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## Full Research Paper

# Simulation of fuzzy temperature controller during infrared dry blanching and dehydration of apple slices by intermittent heating method

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## Abstract

In this study, fuzzy temperature controller was designed using stepwise heating during the infrared irradiation of apple with intermittent heating method. For this purpose, the dry blanching process and dehydration of apple slices were examined at three temperatures of 70, 75 and 80°C based on inactivity of polyphenol oxidase enzyme (PPO) as blanching speed index and vitamin C preservation as maintaining quality index. The samples were removed from the infrared dryer in 2- minute intervals to separate the time required for the dry blanching process and dehydration of apple slices. For all temperatures, the heating process was continued until no sign of color change stemming from catechol reagent (adequacy of blanching). Finally, the fuzzy controller of the temperature with the feedback loop was designed, simulated, and implemented by comparing two first and second order transfer functions in MATLAB software. Simulation efficiency was examined using the indices of integral squared error (ISE), integral absolute error (IAE), integral time-weighted absolute error (ITAE) and steady state error ($e_{ss}$). These parameters must be close to zero. The results revealed that the temperature of 80°C and time of 15 minutes were appropriate for blanching operation and the temperature of 70°C was appropriate for dehydration. The simulation results confirmed that the higher order of the transfer function led to a faster response, but an increase in oscillations and reduction in the stability were not appropriate. For the first-order transfer function, the values of efficiency indices, including (ISE), (IAE) and (ITAE) were calculated to be 0.760, 0.821 and 0.589, respectively, of the second-order transfer function. The simulation indicated the reliability of the fuzzy control model and showed an acceptable computational efficiency, since the fuzzy rule test during simulation showed high sensitivity to maintain steady state error ($e_{ss}$) close to zero.

**Keywords:** Infrared, Apple, Intermittent heating, Fuzzy controller, Simulation.

## Introduction

In recent years, a significant increase in production volume has led to extensive effort to develop controller and automation systems in the food industry, and for this purpose, computer controllers are considered (Odetunji & Kehinde, 2005). The control of food processes due to the heterogeneity in the food product, the lack of accurate sensors to record key variables of the process, the sensitivity of the qualitative characteristics and the interaction of the control variables is relatively difficult. In the control of food processes, the main goal is food safety, high quality, minimal processing, high efficiency with minimal cost, and finally reduced cost (Mittal, 1996; Linko & Linko, 1998). The energy consumed during the process is very important from the point of view of engineering and economics. For consumers, the health, appearance, and sensory characteristics of the final product are very important. Thus, the main goal of a control system is to maintain maximum nutrient and safety of the product while optimizing energy consumption (Rywotycki, 2002).

Nowadays, the use of infrared heating for the drying of food due to its high productivity (between 80 and 90%) has gained popularity (Jaturonglumlert and Kiatsiriroat, 2010). One of the modern processes in the food industry is simultaneous infrared dry-blanching and dehydration (SIRDBD) of fruits and vegetables, which increase the quality of the final product

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and reduce environmental contamination (Zhu *et al*., 2010). Dried fruits and vegetables have been considered as a snack or as ready-to-eat products (Velickova *et al.*, 2014). In this regard, apples play an important role in the fruit basket of consumers. In addition to improving shelf-life, dried apple is also used in producing other products such as baby food (Doymaz, 2010).

Infrared heating is feasible in two continuous and intermittent methods. During continuous heating, the intensity of the radiation is kept constant and the high intensity of the radiation can lead to adverse changes in the color of the product. The use of intermittent heating is a solution to prevent undesirable quality changes during irradiation. In this method, the surface temperature of the product is kept constant. Thus, the advantage of the intermittent state is to save energy and improve the quality of the final product (Zhu and Pan, 2009). One advantage of infrared heating technology in the food industry is that its equipment has the capability of compression and automation with a high degree of control based on process parameters. The fast response time (low thermal inertia) makes the control of the infrared thermal processes easy and fast (Jun *et al.*, 2010).

The performance of many thermal processing operations for food products is strongly dependent on human control and monitoring. Some process control variables are unclear subjective and cannot be expressed merely as numerical data. However, human perceptions can be used in the form of fuzzy techniques presenting experimental data and then used to apply the control measures (Brown *et al*., 2001). The fuzzy logic tool is a mathematical method used to examine the phenomena, providing a structure with human reasoning capability. In fact, this tool provides the capability to express the probability of occurrence of a phenomenon verbally (such as high, low, moderate, and often). It provides diagnostic power in modeling. This method uses the theory of probabilities to explain the occurrence of a phenomenon. Thus, it can be a form of probabilistic modeling used in many engineering areas (Liu & Li, 2005).

Fuzzy logic has high popularity in achieving design and simulation of process control systems, especially in the food processing industry (Lao *et al.*, 2012). This method has provided an appropriate tool to deal with the uncertainties in food processes (Trystram, 2012). Fuzzy control is performed with this goal that it closes more to human thinking and education practices. This leads to automatic control of the process in the form of qualitative expressions such as low temperature, high rate of error other outputs in computer systems (Rywotycki, 2002). In fact, the main characteristic of fuzzy systems is that they are capable to provide the behavior of complex systems in the form of expressive formulations (Birle *et al.*, 2013).

