Optimization of Temperature Sensors for Drying Mangosteen Peel

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This paper presents the design and implementation of temperature sensors for drying mangosteen peel. To enhance the performance of temperature sensors in the drying process, Kalman innovation sequences and natural tracking indicators are employed. The natural tracking indicators can be realized by setting the maximum possible product surface temperature limit (PSTL) as the tracking points. This is very useful for preventing the loss of quality of food products. The use of temperature sensors designed using the PSTL control system is optimal in the sense that the system is adaptively adjusted for faster tracking to the set points and less energy consumption. According to experiments using mangosteen peel as the test material, the dried peel has the desired food quality. This implies that the proposed paradigm can be applied to enhance the performance of temperature sensors.

1. Introduction

In the drying of food , hot air is applied by convection, which circulates around the surface of the product to remove moisture. Consequently, the dried product has reduced weight and volume, which affects packaging, handling, and delivery costs.[1–4] In addition, temperature is the main factor affecting the quality of food products. The biological quality of food is sensitive to high temperatures, which cause changes in color, smell, taste, structure, and nutritional values. Hence, it is necessary to preserve the quality of dried food and maintain the natural characteristics of the material.[3–6]

The effects of the drying temperature on product quality are not fully understood.[6–10] Research has been carried out on the development of automatic dryers to improve the quality of products.[11–14] Controlling the drying chamber air temperature and the product surface temperature are important factors significantly affecting the quality of the dried product.[13,14] In-depth research has been carried out on stratified temperature control profiles that change according to the process and conditions for each stage of drying. It has been demonstrated that the bio-quality of heat-sensitive products can be affected at high air temperatures during the first drying process.[14–17]

In addition, another factor affecting the product in the drying process is the moisture content, which is essential in predicting the behavior of food during processing.[18–22] The use of weight results to calculate the dry base moisture content is complicated and it is easy to make a mistake. To deal with this problem, a weight sensor is installed in both indoor and outdoor driers.[23–26] Our previous work focused on improving the accuracy of weight measurements when temperature changes occurred during drying.[27]

To extend the results of Ref. 27, product surface temperature limits (PSTLs) are used as food quality controls and as criteria for ending the drying process to maintain the required weight.[27] In this process, a time constant is employed to impose a rule for assigning the gain condition. The recursive least squares (RLS) algorithm is used to update an innovative sequence that provides suitable control gains for the drying process to achieve the desired efficiency and satisfactory quality of the final product.

2. Materials and Methods

2.1 Set-point scheduling using time constant

The drying process can be mathematically considered as a first-order system. In practice, we can linearize the input heat power and set a constant fan speed for each time constant. The set point of the food surface at temperature T is assigned a corresponding time constant τ at each step, as shown in Fig. 1. This process can be mathematically described by

$$\bar{T} = (T - T_i) / (T_f - T_i) = 1 - e^{(-t/\tau)}, \tag{1}$$

where $\bar{T}$ is the percentage response, T is the temperature at time t (°C), T_i is the initial temperature (°C), T_f is the final temperature (°C), t is the time, and τ is the time constant of the
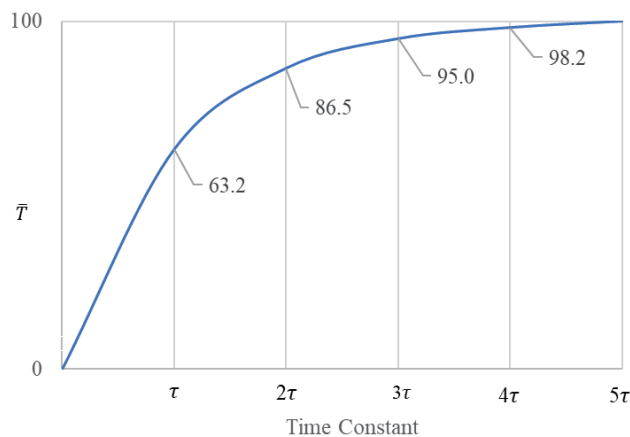

Fig. 1.   (Color online) Natural tracking indicators specified by time constants.

process. As can be seen from Fig. 1, the response curve is exponential. Between $t = 0$ and time constant τ, the response increases from 0 to 63.2% of the maximum limit surface temperature of the product. At time constant 2τ, the response reaches 86.5% of the maximum limit. At $t = 3\tau$, 4τ, and 5τ, the response reaches 95, 98.2, and 99.3% of the maximum limit, respectively. In practice, to retain food quality, we can set the maximum limit surface temperature of the product at four time constants (4τ). This is equal to reaching the 2% line of the maximum limit value in the steady state, which can be reasonably estimated as the response time to reach the target point.

