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Research Article

# Experimental research on the drying process of Pisum Sativum on the Heat Pump combined with a Rotary Drum dryer

Phan Thanh Nhan[1,2,*], Nguyen Thai Son[1,2], Nguyen Minh Quoc[1,2,3]



**ABSTRACT**

A study on a combined heat pump and rotary drum drying system was conducted to evaluate the drying process on pea products. The experiment examined the effects of drying temperature, air speed, and drum speed on drying kinetics and product color deviation. In addition, the drying results between two types of dryers, a combined heat pump and rotary drum dryer, and a conventional heat pump dryer with full reflux, as well as the compatibility analysis of mathematical models, were also analyzed. The results showed that at drying temperatures of 45-60 °C, drying time was significantly reduced, and the quality of the dried product, assessed by color analysis at 45-55 °C, was comparable. By contrast, at 60 °C, although the time was reduced by nearly half compared with 45 °C, the quality changed significantly; the color deviation reached 23, compared with 13.78 when drying at 50 °C. When wind speed increases from 1.5 m/s to 3 m/s, the drying process becomes unstable in the too-weak-wind mode at 1.5 m/s, resulting in longer drying time and greater deviation. Regarding the influence of drum speed on the drying process, the experiment was conducted in the range of 4-14 rpm. The results were remarkable: the higher the speed, the faster the product dried. However, the optimal color deviation results at 8 rpm and 10 rpm were 10.69 and 13.97, respectively. Based on the experimental results, the optimal drying conditions were 50 °C drying temperature, 2.5 m/s wind speed, and 8 rpm drum speed. Another notable result is that, when comparing the drying process of the product on the two drying systems, drying on the combined heat pump and rotary drum system is 10-30% more efficient than the traditional heat pump in terms of time savings. Finally, when analyzing the mathematical model for drying peas on the rotary drum heat pump drying system, Midilli's model yields results consistent with the experimental data across all modes.

**Key words:** Heat Pump, Rotary Drum Dryer, Heat Pump combined with Rotary Drum Dryer, drying Pisum Sativum, Pisum Sativum

[1]*Department of Heat and Refrigeration, Faculty of Mechanical Engineering, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet, Dien Hong Ward, Ho Chi Minh City, Vietnam*

[2]*Vietnam National University Ho Chi Minh City, Linh Trung Ward, Ho Chi Minh City, Vietnam*

[3]*Faculty of Heat and Refrigeration Technology, Cao Thang Technical College*

**Correspondence**

**Phan Thanh Nhan**, Department of Heat and Refrigeration, Faculty of Mechanical Engineering, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet, Dien Hong Ward, Ho Chi Minh City, Vietnam

Vietnam National University Ho Chi Minh City, Linh Trung Ward, Ho Chi Minh City, Vietnam

Email: phannhan@hcmut.edu.vn

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## INTRODUCTION

Drying is a method used to preserve fresh products for long-term storage. Depending on the drying method, the product's quality after drying will vary. Drying modes, including temperature, humidity, and wind speed, affect the product's quality after drying. Temperature is the primary factor and has the most tremendous impact on the product's color and flavor. To maintain the product's color and flavor after drying, research and practical applications have shown that, at medium temperature, the product retains its optimal color and flavor with negligible nutrient loss. The heat pump drying method is the optimal choice for this temperature regime. Research by authors around the world is continuously updated and implemented for heat pump drying systems [1–3] to reduce the vapor content of the drying agent to improve the drying process dynamics, limit the drying temperature to achieve high product quality, and reduce energy consumption by shortening drying time.

According to Goh Y et al [1], a 2-stage decompressing resistive heat pump dryer system was investigated for drying shiitake mushrooms at a medium temperature of 30°C-40 °C. Babu et al. [2] dried tropical amaranth leaves in a large-scale heat pump dryer (HPD), with experimental results of SMER of 0.038542 kg/kWh on a heat pump system with a Coefficient of Performance (COP) of 1.75. Tran et al. [4] studied the optimization of the thermal system for the product and blood to produce R245fa, using a sub-cooler and absorption heat type I with a $H_2O$–LiBr pair to maximize efficiency. A comparative experimental study on drying of small Cardamom using two methods – solar drying and heat pump drying by Jayukumar et al [5]. Heat pump drying at 45 °C yielded the highest green color retention and essential oil content. In contrast, at 50 °C, the best energy efficiency was achieved, requiring approximately 12 hours to reduce the moisture content from 455.5% to 10.2%.