Most of the fuzzy studies published in the food industry focused on controlling the process (Perrot *et al*., 2006). The process of dry-blanching and dehydration with infrared irradiation has not been investigated so far in the form of fuzzy modeling and the design of an automatic temperature controller. Non-linear models have been examined only in other drying methods and infrared heating control related to other products has been examined. For example, Brown et al. (2001) developed a fuzzy controller for the process of roasting wheat seeds with an infrared beam. Control rules were written using observations of the experiment and interviews with system operators. The results showed that in all experiments, the fuzzy controller could act as an operator and react quickly and predictably to process conditions. Some studies have also been conducted on control measures for drying in other thermal methods. Menlik et al. (2010) examined the behavior of apple slices under the effect of the freeze drying process using artificial neural network. Li et al. (2010) examined the control of drying the carrot slices in the microwave using fuzzy logic. Their results revealed that the quality of carrots was not greatly damaged by the fuzzy control strategy and the loss of time and energy was prevented. Cuccurullo et al. (2012) developed a microwave system for drying apple slices with temperature online control. The control system using infrared thermography was used to control the temperature by detecting the maximum instantaneous temperature among several product slices rather than one cut. In the latest studies, Sturm et al. (2014) studied the impact of two different control strategies, such as constant air temperature and constant product temperature on the quality and behavior of apple drying by the air displacement method. Vega et al. (2016) simulated the process of drying apple slices by hot air using feedback control system of the surface temperature. The results of these investigations revealed that the active application of product temperature control can prevent the product from overheating and thus prevent its degradation. Based on Luz et al. (2010) and Guillaume and Charnomordic (2001) in the feedback system, through comparing outputs and inputs and using their differences as a control tool, the pre-determined relationship between output and input is always maintained. If such systems operate without human intervention, it would be called as automatic control system.

In this study, infrared irradiation operation was programmed using an intermittent heating method through software for automatic temperature control and fuzzy control. For this purpose, in the first step, the optimum temperature for each operation of blanching and dehydration of apple product was determined separately based on a nutritional quality index (vitamin C) and the time needed to deactivate the polyphenol oxidase enzyme (PPO). Then, the appropriate timetable to change the temperature was determined. In the second step, the fuzzy controller was developed for controlling the temperature in blanching and dehydration, and its performance was simulated in the simulation environment (SIMULINK). This automation was performed for using the appropriate temperature for blanching and dehydration with the aim of improving the heating process, reducing the adverse qualitative effects, and finally increasing the process speed.