In this study, a PC151MT-0 non-contact infrared temperature sensor (Calex Electronics Ltd., UK) is used to measure product surface temperatures. The sensor has an operating range of 0–250 °C, an accuracy of 0.1 ± 0.5 °C, a measuring range of 15:1, 24 V DC voltage, a current of 4–20 mA, and two signaling wires.

2.2 Control architecture and algorithms

This section describes the control architecture and algorithm used to control the drying process. The RLS algorithm is employed, which has been demonstrated to be highly effective against noise and has long been used in control and communication engineering.[28,29] The discrete time version of the standard RLS algorithm is as follows:

$$P(k+1)= [1/\lambda(k+1)][P(k)-K(k+1)][P(k)\phi(k+1)]^{T} \tag{2}$$

$$\theta(k+1)=\theta(k)+K(k+1)\varepsilon(k+1) \tag{3}$$

$$\lambda(k+1)=\lambda_0\lambda(k)+ (1-\lambda_0) \tag{4}$$

$$K(k+1)= [P(k)\phi(k+1)]/[\lambda(k+1)+ [\phi^{T}(k+1)P(k)\phi(k+1)]] \tag{5}$$

$$\varepsilon(k+1)=y(k+1)-\phi^{T}(k+1)\theta(k) = \text{the innovation sequence}, \tag{6}$$

where k is the discrete time and P, K, θ, λ, and ε are the recursion following an algebraic Riccati equation, the Kalman gain, the parameter vector, the forgetting factor, and the innovation sequence, respectively. The RLS algorithm is used to obtain a process model to regulate the rules for the corresponding area of each constant in the drying process control to adjust the air temperature according to the increase in the product surface temperature. The overall control architecture and a flowchart for product surface temperature control and moisture content measurement while drying food are shown in Figs. 2 and 3, respectively.
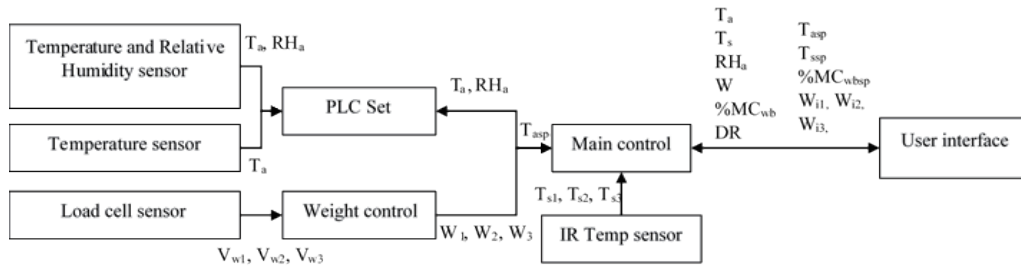
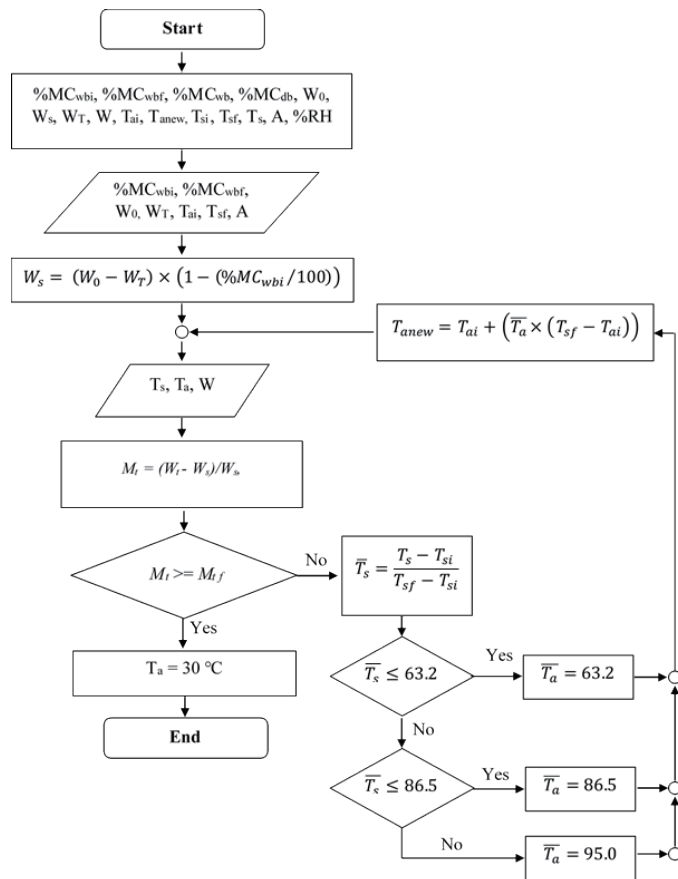Fig. 2.   Overall control architecture of the proposed drying process.

