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# Optimization of Drying Temperature Distribution using CFD and Experimental Methods for Cape Gooseberry Drying

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***Abstract –*** *This study aims to enhance the drying quality of cape gooseberries by addressing the non-uniform temperature distribution typically observed in traditional drying processes. Computational Fluid Dynamics (CFD) was employed to redesign the drying chamber by integrating a centrally positioned baffle duct to improve airflow distribution. Various hot air inlet velocities were simulated to optimize temperature uniformity. The CFD results indicated that an optimal inlet velocity of 3–5 m/s maintaining a consistent drying temperature between 59–60°C. This condition was applied in the actual construction of the drying chamber. Validation experiments showed that CFD-predicted temperatures deviated by less than 10% from measured values across all monitoring points. This confirms the reliability of the CFD. Following the validation, further experiments were conducted to evaluate drying quality of cape gooseberries. Additional factors such as pretreatment duration, ripeness, and drying method were investigated to determine their influence on product quality. Pretreatment duration and ripeness significantly affected drying efficiency and physiochemical properties. A 3-day pretreatment resulted in lower post-drying moisture content (MC) compared to a 5-day treatment, while less ripe fruits (Grade C) demonstrated suboptimal drying quality. Moreover, drying method and ventilation control also played a critical role. The first method, fully opening vents during the initial 6 hours, produced lower average MC and water activity (Aw) than the second method, partially opened the vents.*

***Keywords*** – Cape gooseberry drying, CFD comparison, pretreatment and ventilation variable, temperature distribution.

## 1. INTRODUCTION

Fruit drying is one of the most common preservation processes used to extend the shelf life of fruits for longer-term consumption. In all fruit drying processes, quality control of the final product (physiochemical, sensory, nutritional, and microbiological attributes) is essential to ensure high-quality food for consumers. Several factors affect the quality of dried fruit products, such as the type of drying method, drying techniques [1], [2], air velocity and drying temperature [3]-[5], and pre-treatment processes before drying [6]-[9]. This study focuses on conventional hot air-drying method due to simplicity, cost-effectiveness, ease of maintenance and a long operational lifespan [1], [9]-[11]. The research emphasizes drying of cape gooseberry fruits cultivated under Thailand's Royal Project, promotes local agriculturist for supporting household income. The cape gooseberry product has also a viable market, making it a suitable candidate for value-added processing through drying.

This study investigates key factors that influence the quality of dried cape gooseberries, particularly the effect of air velocity and temperature distribution in the drying chamber, and the impact of pre-treatment processes on drying performance and product quality. Literature reviews have shown these two factors to be critical. For instance, a study using heat pump as heat source for drying of bananas and guavas. This indicated that controlling initial temperature and heating step as optimal significantly improved color retention and reduced drying time [3]. Another study on garlic drying found that raw material properties such as density, porosity, glass transition temperature and drying temperature affected the physical feature of the dried product [4]. This has also suggested that increasing air velocity and drying temperature can improve moisture evaporation rate. However, excessive air velocities diminish the influence of temperature [5].

Pre-treatment is a vital preparation step before drying, as it affects drying time and post-drying physical properties. Vásquez-Parra *et al.,* [6] applied pre-treatment to cape gooseberries using sunflower oil ($K_2CO_3$ at 28°C) and NaOH/olive oil at 96°C, followed by blanching to remove the fruit's waxy surface. The pre-treated samples showed better moisture diffusion of $7.37 \times 10^{-11}$ m²/s from $6.61 \times 10^{-11}$ m²/s (non-pretreatment). Similarly, Junqueira *et al.,* [9] applied pretreatment by immersing fruits in liquid nitrogen (-196°C for 10 s), freezing at -18 ± 2°C, thawing at 25°C for 2 hours, and immersing in 2% ethyl oleate and 2.5% $Na_2CO_3$ solutions at 40°C for 3 minutes. These methods

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resulted in shorter drying times, better texture, higher retention of ascorbic acid, and reduced shrinkage. Insights from the aforementioned studies are applied in this research by focusing on pre-treatment processes and drying parameters such as air velocity and temperature, which serve as the independent variables of the study.