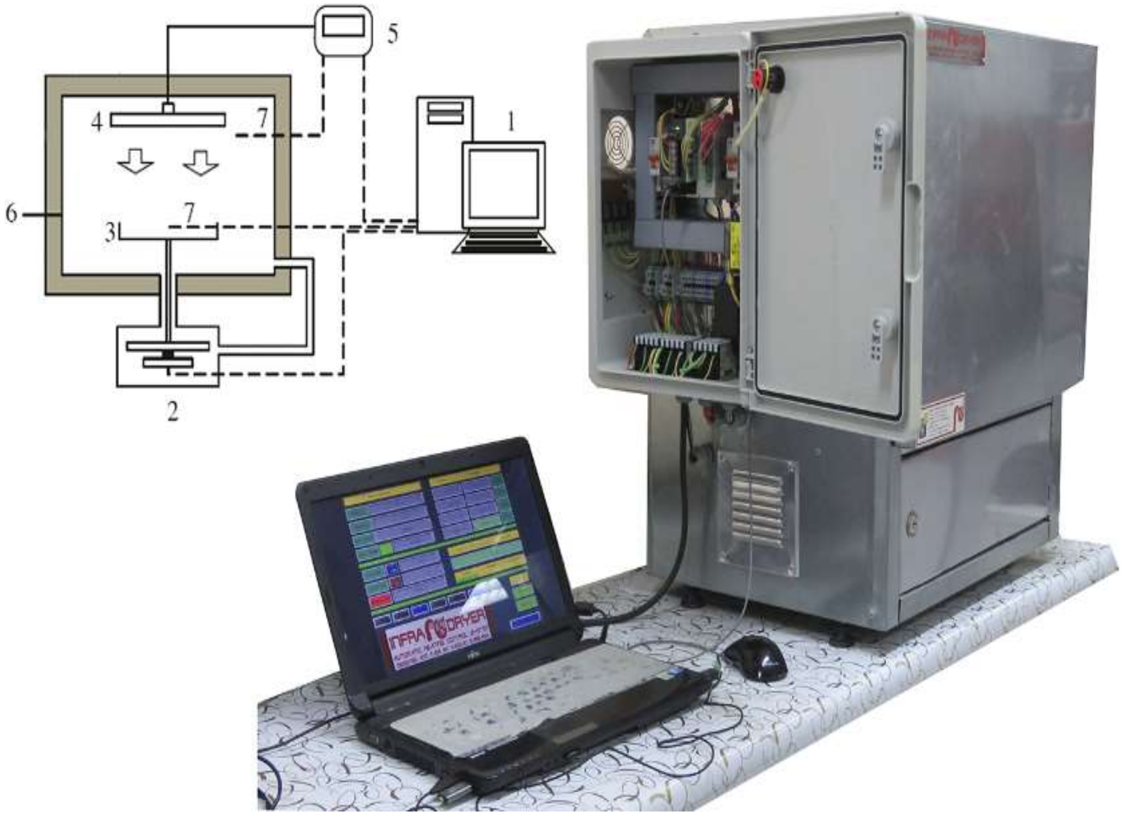


**Fig. 1. Infrared drying system and its accessories, (1) computer (2) balance (3) specimen tray (4) infrared ceramic radiator (5) programmable logic controller (6) drying chamber (7) thermocouples**

## Materials and Methods

### Preparation of Apple Slices

The apple (*Golden Delicious* variety) was kept at 0± 1°C and relative humidity of 90-95% (Acevedo *et al.*, 2008). After peeling the specimens, they were prepared in three sizes as slices with thicknesses of 5, 9 and 13 mm and 20 mm in diameter. The average of moisture content for apples was measured by the oven (Binder FD53) at 103° C for 24 hours and it was equal to 84± 1% based on the wet weight (AOAC, 2000).

### Infrared heating equipment

Figure 1 shows the components of the automatic drying system (Liu *et al*., 2014). This system can monitor the weight and control the temperature during irradiation. The surface temperature of the specimen in the drying chamber is continuously controlled using the K type thermocouple and the programmable logic controller (PLC). For testing, intermittent irradiation, operation was performed at three constant surface temperatures equal to 70, 75, 80°C.

### Process monitoring

Figure 2 shows different sections designed by the ADP 6.6.1 software manufactured by Beijer Company, Sweden. These sections include the temperature setting and monitoring page, weight recording and power setting (Figure 2 a) and the settings designed to perform the stepwise process of temperature (Figure 2 b). SoftPanel 6.6.1 software was used to run the designed program. Based on Octavia et al. (2014), the automatic temperature control system can be run over time using the user panel (Figure 2 b).


**Fig. 2. Different sections designed by ADP software, temperature, power and weight setting and monitoring (a), settings for a stepwise process at different temperatures (b)**

### Product quality characteristics

**A) Enzymatic Activity Investigation (Speed or Adequacy of blanching)**

To evaluate the enzymatic activity of polyphenol oxidase (PPO) and its effect on the product color, apple slices were removed from the infrared dryer in 2- minute intervals. Then, according to the method proposed by Lee et al (2002), 1 ml of catechol reagent was sprayed on the sample surface and the sample was immediately kept at 25°C (ambient temperature) for 15 minutes. To prepare a 0.1 molar catechol solution, 1.1011 gram catechol powder was dissolved in 100 ml distilled water in an Erlenmeyer container to obtain the given concentration level. As can be seen in Figure 3, the enzymatic activity is intensified in the presence of catechol precursor and its effect is manifested in the form of browning. The heating process was continued till the time no sign of color change stemming from catechol reagent addition on sample was observable. Consequently, the sample's color transformation was also scanned and image acquisition was performed. Flatbed scanner (HP Scanjet G2710), made in USA, was used according to the method of Romani et al (2009). The images featured a 300 dpi quality and were saved in TIFF-24 bit format. Color analysis of the obtained images was carried out in color spaces L*a*b* by the use of "color space convertor" plugin in ImageJ software, version 1.6.0.

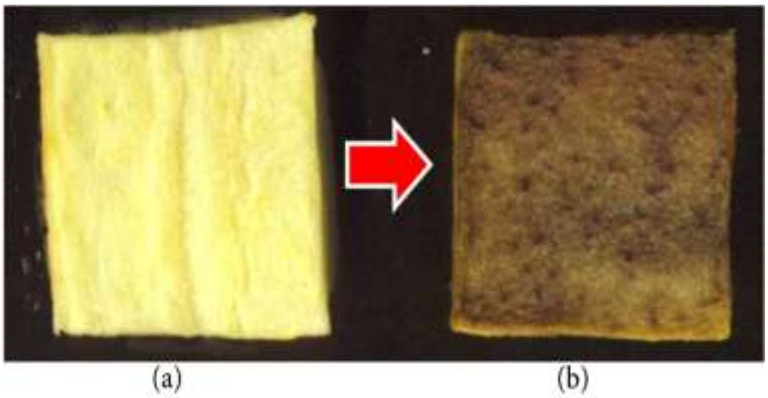


**Fig. 3. Enzymatic activity investigation, (a) Apple slice (5 mm) heated using 70°C for 30 min. (b) intensification of enzymatic activity and sample's change of color as a result of catechol reagent spray and the sample's final color after 15 min at 25°C.**

