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Using of exhaust gas heat from a condenser to increase the vacuum freeze-drying rate

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ABSTRACT

Vacuum freeze dryer is able to remove some of the moisture content of the material. However, the drying rate is very slow because the sublimation process must propagate through the layers of material. Therefore, the aim of this study is to examine the use of exhaust gas heat from a condenser to increase the vacuum freeze-drying rate. Drying was carried out at freezing temperature of −55 °C and the drying time was 7 h. The research parameters observed were water losses, water content, texture, color, weight losses, and total soluble solids. The results showed that the exhaust gas heat in a vacuum freeze dryer can be used to optimize the water sublimation process. As a result, the drying process will be faster. The exhaust gas heat has a significantly effect on changes in water losses, moisture content, texture, weight losses, and total soluble solids, but does not significantly effect on the sample color. The drying system in the exhaust gas heat (EGH) method was more efficient because the final moisture content of the sample was 9.45% lower than the vacuum freeze dryer (VFD) method, which was 15.95%.

1. Introduction

Vacuum freeze drying has been proven to be an effective drying method to produce freeze-dried products with the best quality compared to other drying methods [1–3]. The advantages of freeze-drying products are the texture structure that does not shrink [4], thus allowing very fast rehydration, high flavor retention because drying takes place at low temperatures, and the reconstitution of living cells in freeze-dried products remains high [5,6]. It has been used to obtain high quality freeze-dried products [7,8].

Even though vacuum freeze drying is the best drying process [9], it has several drawbacks, including a slow drying rate because the heat used for the sublimation process must be propagated through the layer of material [10]. The porous structure of the material has a very low conductivity that the transfer of heat to the surface of the material is also very low [11,12].

Heating analysis to increase the efficiency of heat propagation to the material layer has been carried out by Reyes et al. [13], however, the use of exhaust gas heat a condenser has not been disclosed. Freeze drying using additional heating has been reported by Xu et al. [14] that the high drying temperature greatly affects the sublimation rate.

Freeze-drying kinetics are influenced by the freezing rate and heat and mass transfer rates during the sublimation process [15,16]. The freezing process is one of the stages of freeze drying which requires high energy [17,18]. Therefore, the search for a more appropriate method is one of the most needed efforts by the food processing industry today [19,20].

Research on the process of utilizing heat sources from the condenser has not been widely reported. Therefore, this research is very important to explain the efficiency of exhaust gas heat utilization that drying can take place quickly and produce hygienic frozen products. Therefore, the aim of this study was to examine the use of exhaust gas heat from a condenser to increase the vacuum freeze-drying rate.

2. Materials and methods

2.1. Materials

The materials used in the study were fresh cut-jackfruit with a harvest age of 3 months. This fruit was obtained from farmers' gardens in Mataram, West Nusa Tenggara Province, Indonesia. The jackfruit was split, then the skin was separated and the seeds are removed. Another

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material were refrigerant R134A was obtained from a minimarket in Mataram City, West Nusa Tenggara, Indonesia.

2.2. Tools

The main equipment used were a vacuum freeze dryer (VFD) and a modified vacuum freeze dryer with the use of exhaust gas heat (EGH) (Fig. 1). The other equipment were a digital refractometer type DR301-95, moisture tester, color meter TES135 series, and texture analyzer Brookfield model CT3.

2.3. Drying procedure

The drying process was carried out with a freeze temperature of −55 °C and the drying time was 7 h. Each treatment used a sample of 0.5 kg of fresh-cut jackfruit. The experiment was repeated 3 times.

2.4. Water losses analysis

Water losses (WL) describes the amount of water evaporated from the sample during the vacuum freeze drying process which can be calculated by equation (1) [21]:

$$WL = m_0 - m_t \frac{W_t}{W_0} \tag{1}$$

where, m_0 = sample moisture content at time 0 (%), m_t = sample moisture content at time t (%), W_0 = sample weight at time-0 (grams), W_t = sample weight at the time-t (gram).