Furthermore, to ensure uniform temperature distribution during drying, this work employs Computational Fluid Dynamics (CFD) to assist in the drying chamber design as widely applied in many literatures [10]-[17]. Dionissios [12] applied CFD in the design of tray dryers to optimize drying space, energy consumption and improve product quality. Similarly, Amanlou [13] developed a fruit cabinet dryer based on optimized CFD designs, achieving improved uniformity of air velocity and temperature distribution. Escobedo [15] applied CFD to enhance temperature distribution in chili dryers, while Natalia [16] used CFD to investigate the causes of non-uniformity in tray dryers, explaining the high moisture content in dead zones. Design strategies such as the addition of baffle ducts [11], [14] or inlet flow guides [10] have also been shown to improve airflow and temperature distribution, as reported in prior studies [10], [11], [14]

## 2. RESEARCH METHODOLOGY

### 2.1 Design of the Drying Chamber

The drying chamber was designed to accommodate 100 kg of cape gooseberry. The chamber dimensions were 260 x 480 x 170 (width x length x height) cm$^3$. The chamber walls were insulated with 5.5 cm thick rock wool. Inside the chamber, two sets of 13-tier racks were installed. Each rack unit had individual dimensions of 110 x 100 x 125 (width x length x height) cm$^3$. The Cape gooseberries were arranged on each tray with evenly spaced distribution, ensuring that no fruits overlapped. The design of the drying chamber is shown in Figure 1, includes a hot air inlet located centrally at the top of the chamber. The hot air is forced to flow through a baffle duct equipped with fins angled at 50° relative to the horizontal. This baffle duct makes evenly distribute airflow throughout the drying chamber. The four hot air outlets are located at near the four corners of the top wall of the drying chamber.

### 2.2 CFD-Assisted Design

Boundary conditions for CFD simulation are detailed as following.

- The air inlet temperature is 60°C.
- The hot air inlet area is 15 x 15 cm².
- There are 4 hot air outlets, each having area of 15 x 15 cm²
- hot air outlet pressure is 1 atm.
- The inlet air velocity was varied at 2.5, 3.0, 4.0, and 5.0 m/s.

To ensure the accuracy of the CFD simulation results, a mesh-independent method was operated. The turbulence model used was the standard k-ε model, with a turbulence intensity of 3%. The convergence criteria for the numerical solution were set to 200 iterations and residual values not exceeding 0.0001. The simulation results were validated against experimental data by comparing temperatures at 9 points within the drying chamber (Figure 1). Measurement points of 1-3, 4-6, and 7-9 were positioned at the top, middle, and bottom tray levels, respectively. Positions of 1, 4, and 7 were located at the tray edge near the baffle duct. Positions of 2, 5, and 8 were at the center of the tray and Positions of 3, 6, and 9 were at the tray edge near the side wall of the drying chamber. Temperature data were measured using K-type thermocouples and recorded with a data logger (Omega model DP9800). Each experiment was repeated 3 times.

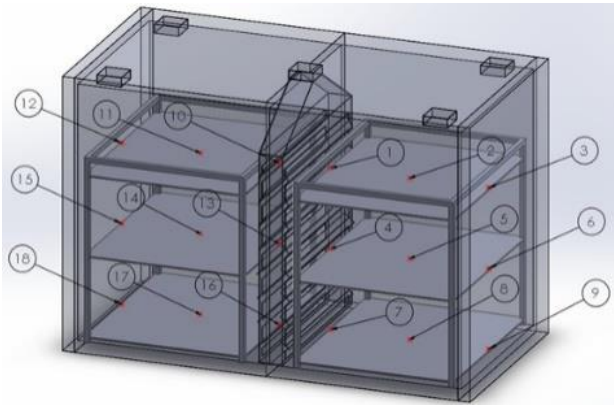



**Fig. 1**. **The measured temperature positions**.

### 2.3 Raw Materials Preparation for Drying Processes

In this research, there are 2 initial independent variables to determine the quality of dried cape gooseberry that meets the Thai Industrial Standard (TIS 919-2532 for Dried Fruit). The fresh Cape gooseberries were prepared into two sample groups, prepared with and without pretreatment processes as detailed in Table 1.