The browning index (BI) of the sample was calculated corresponding to the method proposed by Maskan (2001) based on equation (1) before making use of catechol reagent ($BI_0$) and in the presence of catechol precursor ($BI_c$). The variable "x" given in the equation is calculated based on equation (2). The differential of the browning index ($\Delta BI = BI_c - BI_0$) was computed as the enzymatic activity residual. Finally, the time required for the enzyme degradation until attaining a zero residual between the browning index ($\Delta BI=0$) was taken into account.

$$BI = \frac{[100(x-0.31)]}{0.17} \qquad (1)$$

$$x = \frac{(a+1.75L)}{(5.645L+a-3.012b)} \qquad (2)$$

**B) Vitamin C content (maintaining quality index)**

Vitamin C content determination of the processed sample and degradation modeling was carried out similar to the method of Timoumi et al. (2007) based on the titration by 2, 6-Dichlorophenol-Indophenol (DCPIP). The model can be defined as stated in equation (3). In this equation, C denotes Vitamin C content and k is the degradation kinetic constant ($min^{-1}$).

$$Ln\left(\frac{C}{C_0}\right) = -kt \qquad (3)$$

**Controller system design with the feedback loop**

The fuzzy controller was designed as a classical feedback control technique following the method of Aguilar et al. (2012). As shown in Figure (4), by considering the set temperature (r), the error (e), command (u), and output (y), one fuzzy controller with a feedback loop as considered.

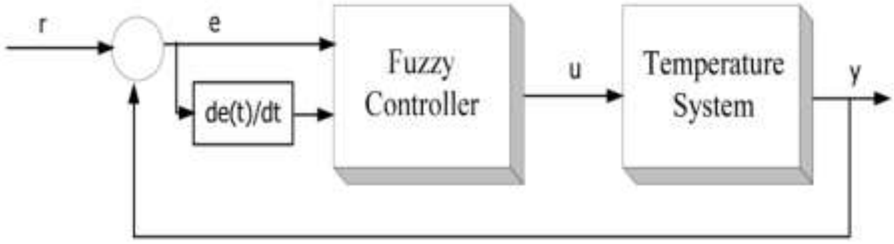


**Fig. 4. The block diagram of fuzzy temperature controller with feedback loop (Aguilar *et al.*, 2012)**

In the controlling operation of the temperature, two parameters as error (e) and the error variations (de) are important for control function and so the control decisions were made based on the results derived from equation (4). Based on Sharma (2011), the goal of designing a controller is to achieve zero-level error (e→0) with the time tendency to infinity (t→∞). The error variations (de) can also be calculated based on equation (5). In the fuzzy controller, error (e) and error variations (de) were used as inputs. The output command variations (du) from the controller were considered as output and can be calculated using equation (6)

$$e(t) = r(t) - y(t) \quad (4)$$

$$de = e(t) - e(t-1) \quad (5)$$

$$du = u(t) - u(t-1) \quad (6)$$

**Fuzzy temperature controller design (FLC)**

**A) Membership function**

To set the histogram of membership functions, the triangular membership function (trimf) as the simplest function was considered for inputs and outputs. This function has three different locational points of a, b, and c, whose variations are shown in Figure 5, and can be calculated by Equation 7 as proposed by Sivanandam et al. (2007) and Singh et al. (2012). Figure 6 shows the setting of membership functions for inputs (Figure 6a) and output (Figure 6b) in the fuzzy temperature controller

$$f(x;a,b,c) = \begin{cases} 0 & x < a \\ \frac{x-a}{b-a} & a \le x < b \\ \frac{c-x}{c-b} & b \le x \le c \\ 0 & c < x \end{cases} \quad (7)$$

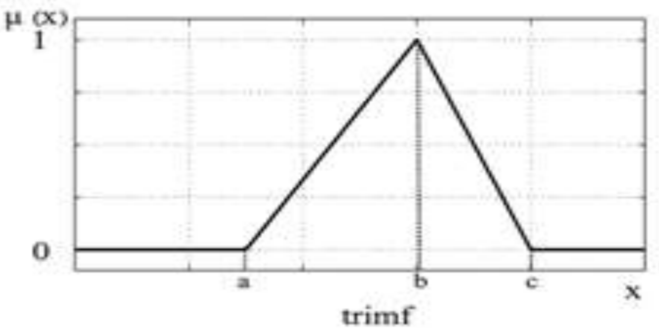


**Fig. 5.Triangular polynomial membership function**

**B. Description of Linguistic variables**

The linguistic description of the fuzzy system variables is presented in Table 1, based on the results of (4) and (5).