To increase drying efficiency, researchers worldwide have proposed combining heat pump drying systems

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with various other systems. Zhu et al.[6] Proposed a novel design that integrates infrared drying technology with a heat pump for licorice processing, aiming to enhance drying efficiency and improve product quality. Drying time was reduced by 23.8%, while color quality improved and nutritional retention increased. A heat pump ejector drying system (HPED) combined with a solar collector was used by the research group of Abadi et al.[7] To provide heat and electricity for the drying process. Kumar M et al.[8,9] Experimentally studied a heat pump drying system in three types of drying chambers: a fluidized bed dryer, a tray dryer, and a combined dryer (a combined bed and tray dryer), used for drying Bermuda grass (Cynodon dactylon)[8] and basil leaves[9]. The results showed that the combined dryer achieved a higher moisture-removal efficiency than the other two types. Additionally, the rotary drum drying system offers numerous advantages in process dynamics and energy optimization. Research on rotary drum drying has also been conducted by many researchers worldwide, including the research team of Gutierrez-Aguinaga, R.A., et al.[10] developed two virtual reality (VR) environments for the drying of ammonium nitrate and low-grade coal in an industrial rotary dryer, integrating heat–mass transfer mathematical models to accurately simulate actual operating behavior and support operator training. Rezaei and Sokhansanj[11] Studied the general behavior of high-moisture biomass in a rotary dryer, analyzing experimental data and correlations to determine the material storage time and identify optimal operating conditions. M. Wae-Hayee et al[12]. Evaluated the effectiveness of installing an impact air jet in a rotary drum dryer with air jet velocity (Vj) set at 5, 10, and 15 m/s, while air jet temperature (Tj) was 70, 80, 90°C, Drum rotation speed (N) 0.5, 1, and 3 rpm on product 5 kg fresh chili in 8 hours. Results showed that the effect of drum rotation speed was negligible, and air jet temperature had a greater impact on heat transfer enhancement than air jet velocity. M. A. Delele et al[13]. Presented a comprehensive review of advances in the application of rotary dryers for the drying of various agricultural products, and they suggested methods to improve the efficiency of the drying process.

In addition, peas are a nutrient-dense food, rich in vegetable protein, fiber, vitamins A, C, and K, and numerous essential minerals. The demand for peas in the market is increasing due to their easy-to-eat texture and suitability for daily dishes. Peas also have a wide range of applications, including the production of frozen peas, canned foods, pea flour, protein extracts used in the functional food industry, and meat substitutes, making a significant contribution to modern nutrition and the food industry. Preserving peas is an urgent and essential need, so many scientists have used drying to achieve long-term preservation[14–16]. Siddique and Wright[14] Studied the effect of drying temperatures between 40 and 100°C on pea products and found that only 40°C was suitable for drying seeds. Ridha Fethi Mechlouch et al[15]. Studied the drying kinetics of peas and tomatoes in a microwave oven and showed that the effective diffusion coefficient of peas is in the range of $0.169\times10^{-9}$ to $1.024\times10^{-9}$ $m^2/s$.

The current heat pump drying method on the market has numerous applications and is produced with high-quality products. However, the product's post-drying cost is relatively high, primarily due to the energy consumed by the drying system. Therefore, the rotary drum heat pump drying method is a new proposal to promote the drying process to take place faster, the drying time for the product is expected to be reduced compared to traditional heat pump drying, thereby increasing the energy consumed for the product drying process will be significantly reduced, the article focuses on the research on the heat pump drying process combined with the rotary drum. It compares the results with those obtained from traditional heat-pump drying of pea products.

# RESEARCH METHODOLOGY

## Theory Method

### *Moisture content of product*

The moisture content of the dried material over time is calculated using the initial moisture content, the initial mass of the material, and the amount of water lost after time *t*. This allows monitoring of moisture removal during the drying process.

Moisture content of product at a drying time t:

$$\triangle H_2O_t = M_i - M_t \quad (1)$$

$$\triangle H_2O_t = M_t \cdot \frac{W_i - W_t}{100 - W_i} \quad (2)$$

$$W_t = W_i - \triangle H_2O_t \cdot \frac{100 - W_i}{M_t} \quad (3)$$

### *Moisture ratio of drying product*

Define the moisture ratio of drying products based on the moisture of the product:

$$MR = \frac{M_t - M_e}{M_i - M_e} \quad (4)$$

The drying rate (DR) of the product was determined:

$$DR = \frac{M_{t+\triangle t} - M_t}{\triangle t} \quad (5)$$

### The color measurement analysis

To evaluate product quality, the color of pea seed samples was analyzed using the CS-10 Precision Colorimeter, which provides L, a, and b values according to the CIE color standard. In each batch, five randomly selected beans were used to measure color and calculate the mean color value. The average color difference between dry and fresh beans was calculated using the Formula:

$$\triangle E = \sqrt{(\triangle L)^2 + (\triangle a)^2 + (\triangle b)^2} \quad (6)$$

### Mathematical model of drying kinetics

Mathematical models analyzing the kinetics of the drying process evaluate the influence of moisture ratio over time, depending on each model to determine different influencing factors, such as the proportionality factor "a", the drying rate constant factor "k", the correction factor "n", and other factors b, c... as shown on the typical models [17] such as Wang and Singh, Logarithmic, Page, Modified Page, Newton, Henderson and Pabis, Midilli et al.

