs Time [28]

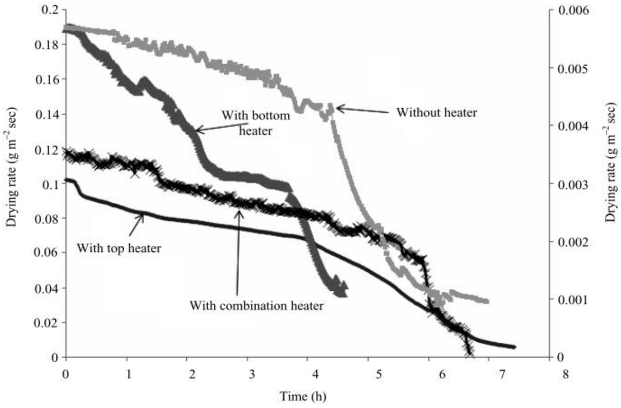

**Fig. 4.** Drying rate vs Time [28]

The comparative data is the drying test of aloe vera with variations in the position of the heater relative to the material, where the data used is the drying data of the position of the heater above the material which corresponds to the simulation case. From the temperature versus drying time graph, the first stage when the material temperature is relatively constant is between 1.5-3 hours. Evaporation rate (+/-) 0.08 $g.m^{-2}.s^{-1}$ for heater position above the material being dried. Other data required for calculations, $P\infty$ = 0.4kPa and drying chamber temperature, $T_\infty$ = 30°C [28].

From Table 2, it was found that the difference between experimental and calculated data was still quite well under ten percent (<10%). The difference between the experimental evaporation rate compared to the simulated evaporation rate is 6.6%, where the calculated results are slightly slower than the experimental results.

**Table 2**
Evaporation rate calculations vs experiment

| No | $P_\infty$ (kPa) | $T_\infty$ (°C) | Evaporation rate ($g.m^{-2}.s^{-1}$) | | Δ (%) |
|---|---|---|---|---|---|
| | | | Experiment | Calculation | |
| 1 | 0.4 | 30 | 0.08 | 0.0747 | -6.6% |

## 3. Result and Discussion

The simulation results show that there is an increase in the evaporation rate when the air humidity ratio becomes smaller. Figure 5 to Figure 7 show changes in the evaporation rate that occur due to changes in the air humidity ratio. The evaporation rate changes quite significantly when the humidity ratio is smaller than 10 and greater than 0.1 ($0.1<\omega<10$). This is because the humidity ratio in the range of $0.1< \omega <10$ has an effect on decreasing the value of the wet bulb temperature. In this simulation calculation it is assumed that the ice temperature will reach wet bulb temperature and will remain constant until the ice completely sublimes. A decrease in the wet bulb temperature (Twb) increases the difference with the drying chamber temperature ($T\infty$ - Twb). The amount of heat (Q) is directly proportional to the temperature difference in the drying chamber. The rate of evaporation is directly proportional to the amount of heat (Q), therefore the rate of evaporation increases as the amount of heat received by the ice increases. For humidity ratio values greater than 10 ($\omega >10$) and smaller than 0.1 ($\omega <0.1$), the wet bulb temperature does not change significantly. These conditions cause the evaporation rate in the humidity ratio range $\omega>10$ and $\omega<0.1$ to not experience significant changes.

