International Journal of Electrical and Computer Engineering (IJECE)
Vol. 14, No. 1, February 2024, pp. 239~247
ISSN: 2088-8708, DOI: 10.11591/ijece.v14i1.pp239-247

Controlling temperature using proportional integral and derivative control algorithm for hybrid forced convection solar dryer

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Article Info

Article history:

Received May 14, 2023
Revised Sep 9, 2023
Accepted Sep 24, 2023

Keywords:

Drying control
Food industry
Forced convection
Hybrid system
Solar dryer

ABSTRACT

Drying is one of the crucial processes in agricultural production, especially in grain processing. The drying process can improve grain quality and affect the grain content. However, maintaining the temperature is a challenge in the drying process. Because it can influence the drying performance and produce a low-efficiency reduction of water content, in this study, the hybrid drying system is proposed to improve the performance of the forced convection dryer system. The proposed system used a proportional integral and derivative (PID) control system to obtain the optimal temperature. The proposed system was compared with natural drying and forced convection methods. The experimental result showed that the proposed system performed excellently for three performance evaluations. The average temperature was obtained as the highest of the other methods, with 54.68 °C and 54.55 °C for coffee and cocoa beans. The water content can be reduced by an average of 27.38% and 42.67% for coffee and cocoa beans. Then, the proposed system also had the highest reduction efficiency of water content than the other methods, with 62.71% and 36.94% reductions for coffee and cocoa beans, respectively. The results indicate that the proposed hybrid system performs better than the other methods.

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1. INTRODUCTION

The drying process is an important step in grain processing. Grain contains a high moisture level and water, leading to faster decomposition. Therefore, removing the moisture level is needed to make the grain stored in long-term condition and easy for shipping [1]. Reducing grain moisture levels can improve grain quality and influence the formation of grain contains, flavor, color, acidity, and chemical content [1]–[6]. Furthermore, the drying process is also used on many agricultural products, such as ginger [7], soybean [8], coffee bean [9], cocoa bean [10], pumpkin seeds [11], sunflower seeds [12], and many more.

Many drying systems is proposed or used to dry the dried material. However, the conventional method is still prevalent. The conventional drying method uses sunlight to dry the dried material, so it can be called sun-drying. This method needs a more expansive open area in which it is directly exposed to the sunlight. Furthermore, sun-drying has an excellent performance in which the dried material can be dried very well and improves the quality. However, this method has many disadvantages. Besides, the temperature cannot be controlled and depends on the weather. Sun-drying causes the dried material to spread in the open air, so it uncovers from animal attacks [10]. Despite many disadvantages, sun-drying can produce high heat, low cost, and is easy to apply [13]. Moreover, the drying process takes much time so it can obstruct production. Thus, this advantage can be used to dry the grain using a greenhouse system as a dryer. The greenhouse drying system absorbs and collects the heat and transfers it into the greenhouse room. This system utilizes the fan to control and stream the temperature [14]. Moreover, the greenhouse system covers the grain and minimizes the risk of animal attack. The convective dryer is another dryer that utilizes a hot gas stream to dry the dried material [15]. This gas stream is obtained from solar energy, which is spread by fans to the dryer chamber. Many convective dryer types have various chamber and heating methods, such as rotary drum dryers, tunnel dryers, belt dryers, fluidized dryers, spouted bed dryers, pneumatic dryers, cabinet tray dryers, chamber dryers, and bin dryers. However, those dryers have a disadvantage because they require massive energy to dry the dried material [1], [9], [16]. Regarding those methods, heat transfer can be differentiated into natural and forced convection [17]. Those types have different performances. Force convection performs better than natural convection because this method is designed to distribute the heat evenly [7], [18]. Then, the drying process can be done by direct and indirect [13], [19], [20]. The drying process has several complexities that must be considered to obtain the optimal drying process, especially for the temperature. Nonetheless, several systems have no temperature controller. Thus, there needs to be optimization and adaptability in the drying process.