| No | Models | Equation | |
|---|---|---|---|
| 1 | Wang and Singh | $MR = 1 + at + bt^2$ | (7) |
| 2 | Logarithmic model | $MR = a.\exp(-kt) + c$ | (8) |
| 3 | Page | $MR = \exp(-kt^n)$ | (9) |
| 4 | Modified Page | $MR = a.\exp[-(kt)^n]$ | (10) |
| 5 | Newton | $MR = \exp(-kt)$ | (11) |
| 6 | Henderson and Pabis | $MR = a.\exp(-kt)$ | (12) |
| 7 | Midilli et al | $MR = a.\exp(-kt^n) + bt)$ | (13) |

Non-linear regression was applied to estimate the drying rate constant and model coefficients of the mathematical drying kinetics model.

**Analyze the experimental data and the mathematical model**

The model fit to the experimental data was evaluated using the correlation coefficient ($R^2$), the reduced chi-square ($\chi^2$), and the root mean square error (RMSE). The most suitable model for describing drying kinetics was the one with the lowest RMSE and $\chi^2$ values and the highest $R^2$ value.

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N-n} \quad (14)$$

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - \overline{MR}_{exp}\right)^2 - \sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{\sum_{i=1}^{N}\left(MR_{exp,i} - \overline{MR}_{exp}\right)} \quad (15)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N}} \quad (16)$$

## Experimental method

### Experimental materials

Pea seeds, scientifically known as Pisum sativum, are a genus of the legume family (Fabaceae), originating from Southwest Asia and Northeast Africa. The pea variety used in the study was grown in Kado commune, Don Duong district, Lam Dong province, and is a popular pea variety in Vietnam, as shown in Figure 1.

**Figure 1**: Pisum Sativum [Source: Authors]

**Moisture content of materials:** The moisture content of the fresh seeds was analyzed using an AND MX-50 material moisture analyzer (Figure 2), with an instrument error of ±0.1%. The moisture content of fresh seeds was analyzed 5 times with a minimum sample mass of 5 grams taken randomly, and the average moisture content of fresh seeds achieved was (68.35 ± 1.3) %.

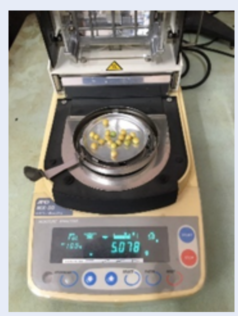

**Figure 2**: Moisture content analysis of samples on AND MX-50 [Source: Authors]

### Experimental Model

The rotary drum heat pump drying system used in this study is illustrated in Figure 3 and Figure 4, with the following system parameters: compressor capacity of 1 HP, refrigerant R404A, evaporator of 3kW, and condenser of 3.75kW. The rotary drum has a length of 892mm and a diameter of 223mm, the drum's speed is controlled by a 120W stepless motor with a 1/20 gear ratio and an electronic speed controller. The external gear drive system of the turntable drum comprises 28 driving gears and 115 driven gears. The drying agent is transported by a 120W centrifugal fan, speed controlled by a dimmer.

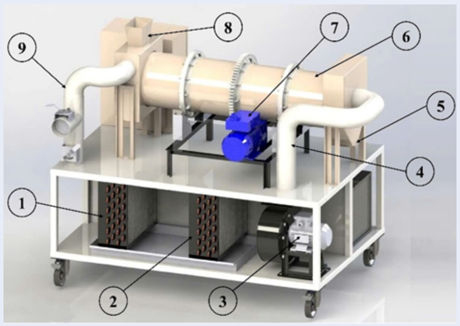


**Figure 3**: Scheme of experimental test – Front side 1-evaporator, 2-main condenser, 3 fans, 4-supply air ducts, 5-product discharge, 6-rotary drum, 7-rotary drum motor, 8-Feeding hopper, 9-return air duct [Source: Authors]

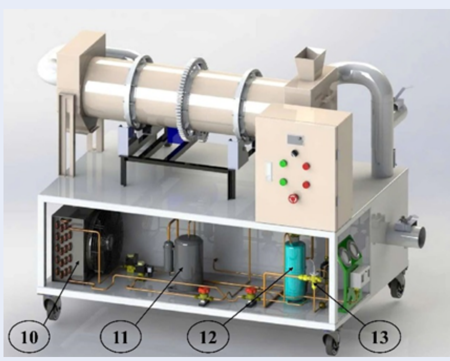


**Figure 4**: Scheme of experimental test – Back side 10-sub condenser, 11-compressor, 12-liquid tank, 13-expansion valve [Source: Authors]

The system uses moist air as the drying agent, which is circulated through the evaporator (1) to reduce the temperature and specific humidity of the air, then continues to be passed through the main condenser (2) by the fan (3) through the air duct (4) to bring the air into the rotating drum (6). The rotating drum drive system utilizes a drive system (7) with a gear located outside the rotating drum. At the rotating drum, the drying air exchanges heat and moisture with the Raw material feed at the feeding hopper (8) and discharges the product at the product discharge (5). To increase drying speed, a blade guide is located within the rotating drum to mix the drying product, thereby enhancing contact between the product and the drying agent. The air exiting the rotating drum is passed through the return air duct (9) and then returned to the evaporator (1), completing the closed circuit for the next cycle.