2.5. Moisture content analysis

The moisture content of fresh-cut jackfruit was determined following the standard method of analysis [3]. Approximately 5 g of the sample was weighed into a can. The sample was heated to 50 + 1 °C until constant weight was reached, transferred to a desiccator, and was weighed soon after it had reached environment temperature. The moisture content was calculate by Equation (2) [5]:

$$M_c = \frac{a - b}{a} \times 100\% \tag{2}$$

where, M_c = moisture content (%), a = initial of moisture content (%), b = final of moisture content (%).

2.6. Texture analysis

The measurement of the sample texture of the result from the vacuum freeze dryer was carried out using a texture analyzer with a compression method. The loading was carried out with a compression speed of 4 mm/s. The result can be calculated using equation (3) [4]:

$$T = \frac{P}{A} \tag{3}$$

where, T = texture (N/mm^2), P = compressive force (N), and A = cross-sectional area (mm^2).

2.7. Color analysis

The color of fresh-cut jackfruit was measurement using the Chroma meter type AT-13-04 Konica Minolta type CR-400. Color measurement using the Hunter L* a* b* color value system [22].

For lightness were defined as:

$$L* = L*_d - L*_f \tag{4}$$

For redness were defined as:

$$a* = a*_d - a*_f \tag{5}$$

For yellowness were defined as:

$$b* = b*_d - b*_f \tag{6}$$

where, L* = lightness (L* = 0 for black, L* = 100 for white), a* = green-red (a*<0 for green, a*>0 for red), b* = blue-yellow (b*<0 for blue, b*>0 for yellow), subscript 'f' refers to fresh samples and 'd' to the values of dried materials.

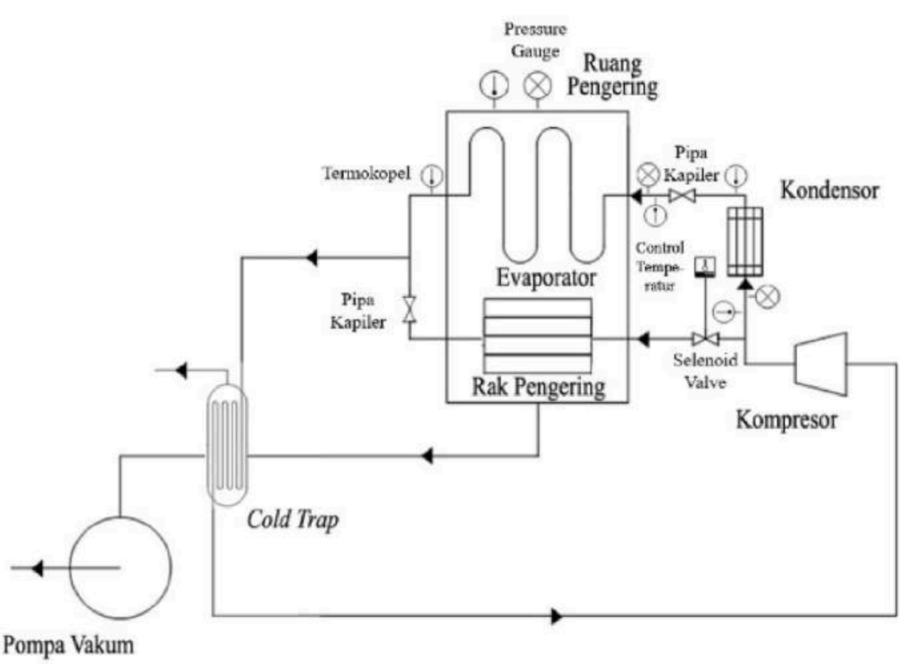

Fig. 1. The vacuum freeze drying equipment sketch.

2.8. Weight losses analysis

The weight losses (WL) of the sample was measured before and after drying. Weight losses was calculated using the following equation (6) [23]:

$$WL = \frac{w_f - w_d}{w_f} 100\% \tag{7}$$

where, WL = weight losses (%), w_f = mass of sample before drying (grams), w_d = mass of sample after drying (gram).