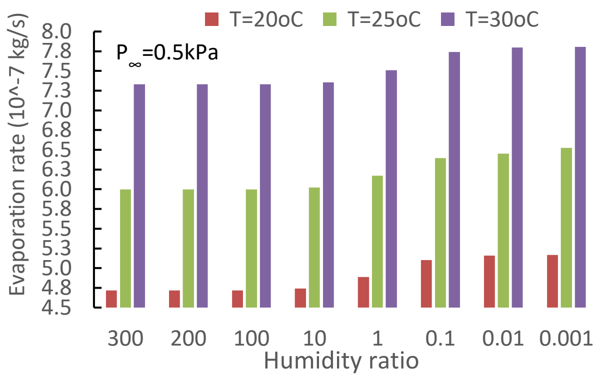


**Fig. 5.** Air humidity ratio vs drying rate at pressure P∞=0.5kPa

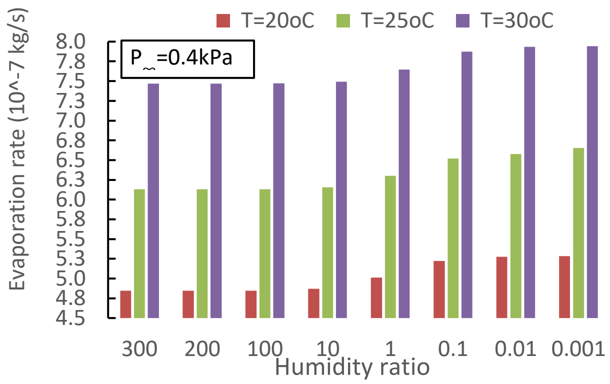


**Fig. 6.** Air humidity ratio vs drying rate at pressure P∞=0.4kPa

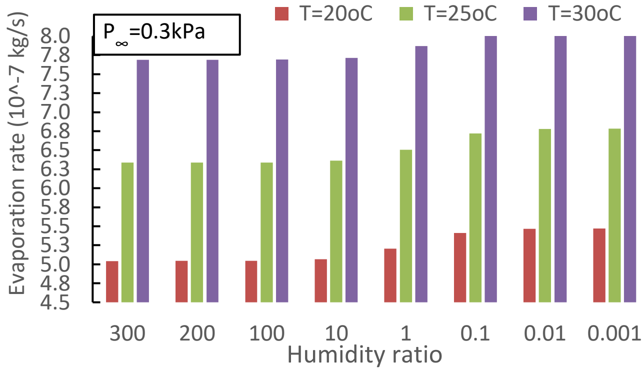


**Fig. 7.** Air humidity ratio vs drying rate at pressure P∞=0.3kPa

Table 3 to Table 5 show details of the calculation results of the effect of changes in the humidity ratio on the evaporation rate. At constant pressure and temperature, the evaporation rate increases as the humidity ratio decreases. For example, changing the humidity ratio from 300 to 0.001 results in an increase in the highest evaporation rate of 9.5% which occurs at a pressure of $P_\infty$=0.5 kPa and a drying chamber temperature of $T_\infty$=20$^o$C. The increase in evaporation rate due to the smallest decrease in humidity ratio of 6.2% occurred at pressure $P_\infty$=0.3 kPa and drying room temperature $T_\infty$=30$^o$C. The simulation results show that the influence of the humidity ratio is greater at higher pressure. The effect of humidity ratio is greater at lower temperatures.

**Table 3**
The ratio of air humidity and evaporation rate to pressure $P_\infty$= 0.5 kPa

| | $P_\infty$ = 0,5kPa | | |
|---|---|---|---|
| | $T_\infty$ =20°C | $T_\infty$ =25°C | $T_\infty$ =30°C |
| ω (kg $H_2O$/kg dryair) | ṁ x $10^7$ (kg/s) | ṁ x $10^7$ (kg/s) | ṁ x $10^7$ (kg/s) |
| 300 | 4,716 | 5,997 | 7,331 |
| 200 | 4,716 | 5,997 | 7,331 |
| 100 | 4,718 | 5,999 | 7,332 |
| 10 | 4,741 | 6,022 | 7,357 |
| 1 | 4,887 | 6,171 | 7,510 |
| 0,1 | 5,103 | 6,393 | 7,739 |
| 0,01 | 5,159 | 6,450 | 7,799 |
| 0,001 | 5,166 | 6,524 | 7,806 |
| Δ max | 9,5% | 8,8% | 6,5% |