**Table 1. The detail of sample groups of prepared cape gooseberries for drying processes.**

| MC (% wb.) | Sample groups | |
|---|---|---|
| | Non-pretreatment | pretreatment |
| Fresh cape gooseberry | 82.10 ± 0.23 | 83.25 ± 1.68 |

Each sample group of cape gooseberry was further classified by ripening stages into three grades: Grade A, Grade B, and Grade C. The classification was based on specific properties including MC, colour, and acidity/basicity. The detailed values of these parameters, along with the measurement instruments used, are presented in Table 2. The pre-treatment processes for Cape gooseberry involved thoroughly washing the Cape gooseberries with clean water, followed by boiling them in hot water for 5 minutes. After boiling, the fruits were soaked in a solution containing 0.5% citric acid and 1,000 ppm potassium metabisulfite (KMS) for 30 minutes.

### *2.4 Drying Processes*

There are two drying methods in this research.
Drying Method 1: ventilation every 3 hr.
Hours 0–3: Drying temperature was set at 50°C (full ventilation of hot moist air, 100%).
Hours 3–6: Drying temperature was set at 55°C (full ventilation of hot moist air, 100%).
Hours 6–12: Drying temperature reduced to 50°C (haft ventilation of hot moist air, 50%).
After 12 hours: Drying continues at 50°C (25% ventilation of hot moist air).
Drying Method 2: ventilation every 6 hours
Hours 0–6: Drying temperature was set at 50°C (haft ventilation of hot moist air, 50%).
Hours 6–12: Drying temperature was set at 55°C (full ventilation of hot moist air, 100%).
Hours 12–24: Drying temperature was set at 50°C (haft ventilation of hot moist air, 50%).
After 24 hours: Drying continues at 50°C (25% ventilation of hot moist air).

The dried products were first left at room temperature, then packed into zip-lock bags and sealed tightly to prevent moisture transfer. The sealed samples were then refrigerated at approximately 4°C until further analysis of their drying properties. The brief diagram for cape gooseberry drying processes with various initial condition presents in Figure 2**.**

**Table 2. classification of raw material, cape gooseberry grade.**

| Physiochemical properties | Measurement and method | Grade A | Grade B | Grade C |
|---|---|---|---|---|
| Fresh cape gooseberry MC (% wb.) | AOAC (2019) Method | 82.63+0.85 | 82.83+0.58 | 82.4+0.1 |
| Color L* | CIELab spectrophotometer | $50.91 \pm 1.65^{a}$ | $45.63 \pm 1.48^{b}$ | $45.32 \pm 2.38^{b}$ |
| a* | | $17.11 \pm 0.85^{a}$ | $14.26 \pm 1.78^{b}$ | $9.26 \pm 0.47^{c}$ |
| b* | | $39.05 \pm 1.87^{a}$ | $36.08 \pm 1.80^{ab}$ | $34.09 \pm 2.03^{b}$ |
| Total Soluble Solid, TSS (°Brix) | Hand refractometer | $12.16 \pm 0.15^{a}$ | $11.40 \pm 0.26^{b}$ | $10.60 \pm 0.51^{c}$ |
| Acidity/ basicity (pH) | pH Meter, YY-1030, Yieryi | $3.76 \pm 0.57^{a}$ | $3.70 \pm 0.00^{ab}$ | $3.66 \pm 0.5^{ab}$ |
| Physical appearance | |  |  |  |