Figure 7 shows the temperature control system based on error and error variations in different modes. Different modes in this Figure include: a). The error in the form of LN and error variations in the form of LP indicate that the temperature is much higher than the considered level and the error rate is increasing b) error in the form of SN and error variations in the form of SP indicate that the temperature is somewhat higher than the set value and is decreasing to reach the considered level, c) the error in the form of zero and the error variations in the form of SN indicate that the temperature is very close to the considered temperature but it is increasing d) the error in the form of zero and the error variations in the form of SP indicate that the temperature is very close to the considered temperature but it is decreasing e) The error in the form of SP and the error variations in the form of SP indicate that the temperature is lower than the considered level and is more decreasing f) The error in the form of LP and error variations in the form of LN indicate the temperature is much lower than the considered level, but it is increasing

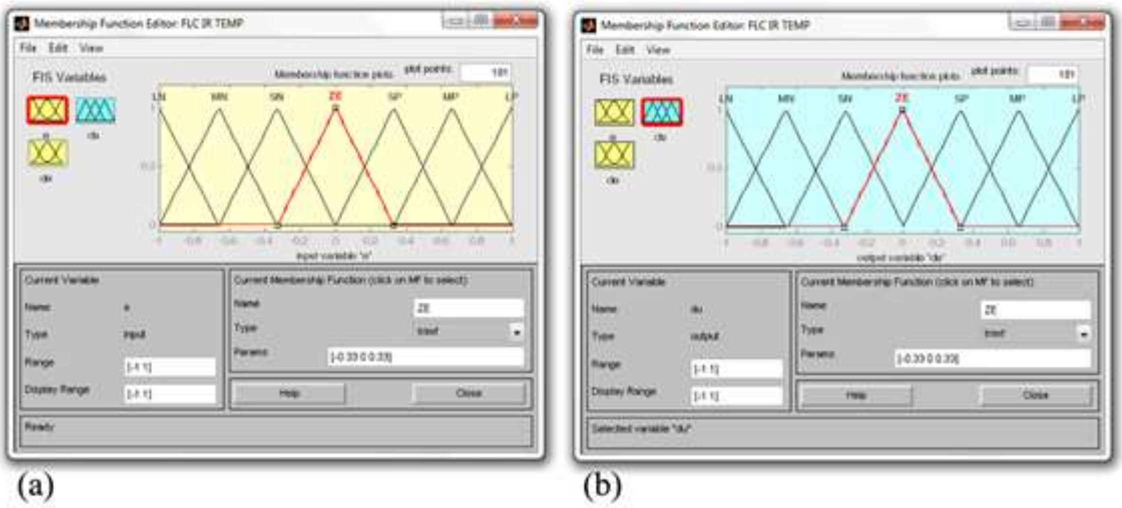


**Fig. 6. Histogram of membership functions for the error input (e) and the error variations (de) (a) and the output command difference (du) (b)**

**Table 1- Error Linguistic scale (e), error variations (de), and output command variations (du) in temperature setting**

| Row | Symbol | Term |
|---|---|---|
| **1** | LN | Large Negative |
| **2** | MN | Medium Negative |
| **3** | SN | Small Negative |
| **4** | ZE | Zero |
| **5** | SP | Small Positive |
| **6** | MP | Medium Positive |
| **7** | LP | Large Positive |

**C) The setting of rules for fuzzy control**

A set of fuzzy rules was considered verbally for system temperature control as equation model 8 in the editor of the fuzzy rule setting. These rules were considered in such a way that process temperature to remain slightly lower and close to the set temperature, and then, the heat is fed slowly to correct the error. The matrix of rules for the 49 possible rules is shown in Table 2. Figure 8 illustrates the three-dimensional diagram derived from the rules of the temperature controller of fuzzy model.

$$\textit{If } e(t) \textit{ is } LP \textit{ and } de(t) \textit{ is } SP, \textit{ then } du(t) \textit{ is } LP. \quad (8)$$

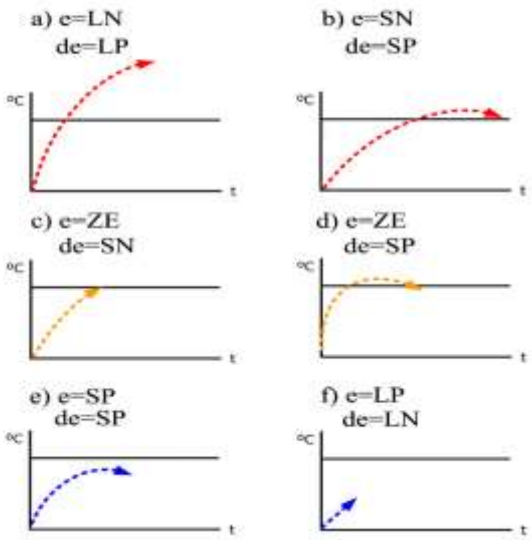


**Fig.7. Temperature setting system in different modes for error (e) and error variations (de)**

**Table 2- Matrix of writing rule for temperature control**

| | **de** | | | | | | |
|---|---|---|---|---|---|---|---|
| **e** | **LN** | **MN** | **SN** | **ZE** | **SP** | **MP** | **LP** |
| **LP** | LN | LN | LN | LP | LP | LP | LP |
| **MP** | LN | LN | LN | MP | LP | LP | LP |
| **SP** | LN | LN | LN | SP | MP | LP | LP |
| **ZE** | LN | LN | LN | ZE | SP | MP | LP |
| **SN** | LN | LN | LN | SN | ZE | SP | MP |
| **MN** | LN | LN | LN | MN | SN | ZE | SP |
| **LN** | LN | LN | LN | LN | MN | SN | ZE |