Table 1 shows the measuring instruments used in the experiment.

### *Wide range of experiments*

The objective of the experiment is to determine the drying kinetics, including the effects of drying temperature and drum speed on drying time, and the impact of two types of dryers. The experiment was conducted with a temperature range of 45°C to 60°C, a drum speed of 4 to 14 rpm, and a wind speed of 1.5 m/s to 3 m/s. The mass of fresh products for each drying batch was 1kg. The range of input experimental parameters was varied for each experiment, as explicitly shown in Table 2.

## RESULTS AND DISCUSSION

### Effect of drying parameters on the drying process in a rotary drum heat pump drying system

#### *Effect of drying temperature*

Experiments were conducted to evaluate the influence of temperature on the drying process under the following conditions: air velocity of 2.5 m/s, drum speed of 8 rpm, and drying temperatures varying from 45°C to 60°C. Figure 5 and Figure 6 illustrate changes in the product's moisture content as a function of drying rate at 45°C, 50°C, 55°C, and 60°C. The drying curves (Figure 5) show that higher temperatures lead to faster moisture reduction: at 45°C, the moisture content decreases to 13% after 480 minutes, whereas at 60°C, it decreases to 13% within only 210 minutes. A similar trend is evident in the drying rate curves (Figure 6), where the rate increases rapidly in the initial stage, peaks at 30–45% moisture content, and then gradually decreases as drying progresses. The maximum drying rate is approximately 0.35%/min at 60°C, compared with 0.2%/min at 45°C; intermediate values are 0.22–0.28%/min at 50°C and 55°C. These results confirm that higher drying temperatures not only reduce drying time but also increase the evaporation rate during the constant-rate period. In contrast, the decline

**Table 1: The list of instruments [Source: Authors]**

| Measure | Instrument | Accuracy |
|---|---|---|
| Air velocity | Testo 425 | ± 0.3 m/s |
| Temperature | Datalogger TC type K | ± 0.1°C |
| Pressure drop | Cole Parmer-PH721 | ± 2% |
| Mass of material | Electric Weight | ± 1gam |
| Moisture of the material | AND MX-50 | ± 0.1% |
| Color deviation measuring instrument | CHN SPEC DS-200 | ± 0,01 |
| High-layer material | Rule | ± 1 mm |

**Table 2: Experimental working conditions [Source: Authors]**

| | |
|---|---|
| Velocity | 1.5, 2.0, 2.5, 3.0m/s |
| Weight of fresh Pea | 1kg |
| Temperature | 45, 45, 50, 60 °C |
| Drum speed | 4, 6, 8, 10, 12, 14 rpm |
| Type of dryers | Heat Pump combined with a Rotary Drum dryer. |

in the falling-rate stage reflects the removal of bound water within the material.

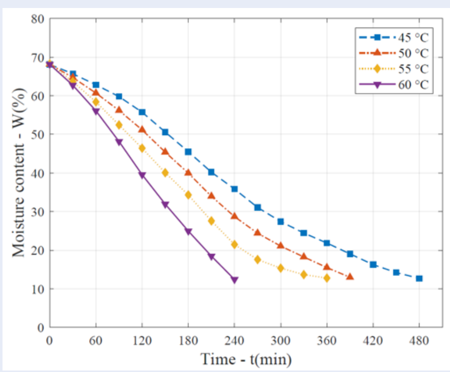


**Figure 5**: The effect of temperature on drying curves of dried products [Source: Authors]

However, high temperatures can affect product quality (color, texture, nutrition). Therefore, Figure 7 shows the quality of dried products (Delta E) at different temperatures. The results show that the color change (Delta E) strongly depends on the drying temperature. At 50°C, the Delta E value is lowest (13.78), indicating that the color quality is best preserved. At 55°C, Delta E increases slightly to 15.50, while at 45°C, it is 16.09. Notably, at 60°C, Delta E jumps to 23.00, indicating an apparent color change and a decline in the product's sensory quality. This shows that although a high temperature (60°C) helps shorten drying time and increase moisture loss rate, it negatively affects product quality due to a substantial color change.