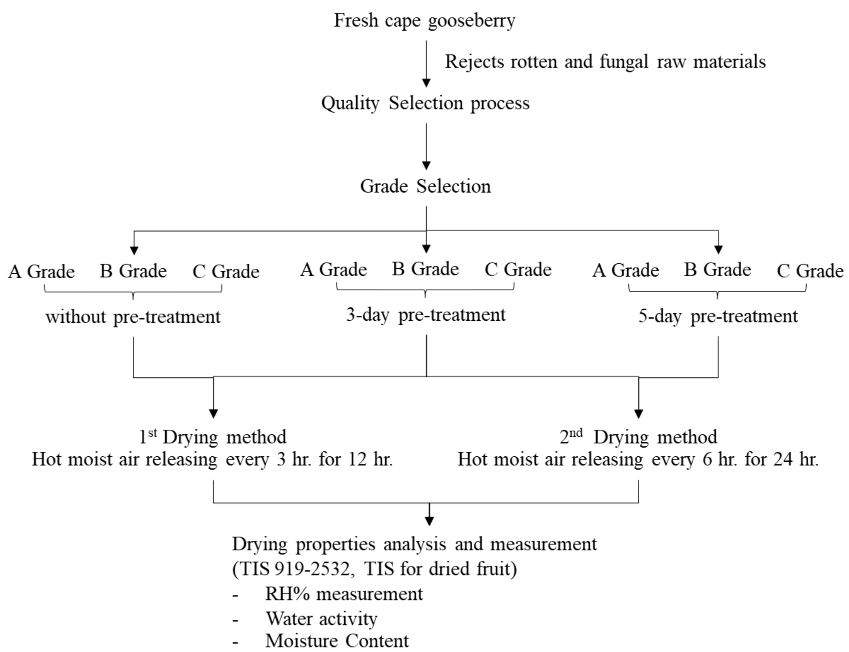



**Fig. 2. The brief diagram for cape gooseberry drying processes for this research.**

## 3. RESULTS

### *3.1 Application of CFD in Drying Chamber Design*

In Figure 3, the inlet velocity of the hot air significantly affects the temperature distribution behavior within the drying chamber. Under all conditions of varied inlet air velocities, the highest temperature distribution consistently occurs in the region of baffle duct, where the hot air firstly enters the chamber. From there, the heat is dispersed through the fins to each tray containing the raw materials. However, the specific distribution pattern varies depending on the hot air velocity. At a hot air inlet velocity of 2.5 m/s (Figure 3a), the average temperature inside the chamber was approximately 57.5°C. Temperatures close to 60°C were observed on racks near the baffle duct, specifically 1st, 5th, 7th, 8th, 11th, and 12th layer tray. The 11th layer tray showed a particularly uniform temperature distribution. Additionally, the highest temperatures were also observed on the wall opposite the baffle duct, at the 7th to 11th layer trays. Conversely, the lowest temperatures (~56.5°C) were observed at the top of 13th layer tray toward the upper chamber wall, and at the 2nd to 5th layer tray.

At a hot air inlet velocity of 3.0 m/s, Figure 3b, the average temperature was approximately 58°C. Temperatures close to 60°C were found near the baffle duct on layer trays No.1, 4, 5, 6, 9, 10, and 11. The 9th and 11th layer trays showed uniform temperature distribution throughout, whereas layer tray No.1, 4, 5, 6, and 10 had the temperature cost to temperatures 60°C only in the central area. The temperature distribution on the wall opposite the baffle duct was similar to that observed at 2.5 m/s. Moreover, the area from the top of 13th layer tray toward the chamber's roof showed improved temperature distribution with an average of 58°C, indicating better performance than at 2.5 m/s.

At a hot air inlet velocity of 4.0 m/s, Figure 3c, the average temperature inside the chamber increased to approximately 59.2°C. Temperatures close to 60°C were observed on the tray level of 1, 2, 5, 6, 7, 10, and 11. Unlike the 2.5 and 3.0 m/s cases, the temperature distribution was uniform across all these trays. Additionally, the area from the top of 13th layer tray toward the chamber's roof presented an increased average temperature of about 58.5°C, showing further improvement.