**Table 4**
The ratio of air humidity and evaporation rate to pressure $P_\infty$= 0.4 kPa

| | $P_\infty$ = 0,4kPa | | |
|---|---|---|---|
| | $T_\infty$=20°C | $T_\infty$=25°C | $T_\infty$=30°C |
| ω (kg $H_2O$/kg dryair) | ṁ x $10^7$ (kg/s) | ṁ x $10^7$ (kg/s) | ṁ x $10^7$ (kg/s) |
| 300 | 4,845 | 6,129 | 7,468 |
| 200 | 4,845 | 6,130 | 7,469 |
| 100 | 4,846 | 6,131 | 7,470 |
| 10 | 4,869 | 6,154 | 7,495 |
| 1 | 5,011 | 6,300 | 7,646 |
| 0,1 | 5,223 | 6,519 | 7,875 |
| 0,01 | 5,277 | 6,576 | 7,935 |
| 0,001 | 5,284 | 6,653 | 7,942 |
| Δ max | 9,1% | 8,5% | 6,3% |

**Table 5**
The ratio of air humidity and evaporation rate to pressure $P_\infty$= 0.3 kPa

| | $P_\infty$ = 0,3kPa | | |
|---|---|---|---|
| | $T_\infty$ =20°C | $T_\infty$ =25°C | $T_\infty$ =30°C |
| ω (kg $H_2O$/kg dryair) | ṁ x $10^7$ (kg/s) | ṁ x $10^7$ (kg/s) | ṁ x $10^7$ (kg/s) |
| 300 | 5,043 | 6,337 | 7,690 |
| 200 | 5,044 | 6,338 | 7,690 |
| 100 | 5,045 | 6,339 | 7,691 |
| 10 | 5,067 | 6,362 | 7,716 |
| 1 | 5,204 | 6,505 | 7,868 |
| 0,1 | 5,411 | 6,722 | 8,101 |
| 0,01 | 5,464 | 6,779 | 8,162 |
| 0,001 | 5,471 | 6,786 | 8,170 |
| Δ max | 8,5% | 7,1% | 6,2% |

The humidity ratio affects the evaporation rate. A graph of the influence of the humidity ratio on the drying time to evaporate the entire mass of ice can be seen in Figure 8 to Figure 10. The simulation results show that to evaporate $2x10^{-2}$ kg of ice it takes a minimum of 11.78 hours, this occurs at pressure $P_\infty$=0.5kPa, temperature $T_\infty$=20°C and humidity ratio of 300. When the humidity ratio is reduced to 0.001, the drying duration is reduced to 10.75 hours. The shortest drying duration occurred at pressure $P_\infty$=0.3kPa, temperature $T_\infty$=30°C and humidity ratio 0.001 for 6.8 hours.

The impact of changing the humidity ratio in the drying room is compared with the evaporation rate in the experiment as shown in Table 2. The experimental evaporation rate is 0.08 ($gr.m^{-2}.s^{-1}$)

while the simulated evaporation rate is 0.0747 (gr.m$^{-2}$.s$^{-1}$). The evaporation rate is calculated at pressure P∞=0.4kPa, temperature T∞=30°C and a humidity ratio of 300. When the humidity ratio is reduced to 0.001, the evaporation rate becomes 0.0794 (gr.m$^{-2}$.s$^{-1}$), an increase of 6.3%. The same conditions are expected to occur in the experiment when drying is carried out under the same operating conditions as the simulation was carried out.