The temperature is the main parameter that takes effect for the drying process. The temperature has to be controlled and manipulated in the drying process because it can affect the process, such as the drying rate [21]. Controlling the temperature is a main issue in several drying process studies. Internal model control (IMC) is proposed to control internal processes in the drying system [22]. The control model is designed as with the original process. However, using inaccurate models in IMC can lead to inaccuracy and increase the noise. Thus, it can take affect the robustness of the system. The automatic drying system is another solution to control the temperature during drying [23]. The system uses programmable logic controller (PLC) to control temperature, which is used as a control parameter to control the drying and fermentation process. PLC uses an on-off control method to control the process. The method is an open-loop system, so there is no feedback to the system. Moreover, the method will switch around the setpoint, so it has a significant deviation from the setpoint when the hysteresis is incorrect. The fuzzy logic method is the improvement of the on-off control system. The fuzzy logic model uses if-then rules that have a linear relationship between the input and output of the system through fuzzy membership functions to obtain the linear model [21], [24]–[26]. This method uses rules that are determined by several factors. However, the rules need a correct relationship to decide the control area [27].

Based on several proposed systems, drying and controlling systems can be combined to obtain and maximize the drying performance. The drying system with forced convection relies on sunlight and weather, so the obtained temperature will vary and be unstable to dry the dried material. The unstable condition influences the dry performance. Besides, it can also interfere the production. Hence, a drying system that can maintain the temperature without depending on the environment is needed. In this study, the hybrid drying system is proposed to improve the performance of the forced convection dryer system. Thus, the proposed system can dry the dried material at optimal temperature and have a high-efficiency reduction of water content.

2. METHOD

2.1. Control system

The chamber temperature of the dryer is an important parameter that needs to control. The temperature comes from the sunlight, collected by a solar collector and streamed into the drying chamber. Besides, the temperature in the drying chamber also comes from the heater. This heater is an additional device that produces heat. A microcontroller controls the heater temperature to maximize the drying process. The temperature is used as the set-point value in the drying chamber, so desired water content in the grain can be achieved. In the proposed system, there are also the intake and exhaust fans which are controlled by relays with feedback data in the form of reading the temperature value in the device. Meanwhile, the resistive seeds water content sensor will read the water content level of the dried product. The value of this sensor will be used as a benchmark to stop the system from working if the dried material has reached the desired moisture level, according to the predetermined set-point value.

The proposed system utilizes a proportional integral and derivative (PID) controller as a temperature controller. PID controller has several proportional, integral, and derivative parameters, as seen in Figure 1 [28]–[32]. From Figure 1, $R(s)$ is the system input/setpoint, $C(s)$ is the system output, $G(s)$ is the system being controlled, that is the positive temperature coefficient (PTC) heater, and $H(s)$ is the system feedback, the AHT10 sensor. Meanwhile, (1) shows that u_P is a proportional controller that minimizes errors between system outputs and reference/feedback values without eliminating the errors [33]. u_I is an integral controller that functions to eliminate errors so that these errors become zero [34]. Then, u_D is a derivative controller that comes from derivation errors. This controller will be the most active when there is a rapid error change in the system [35]. A derivative controller can reduce oscillations in system output [28].

$$u = u_P + u_I + u_D = K_p e(t) + K_I \int_0^t e(t)\, d(t) + K_D \frac{d\, e(t)}{dt} \quad (1)$$

In (1), K_P, K_I, K_D are the parameters of the proportional, integral, and derivative control, and $e(t)$ is the error between the input and output of the system. This study used the trial-and-error method to conduct the PID controller tuning process. This method is one of the easiest PID tuning methods and does not require mathematical processing. However, there is no guarantee that the value issued by this method is the most optimal [36].

2.2. Hardware system

The hardware in the proposed system, as shown in Figure 2, consists of a microcontroller as a device controller, an AHT10 sensor used to sense the temperature and humidity values, and two fans inside the device. The fans in the proposed system have two functions. The first function is an intake channel for getting air into the device. The second function is an exhaust channel that removes hot air while cooling the device if the temperature exceeds the 2% setpoint. Moreover, the proposed system has a PTC heater to heat the air that enters the device. Liquid crystal display (LCD) and keypad are used as an interface between the user and the device, power supply unit serves to supply and convert alternating current (AC) into direct current (DC). Last, the step-down converter reduced the power to match the specifications other components require.