2.9. Total soluble solids analysis

Total soluble solids (TSS) were measured using a digital refractometer type DR301-95. The TSS value is expressed in degrees of brix to indicate the dissolved sugar content in the sample. Measurements were made by crushing 2 g of jackfruit and then placing it on the refractometer sensor. Each treatment was repeated three times.

2.10. Data analysis

Analysis of variance (ANOVA) was used to determine the comparison of the results of the two types of dryers to the characteristics of frozen jackfruit. If the ANOVA table the F-count value is greater than F-crit, it means that there is a difference at the 5% significance level [24].

3. Results and discussions

3.1. Water losses

The data of WL in the sample during vacuum freeze-drying was shown in Fig. 2. In this figure, it can be seen that the water losses in the EGH method is higher than that of the VFD method. This is due to the exhaust gas heat from the condenser as a heating source in the EGH method which can significantly accelerate the evaporation rate of water, whereas in the VFD method the water evaporation process only occurs because of the difference in pressure inside and outside the drying chamber. In line with this, Westerterp et al. [25] also stated that the process of evaporation of the water on the material during vacuum freeze drying occurs because there are difference in pressure on the surface of the material with environmental pressure and the longer the drying process, the more water was evaporated.

Based on the results of the analysis of variance, it was known that the use of different drying methods provides different WL data. The EGH method produces a higher WL value (14.50%) than the VFD method (12.06%). This shows that the use of additional heat energy from the exhaust gas heat of the condenser has a significant effect on the WL value.

Other factors that influence water losses during drying are temperature and drying time. This result in line with the opinion of Mello et al. [26] that many factors influence to the water losses in the drying process, including drying temperature, air humidity, and air flow velocity. The greater the temperature difference between the heating medium and the drying material, the faster the heat transfer into the material, the rate faster of water losses from the dried material. The air humidity was inversely related to drying time. The higher the humidity, the longer the drying process will be. Meanwhile, the air flow rate was directly proportional to the drying time. The higher the air flow rate, the faster the drying process.

3.2. Moisture content

Fig. 2 presents the curves of the reduction in moisture content of the two different drying methods used in this study. To reach the moisture content of the frozen product, these two methods have different times. The final moisture content in the EGH method is much lower than the VFD method. This indicates that the use of exhaust gas heat from a condenser as a heating source can significantly accelerate the rate of decreasing moisture content. These data indicate that one of the important characteristics of vacuum freeze-dryers was the efficient use of energy to reduce moisture content compared to other drying methods.

In Fig. 3 it can also be seen that the final water content of the sample in the VFD method is higher, namely 15.95% than the final water content in the EGH method which is only 9.45%. This happens because there are additional heat energy from the condenser that the water sublimation process in the EGH method takes place faster than the VFD method. The same study have been described by Zhang et al. [27] that by utilizing secondary drying in a freeze dryer can optimize the sublimation process of water that the drying process takes place very quickly.

The moisture content is a very important characteristic of freeze-dried food products because the moisture content can affect the appearance, texture, and taste of the product [28]. The moisture content also affects the freshness and shelf life of the product. The high water content can make bacteria, molds, and yeast easy to reproduce there will be changes in foodstuffs [29]. The vacuum freeze drying process can remove moisture content from the sample. The moisture content produced from the vacuum freeze dryer in this study has met the quality requirements of freeze-dried fruit products a maximum of 15% [30].