Fig. 3.   Flowchart of product surface temperature control and moisture content measurement.

2.3   Drying process

2.3.1   Moisture contents

The moisture content was experimentally estimated using a 61022-3KG-0000M load cell sensor (Sensortronics, USA), which can measure a maximum weight of 3 kg and has a temperature range from 0 to 70 °C with a total output value of 3.0 mV/V. To compensate for the drying temperature tolerance,[27] we define M_t as the sample moisture for each period (kg water/

kg dry solid), W_t as the total weight of the sample for each period (kg), and W_s as the solid weight of the sample (kg). The equation of the sample's moisture content at each sampling time is

$$M_t = (W_t - W_s) / W_s .$$ (7)

2.3.2 Drying rate

To calculate the drying rate of the process, the mass of liquid evaporation per area per time is evaluated as

$$R_a = -(W_w / A)(dm / dt),$$ (8)

where R_a is the drying rate (kg/m^2), W_w is the water weight of the sample at time k (kg), A is the water evaporation area (sq m), and dm/dt is the weight. Note that the evaporated water per unit time has the unit kg/h.

2.4 Drying experiment

2.4.1 Mangosteen peel

The mangosteen peel was coarsely blended and packed in a laminated bag with 2 kg of peel per bag, then frozen by blasting freezing air at −38 °C for 90 min and stored at −18 °C, as shown in Fig. 4. Before drying, the sample was thawed in a cabinet at 4 °C for 8 h.

2.4.2 Drying conditions

To experimentally acquire suitable conditions for the drying process using mangosteen as the product, 300 g of the material was sorted on a sieve with none of the peel overlapping. The effects of drying temperatures of 50 and 60 °C with a wind speed of 1.3 m/s were compared. The product was dried until the final wet base moisture reached 5% (the desired value). The starting

Fig. 4.   (Color online) Frozen mangosteen peel.

air temperature was set at 70 °C. The air temperature, product surface temperature, and weight data were recorded every minute until the end of the process.

2.4.3   Quality analysis

The dried mangosteen peel was ground into powder with a dry food grinder and its moisture content, water activity, and color were analyzed as follows:
(1) Moisture content
The moisture content was determined by weighing the sample before and after drying and using Eq. (7). Approximately 2 g of dehydrated powdered mangosteen peel was first placed in a cup to determine its weight, then it was placed in an oven with an air temperature of 100 °C until the weight was stable. The weights of the sample pre-drying and post-drying were recorded using a four-digit decimal balance, then the moisture content was calculated using Eq. (7). This procedure was repeated three times and the average was taken.
(2) Water activity
Three samples of 3–5 g of powdered mangosteen peel were taken, and their water activity was measured with a water activity meter (Decagon Model, AquaLab, USA).
(3) Color
The color of the mangosteen peel was measured before and after drying with a color meter (ColorFlex, Hunter Lab, USA) using the CIE for the L^*, a^*, and b^* color system. Equations (9) and (10) were used to calculate the hue angle and chroma value.

$$\text{Hue angle} = \begin{cases} \text{arctangent } (b^*/a^*) & \text{when } a^* > 0 \text{ and } b^* \geq 0 \\ \text{arctangent } (b^*/a^*) + 180° & \text{when } a^* < 0 \\ \text{arctangent } (b^*/a^*) + 360° & \text{when } a^* > 0 \text{ and } b^* < 0 \end{cases} \tag{9}$$

$$Chroma = (a^{*2} + b^{*2})^{1/2} \tag{10}$$

2.4.4   Energy consumption

The energy consumption in the drying process was analyzed by recording the power. Energy consumption and energy efficiency or specific energy consumption were calculated using Eqs. (11) and (12), respectively:

$$E = Pt, \tag{11}$$

E: energy consumption (kW/h), P: electric power (kW), t: time (h).

$$SEC = E/W \tag{12}$$

SEC: specific energy consumption (kW/h kg), W: water weight eliminated during drying (kg).