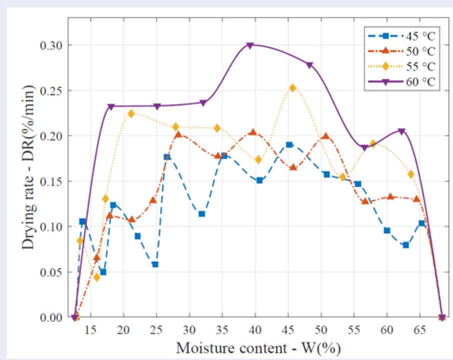


**Figure 6**: The effect of temperature on drying rate curves of dried products [Source: Authors]

## Effect of Air Velocity

In addition to the two main parameters that affect the drying process, namely the temperature of the drying agent and the speed of the rotating drum, wind speed is also a crucial parameter influencing both the drying process and product quality. Figure 8 shows the moisture loss rate at wind speeds of 1.5 m/s, 2.0 m/s, 2.5 m/s, and 3 m/s under drying conditions of 50 °C and 8 rpm, and the color deviation shows the quality of the dried product in Figure 9. At a low speed (1.5

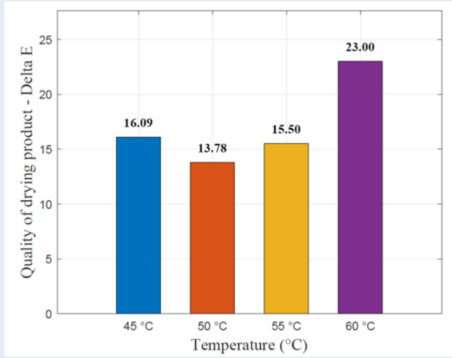


**Figure 7**: The effect of temperature on the quality of dried products (Delta E) [Source: Authors]

m/s), the drying time is nearly 500 minutes, and the Delta E value is high (22.50), indicating a significant color change in the product. At 2 m/s, the drying time is reduced to approximately 400 minutes, and Delta E decreases to 20.74, although it remains high. Notably, at 2.5 m/s, the drying process is faster (approximately 300 minutes), and Delta E is lowest (10.69), indicating the highest product quality. However, as the speed increases to 3 m/s, the drying time shortens, but Delta E increases to 14.90, indicating a decline in color quality. Thus, a wind speed of 2.5 m/s is considered optimal, ensuring high drying efficiency while maintaining optimal product quality.

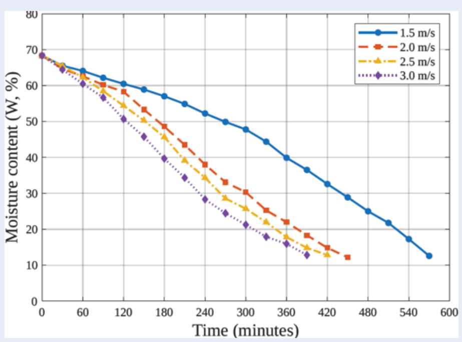


**Figure 8**: The effect of Air Velocity on drying curves of dried products [Source: Authors]

### *Effect of Drum Rotational Speed*

The effect of drum rotation speed on the drying process was evaluated at 4-14 rpm, with a constant air temperature of 50 °C and an air velocity of 2.5 m/s. Analysis of the drying curve in Figure 10 and the product quality (Delta E) in Figure 11 indicates that rotation speed significantly affects both drying time

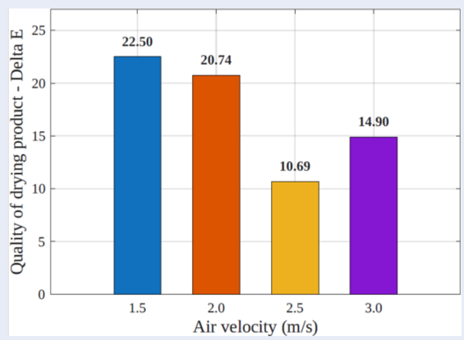


**Figure 9**: The effect of Air Velocity on the quality of dried products (Delta E) [Source: Authors]

and product color. At low speeds (4–6 rpm), drying time exceeds 480 minutes, and Delta E values are high (22.14 and 21.45), indicating a significant color change in the product. In contrast, at medium speeds (8–10 rpm), the dehumidification process is faster, taking approximately 360 minutes to reach the final moisture content, while Delta E decreases to its lowest level (10.69–13.97), indicating improved product quality. However, when the speed is increased to high (12–14 rpm), the drying time is shortened sharply (to approximately 210–240 minutes). Still, Delta E exceeds 24, indicating a pronounced change in product color. Thus, the average rotation speed (8–10 rpm) is optimal, as it balances drying efficiency (shorter time) with product quality (stable color).