At a hot air inlet velocity of 5.0 m/s, Figure 3d, the average chamber temperature reached approximately 59.8°C, almost observed in all racks. Except for 4th and 5th level trays, especially at the wall opposite the baffle duct, the average temperature was around 58°C.

The most suitable hot air velocity for drying appears to be in the range of 3–5 m/s, as it provides effective heat distribution without causing excessive heat accumulation. Based on numerical data, the temperatures within the drying chamber at a velocity of 5.0 m/s remained in the ideal range of 59–60°C, with variations across locations being less than 3°C, indicating optimal performance.

### *3.2 Validation of CFD Results with Experimental Data*

The temperature distribution results from experiment were compared with the CFD results. It was found that, under the actual testing conditions of an inlet air velocity of 5 m/s, a drying temperature of 60°C, and a drying time of 3 hours, the temperature distribution within the drying chamber showed strong agreement between the simulation and the experimental measurements. The drying temperature at each measured position was showed in Figure 4. The difference of actual minimum and maximum temperature was around 3°C. The average temperature at upper tray level showed the lowest temperature trend, with average temperatures of approximately 57.5°C in the simulation and 56.9°C in the actual experiment.

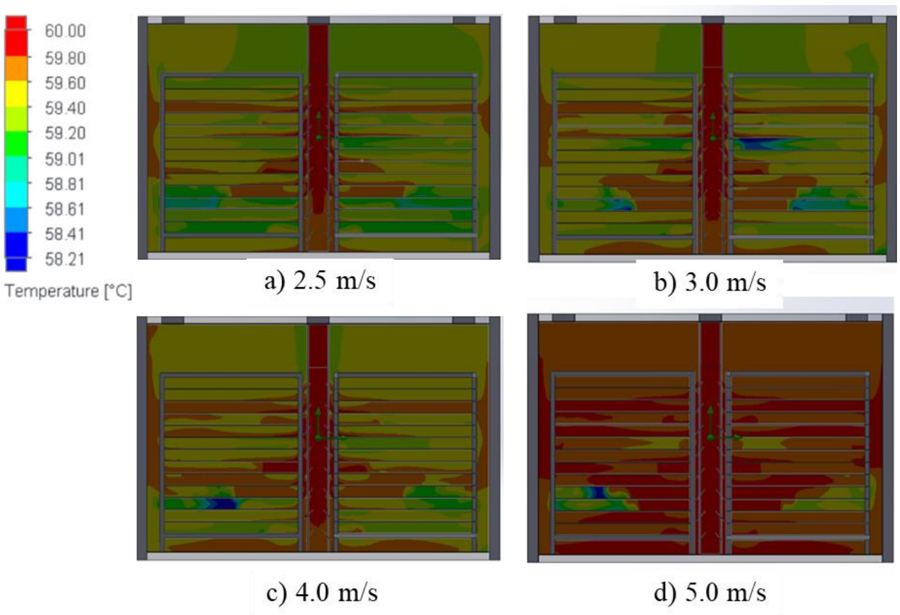
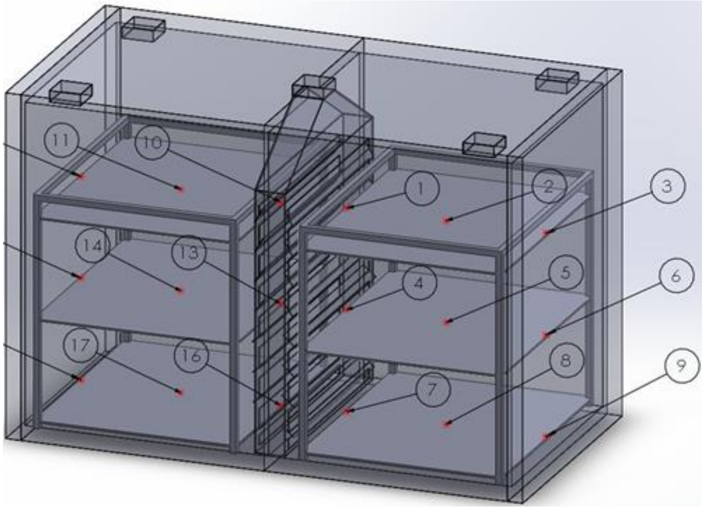