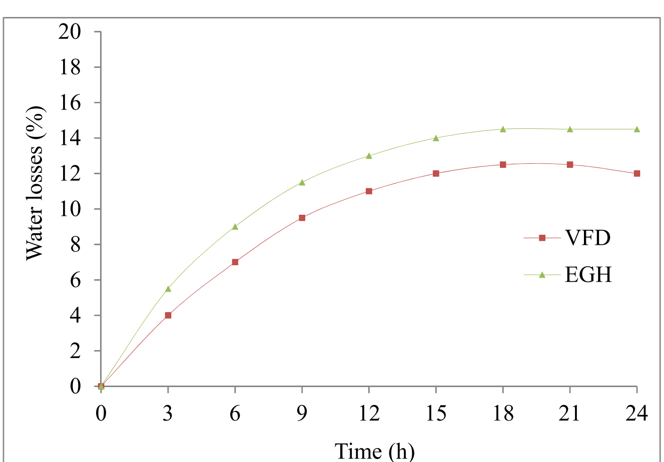

Fig. 2. The water loss profile of fresh cut jackfruit during vacuum-freeze drying.

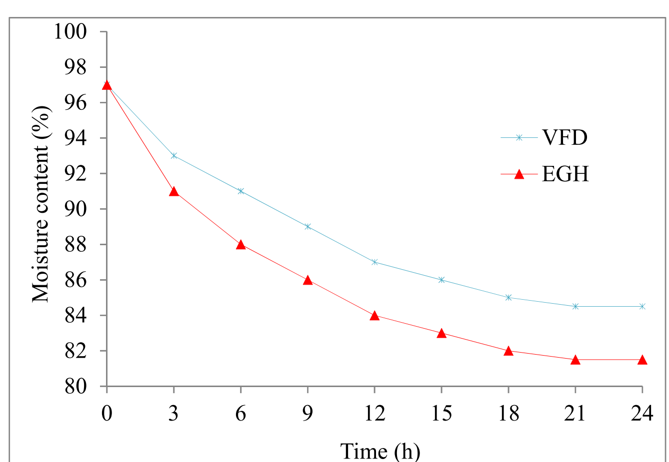

Fig. 3. Curve of the rate of reduction in moisture content during vacuum freeze drying.

3.3. Texture

Vacuum-freeze drying is a drying method that causes sublimation of the water vapor in the material that the structure of the material expands. The results of the texture test using the compression method showed that the samples dried by the EGH method produced a crispier texture than the VFD method (Fig. 4). It shows that the water vapor sublimation process that occurs in the EGH method causes the sample texture to be crunchy and easy to break. The factors causing the crisp texture of the sample are due to the low pressure in the drying chamber and the relatively high internal vapor pressure during the vacuum freeze drying process.

In the EGH method, the sample structure changes due to the effect of additional heating energy from the exhaust gas heat of the condenser, after which the sample ice crystals turn into gas and then evaporate. Compared to the EGH method, the sublimation process in the VFD method was a heating process with low temperatures that the sample ice crystals evaporate more slowly. That's what causes sample shrinkage. The results of the same paper have been described by Liu et al. [31] that the shocking effect of the freezing process then heated to a higher temperature is the change of ice to vapor that the texture of the sample is crispier and more porous.

The changing process of the sample texture has occurred shortly after drying, then evaporation of the water occurs and air bubbles form. Previous studies have reported by Zielinska et al. [32] that the vacuum freeze drying process can cause water evaporation, then the product expands and forms air cavities. The high and low texture value of a material according to Bozkir et al. [33] depending on the characteristics of the material, such as thickness, homogenization, and composition.

The samples dried using the EGH method caused the water to come out of the fruit cell walls faster than the VFD method. This difference in the evaporation of high water content causes the texture structure of the sample to become more brittle and expand. This result in line with the study reported by Sobaszek et al. [34] that the vacuum freeze drying process resulted in water evaporation that the texture of the fruit would become hard.

In general, the texture of the jackfruit from vacuum freeze drying depends on the cell wall tissue. The texture change occurs in the vacuum freeze drying process because the sample has lost some of its moisture content. This view is supported by Pei et al. [35] who writes that the texture structure of the fruit depends on the cell wall tissue that in the vacuum freeze dryer there is a hardening on the surface of the material accompanied by changes in the size of the product texture.