3.   Results and Discussion

This section provides results and a discussion of the proposed control paradigm presented in the previous section. The results obtained using the proposed control parameter (PSTL) and the conventional constant air temperature (CAT) are compared. The test material in the experiment was mangosteen peel.

3.1   Hardware and experimental setup

Our built-in dryers[27] using heat pump technology with an extended operating range were operated between 30 and 70 °C. The system was equipped with a surface temperature sensor and a weight sensor to collect data. Figure 5 shows the installation of the mangosteen peel on the tray as the food material in the experiments.

3.2   Drying results

Figures 6 and 7 show drying characteristics obtained using PSTL and CAT control. PSTL control has better initial moisture transfer and a similar decrease in moisture to that of CAT control over time, which was consistent with the drying temperature effect. In Fig. 6, the drying time for PSTL control was determined for final values of around 22% RH and 19% RH at 50 °C in Fig. 6(a) and 60 °C in Fig. 6(b), respectively, and was less than that for CAT control. These effects yielded the result in Fig. 7 that the mass of moisture transferred from the product using PSTL control was greater than that using CAT control. Note that a greater difference between the air temperature and surface temperature of the product will result in greater moisture mass transfer.

Figure 7 shows a comparison of the two drying conditions at drying temperatures of 50 and 60 °C. Initially, PSTL control has a higher drying rate than CAT control. The drying rate decreases with time. As the drying temperature decreases, the relative humidity increases, resulting in a lower mass transfer, lower moisture content, and lower drying rate. In PSTL control at 50 °C, the temperature is set to lower than the air temperature at the start of the process, causing the drying rate to increase. However, at 60 °C, the response curve shows a
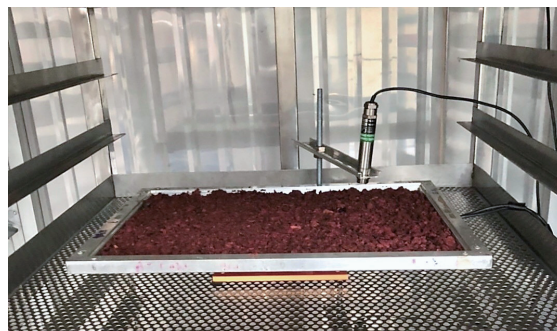

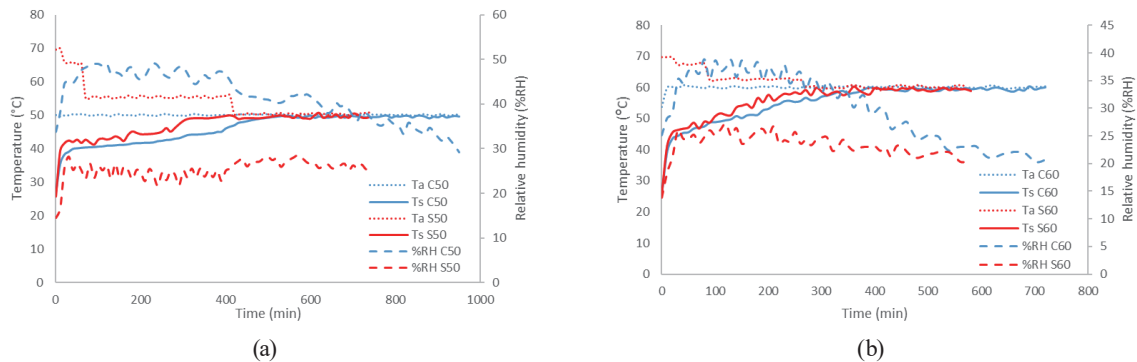Fig. 5.   (Color online) Mangosteen peel setup for drying experiment.