**Fig. 3. Temperature distribution in drying chamber at inlet air velocity of a) 2.5 m/s b) 3.0 m/s c) 4.0 m/s and d) 5.0 m/s.**



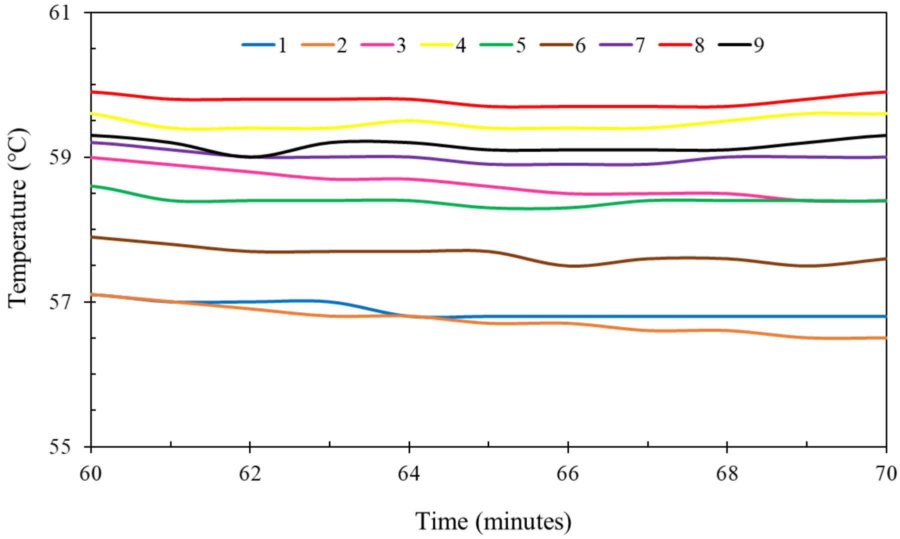




**Fig. 4. The drying temperature at each measured position varied by drying time.**

The middle tray level showed higher temperatures, with average values of 59.5°C from the simulation and 58.9°C from the experiment. Similarly, the lower tray level had average temperatures of 59.5°C (simulation) and 59.2°C (experiment).

The maximum deviation between the simulated and experimental temperature distributions was approximately 8.33%. Therefore, it can be concluded that the initial design and development of the drying chamber using computational fluid dynamics (CFD) is an effective method for predicting hot air flow behavior and temperature distribution inside the drying chamber. The preliminary CFD-based design can be realized in physical construction and delivers performance results consistent with the simulation.

### *3.3 Drying Results*

#### *3.3.1 Comparison of drying results from raw material, cape gooseberries prepare with different processes*

Dried cape gooseberries prepared from the pretreatment process exhibited a higher sweetness level, increasing to approximately 19°Brix from around 12°Brix. This increase resulted from the diffusion of concentrated solution into the fruit via osmotic pressure, which draws water out of the fruit tissue and replaces it with sugars in the solution. After the pretreatment, the MC decreased from 83.25% to 79.02%, indicating water loss through the osmotic process. After 45 hours of drying, the MC of dried cape gooseberries from without pretreatment processes was reduced to $18.42 \pm 1.65\%$, while those with pretreatment retained a higher MC at $22.72 \pm 0.93\%$. This higher MC is due to the absorption of sugar into the fruit, which helps preserve the texture, reduce shrinkage, and slow down water loss.