3.4. Color

Changes in the color of fresh cut jackfruit before and after vacuum freeze drying can be seen from the data in Fig. 5. The graph of the color change of the fresh-cut jackfruit during vacuum freeze drying can be seen from the data in Table 1. Based on the Table 1 we can see that the type of dryer has no significant effect on lightness (L*), redness (a*), and yellowness (b*).

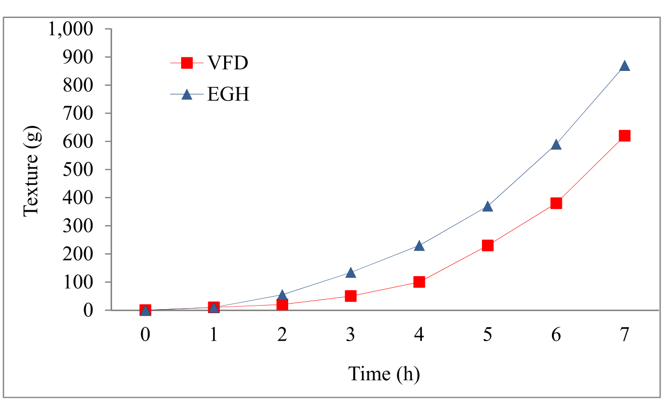

Fig. 4. The texture profile of cut jackfruit during vacuum freeze dryer.

Based the data in Table 1, it is apparent that the change in the lightness color of the freeze-dried jackfruit tended to decrease during the drying process. The sample color changes from shiny yellow become opaque yellow in both types of drying methods. The lightness value in the VFD method was lower (57.12) than the EGH method (57.23) although it was not significantly different. The lightness color shows a decreasing trend during drying in both methods. This is caused by a biological reaction, resulting in an enzymatic process that causes the color of the sample to decrease in brightness. This result is in line with Keutgen and Pawelzik [36] have reported that low temperatures in the vacuum freeze drying process have not been able to activate the polyphenolic enzymes in the sample and the enzymes can still be active at temperatures as low as −73 °C, although with very low reaction rates.

The redness and yellowness color intensity did not change during the vacuum freeze drying process. The sample color before and after drying did not change significantly. Several investigators have also reported that the use of a vacuum freeze dryer did not result in color changes in the samples [37]. Sample color change usually occurs at high drying temperatures [38]. The same analogy has been explained by Falah et al. [39] that a significant change in sample color during high temperature drying can occur, but the change is not significant at cold temperature.

3.5. Weight losses (WL)

The results of the WL calculation of fresh-cut jackfruit during vacuum freeze drying are shown in Table 2. At the beginning of the drying process, the WL occurs very rapidly until 6th hour, then slowly until the end of drying. After reaching the saturated condition, the sample WL no longer changes. Table 2 also shows that the WL is higher in the EGH method compared to the VFD method.

From the table above we can see that the samples dried in the EGH method had a final WL of 37.32 g, while those dried in the VFD method had a final WL of 31.82 g. These data indicate that the use of exhaust gas heat form a condenser in the EGH method has a significant effect on reducing WL of fresh-cut jackfruit.

The duration of the drying process also has a significant effect on the WL of fresh-cut jackfruit. The long drying process can trigger an increase in the percentage of WL in the sample. The same it cases has been reported by Singh and Khan [40] that WL is generally affected by the evaporation of moisture during drying due to the breakdown of organic compounds into inorganic compounds, namely compounds are oxidized to CO_2 and absorb O_2, then reduced to H_2O.

3.6. Total soluble solids (TSS)

The results of measuring the TSS value of fresh-cut jackfruit from vacuum freeze drying are shown in Table 3.