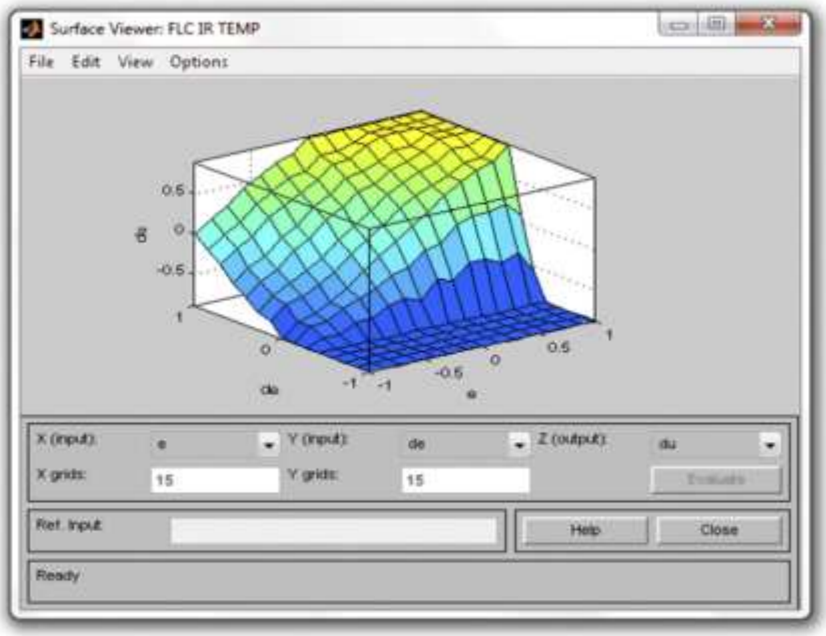


**Fig. 8. The three-dimensional diagram of error (e), error variation (de) and command difference (du) based on fuzzy rules**

**Simulation and implementation of fuzzy temperature controller**

The simulation was performed in the SIMULINK environment in MATLAB software. The output of the controller system was recorded dynamically based on two transfer functions. According to Berk et al. (2010), the first-order transfer function was considered as equation 9 and the second-order transfer function was considered as equation 10. These two functions were compared with each other. In these equations, S is the operator. The parameters of this simulation are listed in Table 3.

$$G(s) = \frac{1.2}{10s+1} \tag{9}$$

$$G(s) = \frac{1}{25s^2+5s+1} \tag{10}$$

**Table 3- Simulation model parameters**

| Simulation parameter | value |
|---|---|
| Solver | ode45 |
| RelTol | 1e-3 |
| Refine | 1 |
| MaxOrder | 5 |
| ZeroCross | on |

The fuzzy controller was simulated and implemented following the final model shown in Figure 9 by testing the first-order and zero-order functions. Figure 10 shows the structure of the fuzzy controller model in the simulation.