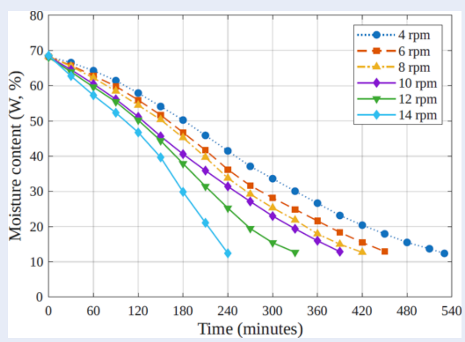


**Figure 10**: The effect of Drum Rotational Speed on drying curves of dried products [Source: Authors]

## Compare the drying process between the heat pump dryer and the rotary drum heat pump dryer

A traditional heat pump dryer is used to dry peas at wind speeds of 2 m/s and temperatures of 45 °C, 50

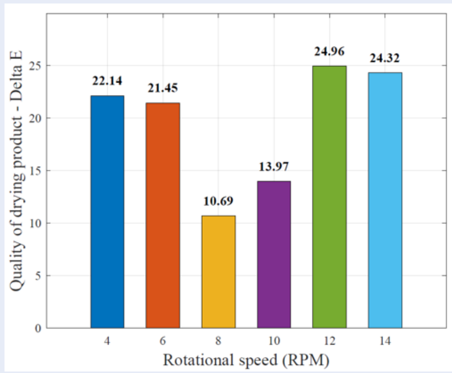


**Figure 11**: The effect of Drum Rotational Speed on the quality of dried products (Delta E) [Source: Authors]

°C, and 55 °C. The results presented in Figure 12 show that in the 55 °C mode, it takes only 390 minutes to reach 13% moisture, whereas in the 50 °C and 45 °C modes, it takes 470 and 540 minutes, respectively. In addition, it compares the results of two traditional heat pump drying systems with those of a heat pump combined with a rotary drum. The results show that the efficiency of the rotary drum heat pump across different modes is superior to that of the traditional heat pump system, saving about 1 hour at the same temperature.

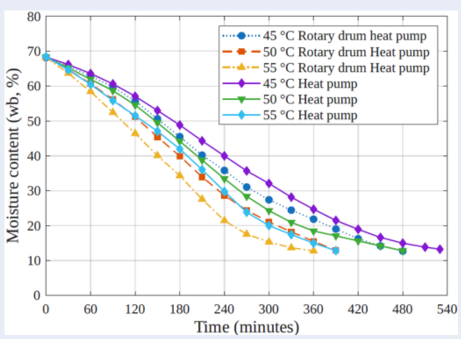


**Figure 12**: The comparison drying process between the heat pump dryer and the rotary drum heat pump dryer [Source: Authors]

## Evaluation of Mathematical Drying Models

Using experimental data and built-in MATLAB functions, the coefficients a, k, n, b, and c were determined using the following mathematical models: Wang and Singh, Logarithmic, Page, Modified Page, Newton, Henderson and Pabis, and Midilli et al. The results were then processed, and a model was constructed based on the experimental data.

Based on the mathematical model and experimental results, the drying process is analyzed using drying-rate and model-coefficient data. The suitability of the mathematical model relative to the experimental data was evaluated using the correlation coefficient ($R^2$), the reduced chi-square ($\chi^2$), and the root mean square error (RMSE). Table 3 presents the statistical results to measure the suitability of each model through the coefficients $R^2$, $\chi^2$ and RMSE corresponding to experimental data in drying modes under the conditions of temperature (45°C, 50°C, 55°C, 60°C), air velocity (0.5 m/s, 1.0 m/s, 1.5 m/s, 2 m/s) and drying drum speed (4rpm, 6rpm, 8rpm, 10rpm, 12rpm, 14rpm).

Based on the correlation coefficient results in Table 3, all kinetic models for the drying process can reasonably and appropriately describe the process. However, the Midilli et al. model provides the best fit, with an $R^2$ ranging from 0.9947 to 0.9997 at the highest level, a $\chi^2$ ranging from 0.0001 to 0.0024, and an RMSE ranging from 0.0054 to 0.0226 at the lowest level. From there, the Midilli model is applied to predict the kinetics of pea drying using a rotary drum heat pump system.

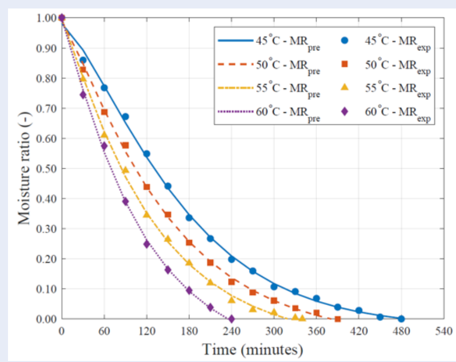


**Figure 13**: Experimental and predicted drying ratios obtained using the Midilli model at various temperatures [Source: Authors]

Figures 13 and 14 and Figure 15 compare the agreement between the experimental data and the predicted results obtained by applying the Midilli model as a function of temperature, air velocity, and drying drum rotation speed. Figure 13 shows that as the drying temperature increases from 45°C to 60°C, the drying rate increases significantly, the moisture ratio curve decreases more rapidly, and the Midilli model accurately simulates the experimental trend.