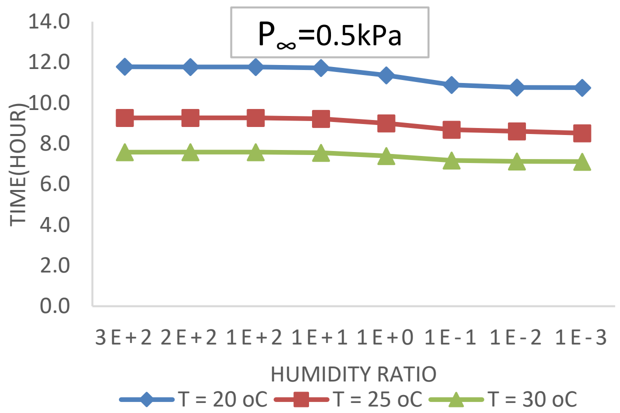


**Fig. 8.** Air humidity ratio vs drying duration at pressure P∞=0.5kPa

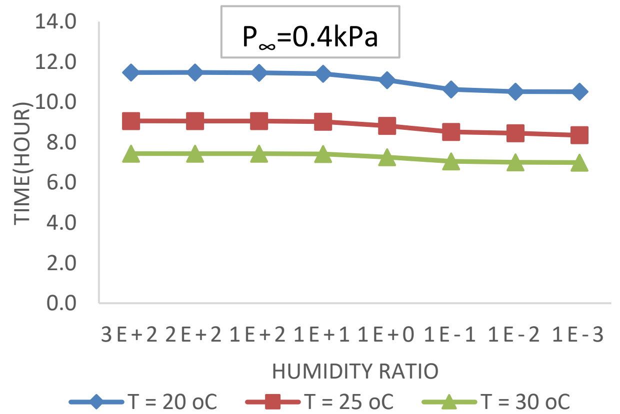


**Fig. 9.** Air humidity ratio vs drying duration at pressure P∞=0.4kPa

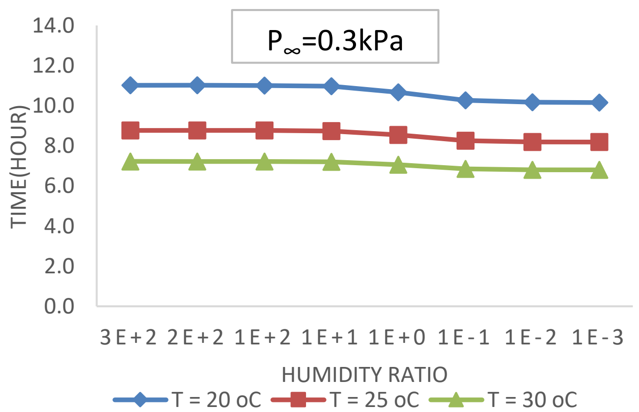


**Fig. 10.** Air humidity ratio vs drying duration at pressure P∞=0.3kPa

Simulations confirm that under the same air humidity conditions, the evaporation rate of the vacuum freeze drying system is affected by the operating pressure and temperature in the drying chamber. If the pressure is reduced, the evaporation rate increases. The evaporation rate also increases if the temperature in the drying chamber is increased. For example, reducing the drying chamber pressure from 0.5kPa to 0.4kPa, at a constant drying chamber temperature of 20$^o$C, will increase the evaporation rate by 2.7% at a humidity ratio of 300. Meanwhile, increasing the drying chamber temperature from 20$^o$C to 25$^o$C at a pressure of 0 .5kPa will increase the evaporation rate by 27.1% at a humidity ratio of 300.

## 4. Conclusions

To increase the evaporation rate of the vacuum freeze dryer, air is introduced to reduce the humidity ratio of the drying chamber. The simulation results show that decreasing the humidity ratio in the drying chamber will increase the evaporation rate. The increase in evaporation rate ranges from 6.2% -9.5% depending on the humidity ratio of the drying chamber, pressure and temperature when the vacuum freeze drying machine is operated. An increase in the evaporation rate of 6.2% was obtained at $P_\infty$=0.3kPa, $T_\infty$=30$^o$C and a humidity ratio of 0.001. The maximum evaporation rate of 9.5% occurs when operated at pressure $P_\infty$=0.5kPa, temperature $T_\infty$=20$^o$C and humidity ratio 0.001. Increasing the evaporation rate by 6.2% will shorten the drying time by 0.42 hours. Meanwhile, increasing the evaporation rate by 9.5% will shorten the drying time by 1.03 hours. Increased evaporation rates and shorter drying times have the potential to reduce the energy consumption of vacuum freeze drying. In consequently, the results of the simulation show that the effect of reducing air humidity also has the potential to increase the operating efficiency of the vacuum freeze dryer. Furthermore, to prove this, an experiment needs to be carried out to obtain the actual magnitude of the change in evaporation rate that occurs when the humidity ratio in the drying chamber is varied.

In this simulation, the heater is above the material so it is assumed that heat transfer occurs by radiation and diffusion. The heat received by ice as a dry material if heat transfer occurs by diffusion is relatively small. Design alternatives that allow higher heat transfer coefficients can be considered to improve vacuum freeze drying systems.

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