The sensory characteristics of dried cape gooseberries from without pretreatment processes showed noticeably dry and wrinkled skins. The internal texture was slightly soft, with a predominantly sour taste and slight sweetness. The skin color appeared dark orange. In contrast, the sensory characteristics of dried Cape gooseberries with pretreatment processes showed less skin dryness, a soft inner texture, a balanced sourness with slightly increased sweetness, and a brighter orange skin color. The pretreatment process helps reduce the wrinkle on the fruit's outer skin and assists in maintaining the cellular structure, allowing the fruit to better retain its original shape.

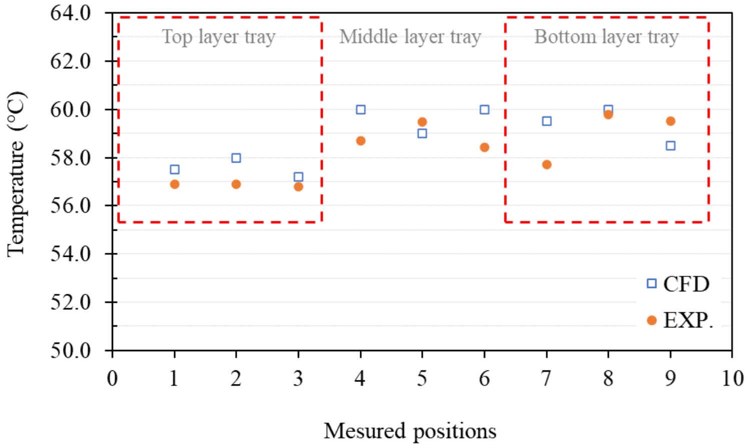



**Fig. 5. Experiment and CFD result comparison of average temperature at each measured position.**

### *3.3.2 Determination of evaporation rate*

The raw material prepares by a 3-day pretreatment process showed a relatively steady rate of weight reduction during the first 16 hours, with an evaporation rate of approximately $10 \pm 3$ g/hr. The sample initial weigh of 291–300g was gradually decreased to 80–98 g within 40 hours. In contrast, raw material prepares by a 5-day pretreatment exhibited a faster rate of weight loss during the first 20 hours. The initial weight of 295–303 g was reduced 100–115 g within 40 hours. Overall, the 3-day pretreatment samples demonstrated a higher initial evaporation rate and required less time to reduce the MC to the desired quality. However, in addition to the pretreatment parameters, factors such as raw material size and harvesting methods also affect the evaporation rate. These factors were not controlled in this study since all raw materials needed to be preserved immediately to prevent spoilage.