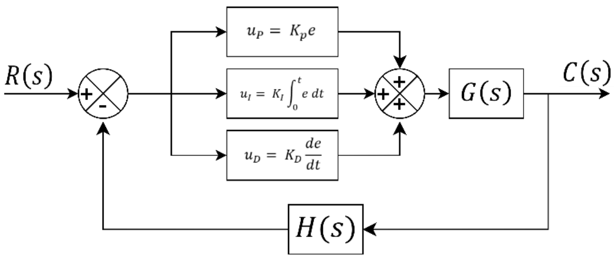


Figure 1. Control system block diagram

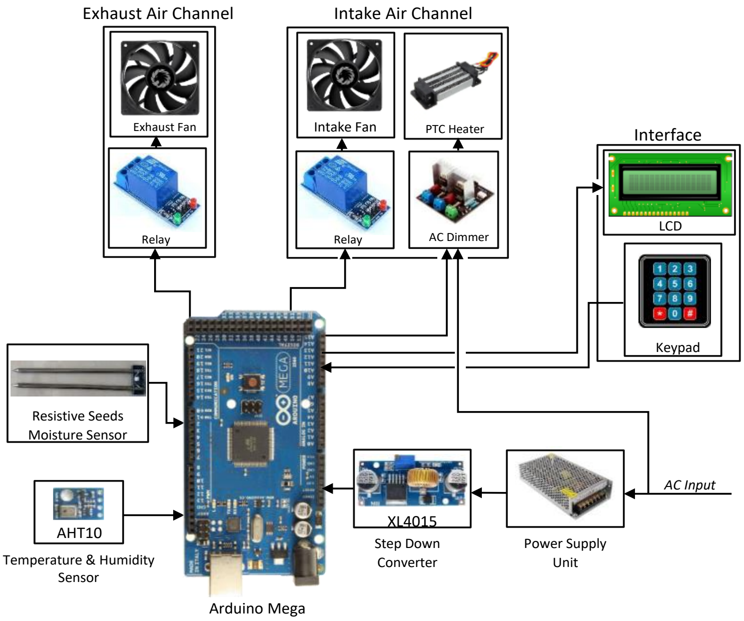


Figure 2. Electronic system design

In this study, the mechanical device is designed to be three main parts: solar collector, drying chamber, and panel box, as shown in Figure 3. The proposed system is also designed as a hybrid system. When the hybrid drying function is turned on, the solar collector is activated to collect solar heat. Inside the solar collector, an intake fan circulated the air into the drying chamber. The drying chamber has a solar window so sunlight can enter the device to help the drying process. In the drying chamber, a PTC heater functions as an electrical heat generator if needed. The panel box is placed to contain other supporting instruments. The mechanical design and dimensions of the solar collector, drying chamber, and panel box can be seen in Figure 3.

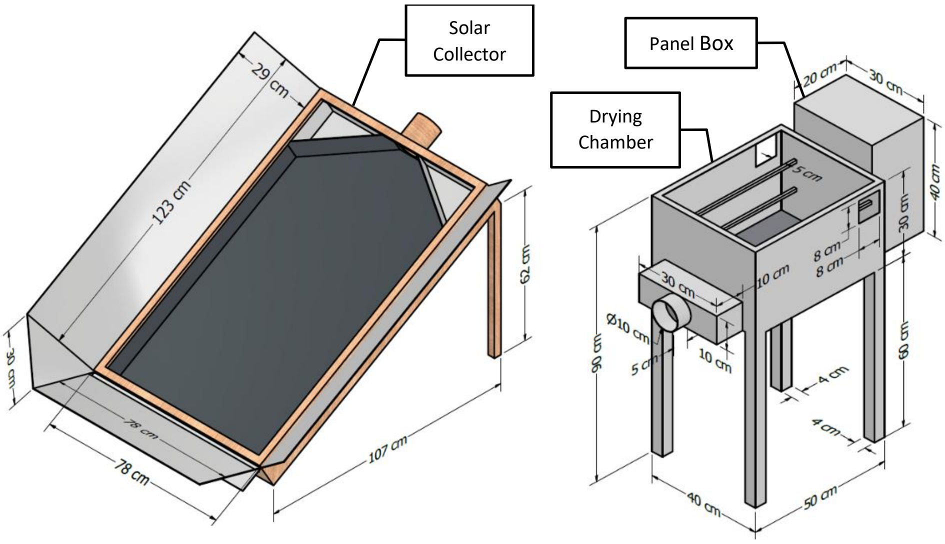


Figure 3. Mechanical design and dimensions of solar collector, drying chamber, and panel box