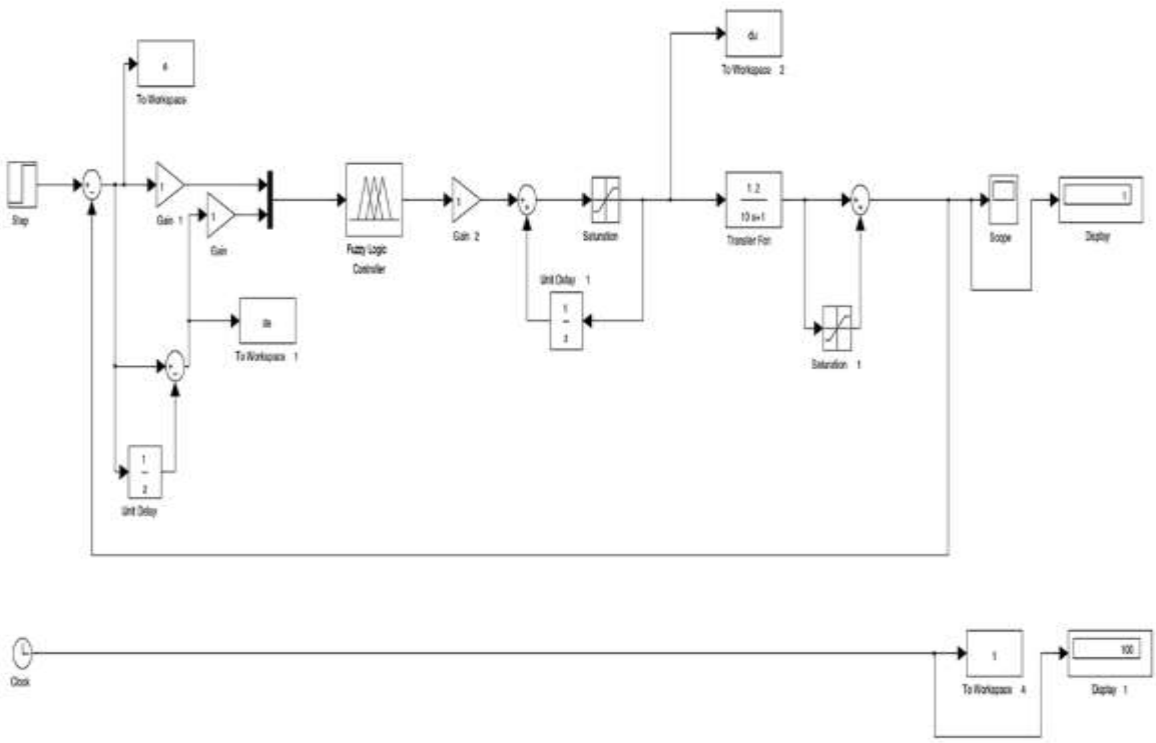


**Fig.9. Block diagram of closed loop simulated model for the implementation of fuzzy temperature controller**

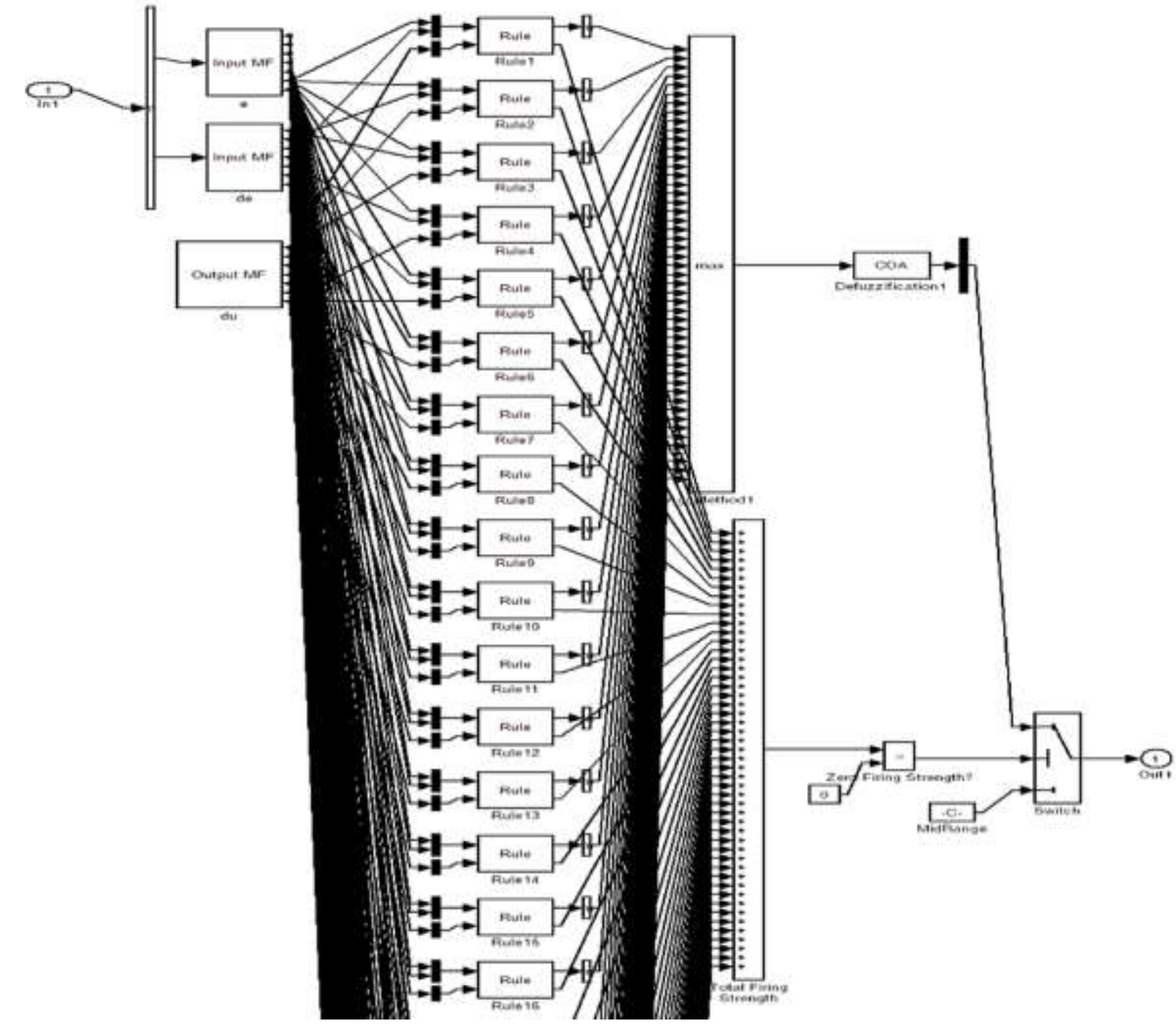


**Fig. 10. Fuzzy controller model structure in simulation (49 rules)**

**Simulation efficiency**

According to Pirrello et al. (2001), the controller efficiency was examined using Integral Squared Error (ISE) obtained by equation (11), Integral Absolute Error (IAE) by equation (12), and Integral Time-weighted Absolute Error (ITAE) by equation (13). Also, based on Vaishnav and Khan (2007), steady state error (ess) was also evaluated and compared for two transfer functions.