The data in Table 3 shows that during drying, there was an increase in the TSS value in the sample due to the respiration and transpiration processes that were still ongoing even though the fruit had been harvested. The increase in TSS value is also accelerated by vacuum freeze drying. The TSS value was higher in the EGH method than the VFD method. This is thought to be due to the influence of the exhaust gas heat from a condenser which triggers the carbohydrate content to become sugar levels. A similar thing has been reported by Rydzak et al. [41] that immature fruit stores a lot of carbohydrates in the form of starch and during the process towards maturity the content will turn into sugar. According to Yusufe et al. [42], fruits at advanced maturity levels have the highest TSS content, due to hydrolysis of starch to sugar.

Total soluble solids are the combination of all inorganic and organic substances present in food. Based on the data in Table 3, it can be seen that at the beginning of drying the TSS value is still low. With the length of drying time, the TSS value tended to be higher in the two methods,

Fig. 5. The color of fresh cut jackfruit before (A) and after (B) vacuum freeze-drying. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Value of lightness (L*), redness (a*), and yellowness (b*) of the fresh-cut jackfruit during vacuum freeze drying.

Drying methods	Color		
	L*	a*	b*
Control	58.62 ± 0.55^{a}	5.75 ± 0.78^{a}	67.23 ± 0.14^{a}
EGH	57.23 ± 0.21^{a}	5.92 ± 0.14^{a}	68.37 ± 0.42^{a}
VFD	57.12 ± 0.34^{a}	5.42 ± 0.56^{a}	69.63 ± 0.12^{a}

Note: numbers followed by different letter notations in the same column show significant differences at the 0.05 significance level ($P < 0.05$).

Table 2
Average of WL value of fresh cut jackfruit from vacuum freeze drying.

Drying time (hour)	Weight losses (g)	
	EGH	VFD
1	0.00^{a}	0.00^{a}
2	7.29^{b}	6.53^{b}
3	10.12^{c}	9.41^{c}
4	15.13^{d}	13.75^{d}
5	23.14^{e}	18.65^{e}
6	35.67^{f}	29.42^{f}
7	37.32^{f}	31.82^{g}

Note: numbers followed by different letter notations in the same column show significant differences at the 0.05 significance level ($P < 0.05$).

Table 3
Average TSS value of fresh-cut jackfruit from vacuum freeze drying.

Drying time (hour)	Total soluble solids (°Brix)	
	EGH	VFD
1	8.04^{a}	8.04^{a}
2	10.19^{b}	09.83^{b}
3	11.23^{c}	10.31^{c}
4	12.33^{d}	11.67^{d}
5	14.46^{e}	13.55^{e}
6	15.67^{f}	14.92^{f}
7	17.32^{g}	16.22^{g}

Note: numbers followed by different letter notations in the same column show significant differences at the 0.05 significance level ($P < 0.05$).

but had different values. The difference in TSS value is thought to be due to the difference in temperature used between the EGH and VFD methods. The driving force of the exhaust gas heat from condenser in the EGH method causes some of the water to evaporate faster. In addition, the faster sublimation process can open larger pores of the sample surface. When the pores of the sample surface as the permeability membrane opens wider, the amount of water evaporating from the material will also increase [43].

4. Conclusions

The exhaust gas heat from a condenser can be used to accelerate the sublimation process during the vacuum-freeze drying process, the drying process can take place faster. The results of this study have proven that the use of exhaust gas heat from a condenser has a significant effect on the parameters of water losses, moisture content, texture, weight losses, and total dissolved solids, but it does not affect the sample color.

This new finding provides a better scientific understanding of the vacuum freeze-drying process. Therefore, the results of this study are recommended to be applied to vacuum freeze dryers for drying food products.

Credit author statement

Ansar: conceived and designed the experiments; analyzed and interpreted the data; wrote the paper. Sukmawaty: performed the experiments; analyzed and interpreted the data. Murad: performed the experiments; analyzed and interpreted the data. Maria Ulfa: analyzed and interpreted the data; contributed reagents, materials, analysis tools, or data. Atri Dewi Azis: analyzed and interpreted the data; contributed reagents, materials, analysis tools, or data. Editing.

Declaration of competing interest

The authors 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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