2.3. Experimental procedures

In this study, the experiment has been done on three drying methods carried out by the device. PID controller is used to regulate the temperature inside the device. The media used in this experiment are honey-processed coffee beans and wet cocoa beans. These two seeds have previously been separated from the fruit's skin and will be tested as a medium for the experiment of the three drying methods.

The optimal drying temperature of coffee beans is around 50 °C. However, the temperature used as the drying setpoint in this experiment is 60 °C. This temperature is still within safe limits without too much damaging the chemical content of the coffee beans [9]. Then for cocoa beans, the drying temperature is 60 °C. The drying temperature above 60 °C might increase bitterness and retention of the acetic acid [10]. According to Indonesia National Standard (SNI) regulation number 01-2907-2008, the maximum water content for coffee beans is 12.5%. According to SNI number 2323-2008, the maximum water content for cocoa beans is 7.4%. SNI itself is a standard set by the Indonesian government for various products. Unfortunately, this device's resistive seeds moisture sensor can only sense water content up to 16.60%. Because of this, the final setpoint of water content is 16.60%, and a drying temperature setpoint is 60 °C for coffee beans and cocoa beans. At the end of the experiments, the performance of all the drying methods is evaluated. The final water content of the seeds from all three drying methods was measured and compared to find out the performance. The experimental procedures for each drying method are as follows:

a. Natural drying

The experiment was carried out for this method during peak sun hour (PSH). PSH is a parameter that indicates the maximum sunlight time in one day. PSH for Bandung City, where the experiment was conducted, is ± 4 hours, around 10 AM to 2 PM. In this method, the seeds are dried in direct sunlight. The drying process is carried out without the help of any drying device.

b. Forced convection

The drying process in this method is carried out entirely by the device at night without the help of the sun's heat. The temperature setpoint in this experiment is 60 °C. It was done to determine how effective the device is at drying the seeds in a condition without any sun's heat. The experiment was carried out for 4 hours to match the duration of the experiment on the other two methods.

c. Hybrid drying

Similar to natural drying, the experimental procedure for this method is carried out for 4 hours at PSH time in Bandung City. The difference is that the drying device is activated to assist the drying process. So, for 4 hours, the seeds are dried by the sun's heat-assisted and drying device combination. In this experiment, the temperature setpoint is set at 60 °C.

3. RESULTS AND DISCUSSION

3.1. Device visualization

Figure 4 shows the realization of the device that has been made. The device comprises a solar collector, a drying chamber, and a panel box. The solar collector collects solar heat when the device activates the hybrid drying function. Inside the solar collector, an intake fan channels the air into the drying chamber. The drying chamber has a solar window to enable sunlight to help the drying process. A PTC heater is placed in the drying chamber as a heat generator. Lastly, there is a panel box that contains other supporting instruments.

Figure 4. Device visualization

3.2. Tuning and testing of the system with PID controller

The PID controller was tuning by six times with random options of PID parameters to obtain the best value, as shown in Table 1. Each tuning was carried out for 25 minutes in the room with an average temperature of 27 °C and an average humidity of 65% RH. The result of the temperature response for each PID parameter value shows in Table 2. The temperature response takes quite a long time to reach the threshold value and steady state. A constant variant with the fastest response to reach 100% set-point and settling point within the threshold area is needed in this study. Therefore, the parameters, such as rise time (T_r), peak time (T_p), settling time (T_s), and steady-state error (Offset), were compared to obtain the performance of each parameter. The set-point for this comparison is set at ±2%. It is because seeds are very sensitive to heat change. Suppose the drying temperature exceeds a specific value. In that case, it can damage the chemical compounds of the seed, which can be essential, especially in terms of the taste and the aroma released by these seeds.