(a)

(b)

Fig. 6.   (Color online) Changes in air temperature, surface temperature, and weight during drying of mangosteen peel. Note that C50 stands for CAT control at 50 °C and S60 stands for PSTL control at 60 °C.
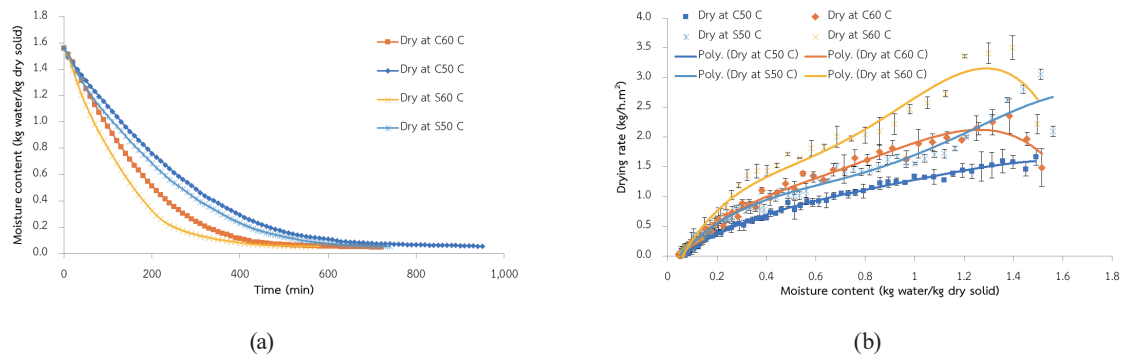

(a)

(b)

Fig. 7.   (Color online) (a) Moisture content (dry base) of products per drying period and (b) drying rate per moisture content (dry base) during drying of mangosteen peel. Note that C50 stands for CAT control at 50 °C and S60 stands for PSTL control at 60 °C.

higher drying rate. Thus, PSTL control realized a higher drying rate than CAT control at the same temperature.

3.3   Food quality and energy consumption

Table 1 shows the moisture content, water activity, and color value of the powdered mangosteen peel. By comparing the percentage moisture content using the dry basis, it can be seen that the results obtained using PSTL control are only slightly lower than those obtained using CAT control, indicating no significant difference. In terms of the water activity of the product, corresponding to the relative humidity of the final air in the drying process, PSTL control provides a lower final relative humidity than CAT control. The hue angle and chroma values were in the range of 58.85–60.54. These values corresponded to brown colors. There was no significant difference in the color changes for both PSTL temperatures. However, for CAT control, there were significantly different hue angles and chroma values between drying at 50 and 60 °C.

Table 1
Moisture content, water activity (aw), and color value of powdered mangosteen peel.

Condition	% Moisture content (dry basis)	Water activity	Hue angle	Chroma
CAT50	5.71 ± 0.15^{ns}	0.2818 ± 0.0033^a	58.85 ± 0.11^b	30.57 ± 0.18^b
CAT60	5.69 ± 0.11^{ns}	0.2040 ± 0.0021^c	60.63 ± 0.15^a	31.81 ± 0.24^a
PSTL50	5.60 ± 0.14^{ns}	0.2371 ± 0.0019^b	60.20 ± 0.13^a	31.74 ± 0.21^a
PSTL60	5.56 ± 0.09^{ns}	0.2010 ± 0.0027^d	60.54 ± 0.19^a	31.94 ± 0.27^a

Values shown in the table are mean ± standard deviation. Different letters a–d indicate statistically significant differences ($p \le 0.05$), ns indicates no significant difference.

Table 2
Energy consumption analysis.

Condition	Energy consumption (kW.h)	Specific energy consumption (kW.h/kg)
CAT50	70.93 ± 0.85^a	3.65 ± 0.04
CAT60	60.82 ± 0.79^b	3.13 ± 0.04
PSTL50	42.81 ± 1.12^c	2.20 ± 0.06
PSTL60	39.26 ± 1.04^d	2.02 ± 0.05

Values shown in the table are mean ± standard deviation. Different letters a–d indicate statistically significant differences ($p \le 0.05$).

From Table 2, it can be seen that PSTL control can reduce the energy consumption of the process by approximately 40% due to the reduction in drying time. Consequently, the specific energy consumption is also reduced.

It is clear that the temperature sensors can be optimally used in the drying processes if they are placed to sense the maximum surface temperature of the product. In doing so, the desired product quality is achieved, and the power consumption of the proposed PSTL control is reduced compared with that of CAT control.

4.   Conclusion

The objective of this study was to optimize the use of temperature sensors in the drying process. Appropriately placing the sensors and utilizing them to limit the surface temperature of food products helps maintain the quality of the products while reducing the energy consumption of the drying process, as demonstrated for mangosteen peel. The control algorithm uses the PSTL and time constants of the system to estimate the model reference and to monitor the parameters to be controlled. The experimental results show that the proposed method is not only effective in preserving the quality of the food, but also reduces the drying time and increases the energy efficiency compared with conventional drying methods that use room air temperature as a tracking parameter.

Acknowledgments

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