**Table 3: Statistical variables of analysis results form athematical models [Source: Authors]**

| Model | Coefficients | Min | Max |
|---|---|---|---|
| Wang and Singh | $R^2$ | 0.9940 | 0.9994 |
| | $\chi^2$ | 0.0004 | 0.0027 |
| | RMSE | 0.0075 | 0.0235 |
| Logarithmic model | $R^2$ | 0.9933 | 0.9993 |
| | $\chi^2$ | 19541 | 452488 |
| | RMSE | 0.0079 | 0.0257 |
| Page | $R^2$ | 0.9802 | 0.9989 |
| | $\chi^2$ | 0.0023 | 0.0130 |
| | RMSE | 0.0106 | 0.0416 |
| Modified Page | $R^2$ | 0.9876 | 0.9992 |
| | $\chi^2$ | 0.0009 | 0.0061 |
| | RMSE | 0.0088 | 0.0326 |
| Newton | $R^2$ | 0.9635 | 0.9897 |
| | $\chi^2$ | 0.0066 | 0.0154 |
| | RMSE | 0.0310 | 0.0569 |
| Henderson and Pabis | $R^2$ | 0.9659 | 0.9915 |
| | $\chi^2$ | 0.0055 | 0.0132 |
| | RMSE | 0.0281 | 0.0534 |
| Midilli et al | $R^2$ | 0.9947 | 0.9997 |
| | $\chi^2$ | 0.0001 | 0.0024 |
| | RMSE | 0.0054 | 0.0226 |

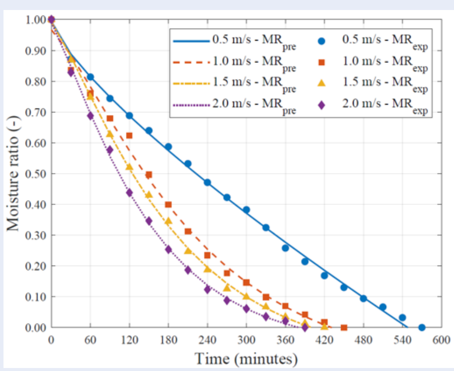


**Figure 14**: Experimental and predicted drying ratio obtained using the Midilli model at various velocities [Source: Authors]

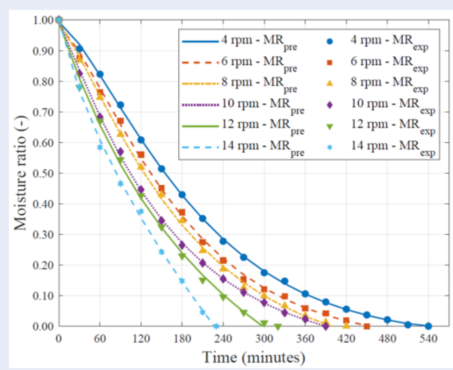


**Figure 15**: Experimental and predicted moisture ratio obtained using the Midilli model at various Drum Rotational Speed [Source: Authors]

Figure 14 shows that as air velocity increases from 0.5 to 2.0 m/s, heat and moisture exchange improve, significantly reducing drying time. Figure 15 illustrates the effect of drum rotation speed, ranging from 4 to 14 rpm; higher speeds promote more even material mixing and reduce moisture more quickly. The Midilli model's prediction curves in all three cases closely match the experimental data, demonstrating its ability to accurately describe drying kinetics. Overall, the Midilli model showed a good fit to the experimental data, accurately reflecting the influence of operating factors on the drying process.

## CONCLUSION

Experimental research on the drying of peas in a rotary drum heat pump drying system was conducted to evaluate the influence of drying modes on drying time and product quality, with results showing that the optimal mode in terms of time and color deviation was 50 °C, 2 m/s, and 8rpm. Comparison and evaluation of drying efficiency between the full-recirculation heat pump dryer and the rotary drum heat pump dryer on pea products at the same drying mode in terms of temperature and wind speed. The results showed that the rotary drum heat pump dryer was more efficient than the heat pump dryer. Seven typical mathematical models of drying process kinetics of Wang and Singh, Logarithmic, Page, Modified Page, Newton, Henderson and Pabis, Midilli et al, were selected and evaluated based on experimental data with analysis of correlation coefficient ($R^2$), the reduced chi-square ($\chi^2$), and the root mean square error (RMSE). The models all showed high compatibility, with the Midilli et al. model being the most suitable and providing the best fit for this drying system.


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## NOMENCLATURE

$M_i$: mass of fresh product;
$M_e$: mass of dried product
$M_t$: mass of product after drying period time t;
Dt: time interval;
$W_i$: initial moisture content of fresh product;
$W_e$: moisture content of dried product;
$W_t$: moisture content of product at the drying time t;
DR: drying rate;
$MR_{exp,i}$: experimental value of moisture ratio.
$MR_{pre,i}$: predicted value from the model.
$\overline{MR}_{\text{exp}}$: average experimental value.
N: number of data.
n: number of model parameters

## CONFLICT OF INTEREST

The authors hereby declare that there is no conflict of interest in the publication of this paper.