Table 1. Options of the PID parameter value

Option	K_p	K_i	K_i
1	7,400	0	0
2	3,700	0	0
3	3,700	0	1.35
4	3,700	3.6	1.35
5	3,700	7.2	1.35
6	3,700	7.2	0

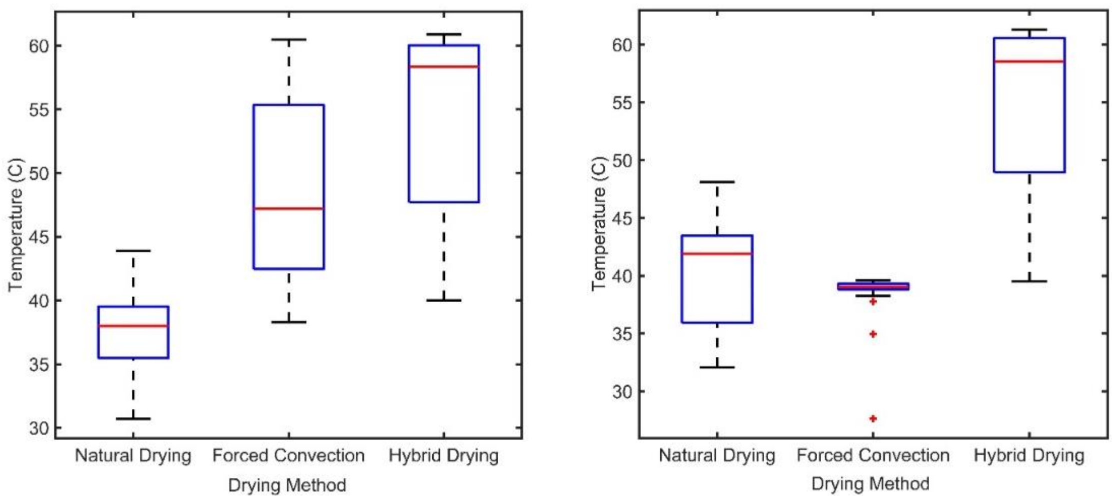
According to Table 2, the best gain value for applying the PID parameters in the system is option 5 with K_p=3,700, K_i=7.2, and K_d=1.35. These parameter values were embedded in the microcontroller and were used as the proposed system parameters because they had the fastest response among the other options. The response times were T_r at the 15th minute, T_p at the 17th minute, and T_s at the 12th minute. Additionally, the offset percentage for this variant is the smallest at 0.57%.

Table 2. The result of PID parameter tuning

Option	Measurement time (minutes)			Offset percentage (%)
	T_r	T_p	T_s	
1	-	-	22	2.00
2	-	-	-	2.53
3	-	-	-	3.35
4	21	25	13	0.78
5	15	17	12	0.57
6	-	-	14	1.58

3.3. Performance evaluation

This section describes the examination result of the proposed system by following the experimental procedures described in section 2.1 to find the performance system. Figure 5 shows the performance system in maintaining the coffee as shown in Figure 5(a) and cocoa bean temperature as shown in Figure 5(b). The proposed system, or hybrid drying system, has better performance than the other two drying systems for coffee and cocoa drying. The hybrid system can maintain the temperature in the drying chamber and has a higher temperature than the others, with an average temperature of 54.68 °C for coffee bean drying and 54.55 °C for cocoa bean drying. Although, the hybrid system produces an average temperature below the desired temperature of 60 °C. The controller not only tries to maintain the temperature still on high temperature, around 50 °C to 60 °C, but also controls the temperature not to exceed 60 °C as shown in Figures 5(a) and 5(b). Thus, the hybrid system can decrease the bean's water content faster and more effectively.