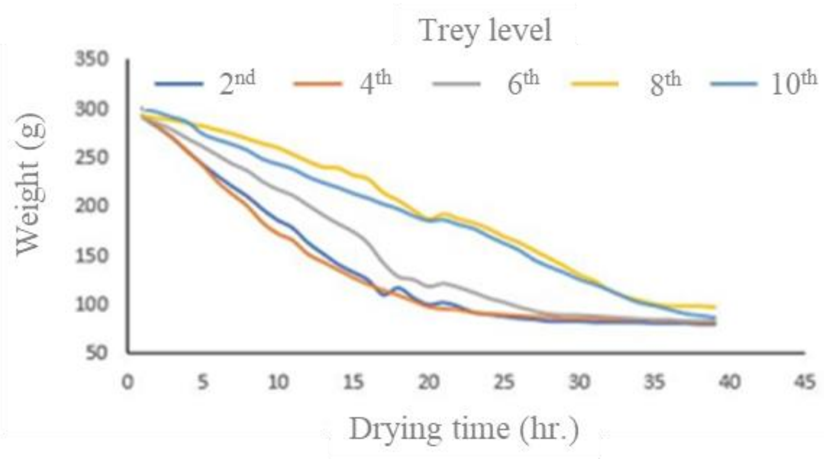



**Fig. 6. The weight losses during drying of cape gooseberry samples prepared by 3-day pretreatment.**

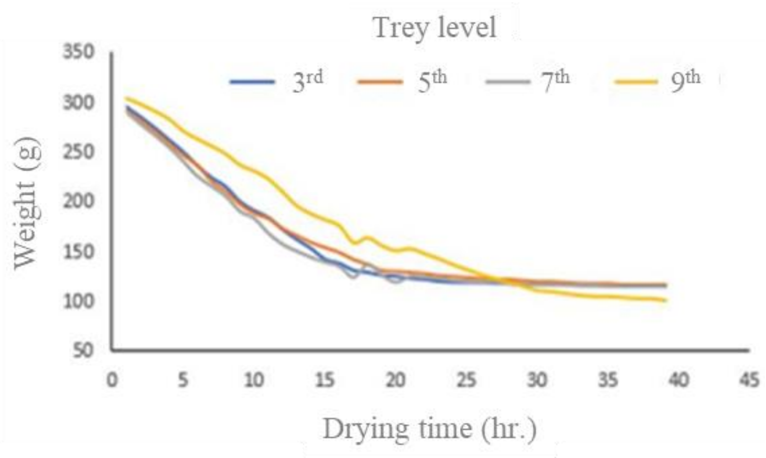



**Fig. 7. The weight losses during drying of cape gooseberry samples prepared by 5-day pretreatment.**

#### 3.3.3 Physiochemical analysis

The physiochemical properties of cape gooseberry differed depending on the pretreatment duration and ripening stages of raw material. The measured properties of dried Cape gooseberry are shown in Table 3. The differences in MC and Aw of dried products were influenced by the pretreatment duration. The dried product from samples of CF_X, CS_Y, and CF_Y showed MCs exceeding the TIS 919-2532 standard, limit of 18%. The product of CS_Y sample showed the highest MC at 22.34 ± 0.86%. Products made from Grade C raw materials, lowest ripeness, retained the highest post-drying MC. This could be due to their initially high total soluble solids (TSS), may affect difficulty of water diffusing out of the cellular structure during drying. This indicates insufficient drying efficiency for Grade C materials in removing MC. Regarding Aw, all dried samples were acceptable limit of ≤ 0.75. Their Aw values were in the ranged from 0.46 to 0.65, sufficient to inhibit microbial growth. However, sample CF_Y had the highest Aw at 0.65 ± 0.01, is close to the threshold and should be monitored carefully. When comparing the 1st and 2nd drying method, the product from 1st drying method exhibited lower average MC and Aw, indicating better drying efficiency. This improved efficiency is attributed to the 100% ventilation of hot moist air during the first 6 hours of 1st method, which contrasts with only 50% ventilation of 2nd drying method. Since at the initial drying stage, the evaporated rate occurs highly, fully releasing moisture early in the process enhances drying performance.

## 4. CONCLUSIONS

The temperature distribution obtained from the CFD simulation, and the actual test were close each other, with a maximum temperature distribution error from the experiment approximately 8.33%. The appropriate hot air inlet velocity was 3-5 m/s, and can maintain the temperature distribution in the range of 59 - 60°C. The different temperature in drying chamber in each measured point was less than 3°C. This CFD information was applied for actual construction of drying chamber for drying cape gooseberry. The CFD results exhibited the same trend and shifted from experiment less than 10%. The evaporation rate of cape gooseberry depends on the pretreatment method. The cape gooseberry samples prepared by the fast pretreatment method showed a higher evaporation rate than that by the slow pretreatment method, especially in the initial early drying time.

The physical properties of dried cape gooseberry prepared by pretreatment processes present the batter skin wrinkle, brighter color, and sensory compared to that by without pretreatment processes. The duration of pretreatment also affects drying efficiency. The pretreatment duration and ripening stages of raw material significantly affected the physiochemical properties of dried cape gooseberry. The 3-day pretreatment of raw materials showed MC after drying less than 5-day pretreatment. The samples with lowest ripening stages (Grade C) showed unacceptable drying quality.

The duration time and opening area of hot moist air ventilation influenced dried product quality. The 1st drying method (fully opening hot moist air ventilation at first 6 hr. drying) provided lower average MC and Aw of product compared to 2nd drying method (partially opening hot moist air ventilation for 50% at first 6 hr. drying.

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