## AUTHORS' CONTRIBUTIONS

Thanh Nhan Phan contributed to the paper's idea, the design of the experimental model and experimental plan, the analysis of results, the analysis of the mathematical models, the calculation results for the mathematical model, and the main writing.
Thai Son Nguyen and Minh Quoc Nguyen contributed to the experimental model, the experiment, and the recording of experimental results.

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*Bài nghiên cứu*

# Nghiên cứu thực nghiệm về quá trình sấy đậu Hà Lan bằng hệ thống sấy bơm nhiệt kết hợp thùng quay

**Phan Thành Nhân[1,2,*], Nguyễn Thái Sơn[1,2], Nguyễn Minh Quốc[1,2,3]**



**TÓM TẮT**
Nghiên cứu được thực hiện trên hệ thống sấy kết hợp bơm nhiệt và trống quay để đánh giá quá trình sấy sản phẩm đậu Hà Lan. Thí nghiệm đã kiểm tra ảnh hưởng của nhiệt độ sấy, tốc độ gió và tốc độ quay trống đến động học quá trình sấy và sự thay đổi màu sắc của sản phẩm. Ngoài ra, kết quả sấy giữa hai loại máy sấy, máy sấy kết hợp bơm nhiệt và trống quay, và máy sấy bơm nhiệt thông thường có hồi lưu hoàn toàn, cũng như phân tích tính tương thích của các mô hình toán học, cũng được phân tích. Kết quả cho thấy ở nhiệt độ sấy 45-60 °C, thời gian sấy giảm đáng kể, và chất lượng sản phẩm sấy khô, được đánh giá bằng phân tích màu ở 45-55 °C, là tương đương. Ngược lại, ở 60 °C, mặc dù thời gian giảm gần một nửa so với 45 °C, chất lượng lại thay đổi đáng kể; độ lệch màu đạt 23, so với 13,78 khi sấy ở 50 °C. Khi tốc độ gió tăng từ 1,5 m/s lên 3 m/s, quá trình sấy trở nên không ổn định ở chế độ gió quá yếu ở 1,5 m/s, dẫn đến thời gian sấy dài hơn và độ lệch lớn hơn. Về ảnh hưởng của tốc độ trống đến quá trình sấy, thí nghiệm được tiến hành trong phạm vi 4-14 vòng/phút. Kết quả rất đáng chú ý: tốc độ càng cao, sản phẩm càng được sấy khô nhanh hơn. Tuy nhiên, kết quả độ lệch màu tối ưu ở tốc độ 8 vòng/phút và 10 vòng/phút lần lượt là 10,69 và 13,97. Dựa trên kết quả thực nghiệm, điều kiện sấy tối ưu là nhiệt độ sấy 50 °C, tốc độ gió 2,5 m/s và tốc độ quay trống 8 vòng/phút. Một kết quả đáng chú ý khác là, khi so sánh quá trình sấy sản phẩm trên hai hệ thống sấy, việc sấy trên hệ thống kết hợp bơm nhiệt và trống quay hiệu quả hơn 10-30% so với bơm nhiệt truyền thống về mặt tiết kiệm thời gian. Cuối cùng, khi phân tích mô hình toán học cho quá trình sấy đậu Hà Lan trên hệ thống sấy trống quay kết hợp bơm nhiệt, mô hình của Midilli cho kết quả phù hợp với dữ liệu thực nghiệm trên tất cả các chế độ.
**Từ khoá:** Bơm nhiệt, Máy sấy thùng quay, Bơm nhiệt kết hợp thùng quay, sấy đậu Hà Lan, Đậu Hà Lan

[1]*Bộ môn Công Nghệ Nhiệt Lạnh, Khoa Cơ khí, Trường Đại học Bách Khoa Thành phố Hồ Chí Minh (HCMUT), 268 Lý Thường Kiệt, Phường Diên Hồng, Thành phố Hồ Chí Minh, Việt Nam*

[2]*Đại học Quốc gia Thành Phố Hồ Chí Minh, Phường Linh Trung, Thành phố Hồ Chí Minh, Việt Nam*

[3]*Khoa Công Nghệ Nhiệt - Lạnh, Trường Cao đẳng Kỹ Thuật Cao Thắng*

**Liên hệ**

**Phan Thành Nhân**, Bộ môn Công Nghệ Nhiệt Lạnh, Khoa Cơ khí, Trường Đại học Bách Khoa Thành phố Hồ Chí Minh (HCMUT), 268 Lý Thường Kiệt, Phường Diên Hồng, Thành phố Hồ Chí Minh, Việt Nam

Đại học Quốc gia Thành Phố Hồ Chí Minh, Phường Linh Trung, Thành phố Hồ Chí Minh, Việt Nam

Email: phannhan@hcmut.edu.vn

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