(a) (b)

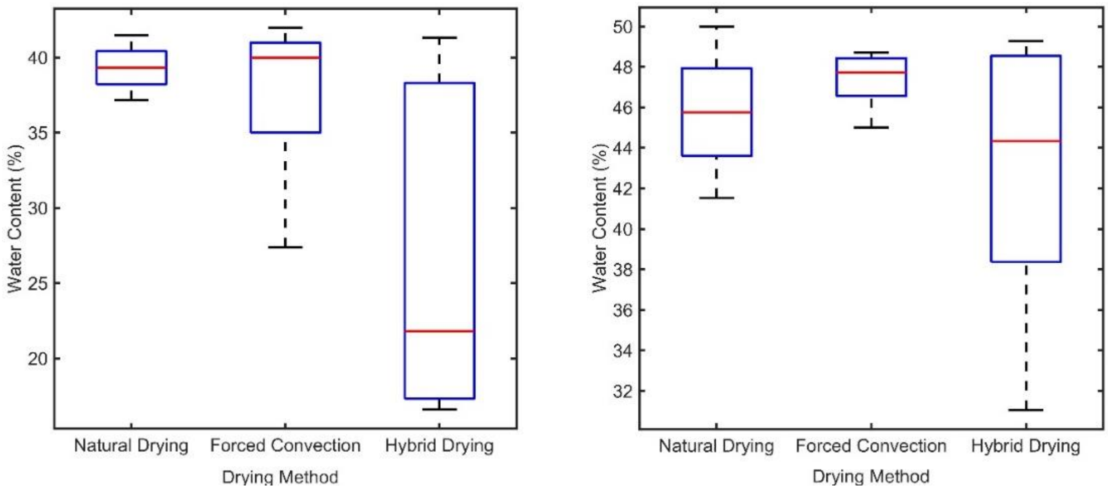
Figure 5. Performance comparison to maintain the temperature (a) coffee bean and (b) cocoa bean

The water content decreasing value of the drying process is shown in Figure 6 with Figure 6(a) for coffee bean and Figure 6(b) for cocoa bean. The proposed system performance was also evaluated based on the water content value after drying. Then, it was compared with the other methods. The result shows that the proposed system or hybrid drying performs better, with the water content value having the lowest value than the other methods. Moreover, the obtained average value of the proposed system is 27.38% and 42.67% for coffee and cocoa beans, respectively.

Based on the obtained result, the proposed system performs better than the other methods. Although, the result does not accord with the Indonesia National Standard (SNI) regulation. Still, the proposed system can show excellent performance in 4 hours. The outside temperature of the drying chamber can also affect the performance. Nevertheless, the proposed system manages the temperature inside the drying chamber by activating the fans so that the temperature stays at 60 °C.

$$Reduction\ (\%) = \left(\frac{X-Y}{X}\right) \times 100\% \quad (2)$$

Moreover, the reduction efficiency of bean water content was measured by (2). The reduction efficiency measures the ratio difference of bean water content before (X) and after (Y). The result shows that the proposed system produces the highest efficiency than other methods, as shown in Table 3, with 62.71% and 36.94% for coffee and cocoa beans, respectively.



(a) (b)

Figure 6. Performance comparison in reducing the water content (a) coffee bean and (b) cocoa bean

Table 3. The reduction efficiency of water content in beans

Method	Coffee bean			Cocoa bean		
	X (%)	Y (%)	Reduction (%)	X (%)	Y (%)	Reduction (%)
Natural drying	41.27	37.15	10.42	50.00	41.53	16.94
Forced convection	41.83	38.11	8.89	48.71	45.02	7.57
Hybrid drying (proposed system)	41.30	15.40	62.71	49.27	31.07	36.94

4. CONCLUSION

A drying system with a hybrid system was proposed in this study. The experiments examined the proposed system performance of two bean types, coffee and cocoa beans. Moreover, the proposed system was also compared with natural drying and forced convection methods. The experimental result showed that the proposed system performed excellently for three performance evaluations. The average temperature was obtained as the highest of the other methods, with 54.68 °C and 54.55 °C for coffee and cocoa beans. The water content can be reduced by an average of 27.38% and 42.67% for coffee and cocoa beans. Then, the proposed system also had the highest reduction efficiency of water content than the other methods, with 62.71% and 36.94% reductions for coffee and cocoa beans, respectively. The results indicate that the proposed hybrid system provides an advantage to the drying process, especially for obtaining and maintaining the temperature stays on a higher temperature and the desired heat. Thus, the water content during the drying process can be reduced and has the highest efficiency. However, the proposed system has to be improved to a heat distribution system to allow heat distribution evenly and accelerate the drying process.

ACKNOWLEDGEMENTS

The authors thank Telkom University for funding and support for this Hybrid Forced Convection Solar Dryer research.

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