$$ISE = \int_0^\infty e^2 dt \quad (11)$$

$$IAE = \int_0^\infty |e| dt \quad (12)$$

$$ITAE = \int_0^\infty t\,|e| dt \quad (13)$$

**Results and discussion**

**Blanching time and vitamin degradation**

**A) The time required for Blanching**

Figure 11 demonstrates the mean comparisons of the time required for enzyme inactivation of apple slices in various thicknesses and various temperatures studied ($P<0.05$). As can be seen, the time required for polyphenol oxidase is significantly decreased with the increase in temperature or reduction in thickness. In line with this, Zhu et al. (2010) expressed that enzyme inactivation takes place faster generally in IR radiation on thinner slices and/or in higher surface temperatures. As reported by Lin et al. (2009), the increase in thickness causes a reduction in the uniform distribution of temperature inside the product. Many of the researchers have reported rapid heating rates and temperature as factors influencing the enzyme inactivation (MacDonald & Schaschke, 2000; Bingol *et al*., 2012; Jeevitha *et al*., 2013; Bingol *et al*., 2014 and Guiamba *et al.,* 2015).

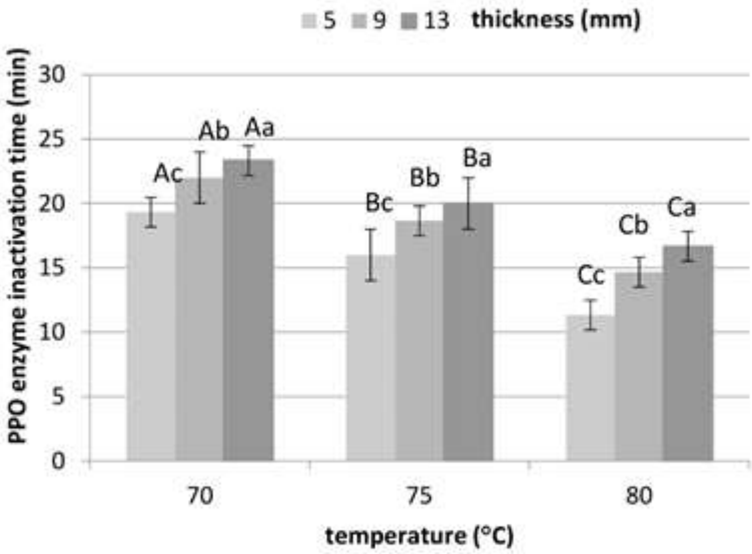


**Fig. 11. Statistical comparison of the time required for polyphenol oxidase inactivation in various treatments, the capital letters are comparisons between various temperatures and the small letters are comparisons between various thicknesses (P<0.05)**

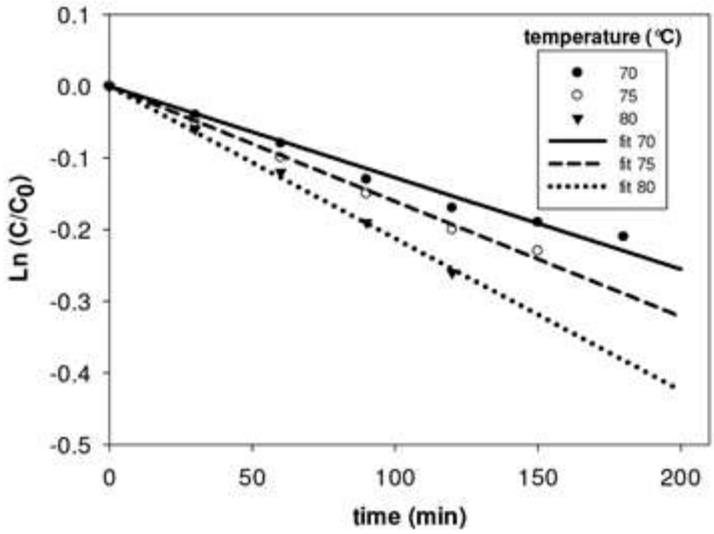


**Fig. 12. Vitamin C degradation kinetic model fit estimation in various radiation temperatures for a thickness of 5mm**

**B) Vitamin C degradation**

Figure 12 shows the diagram of kinetic model fit estimations for ascorbic acid degradation in various temperatures (thickness= 5mm). Table 4 summarizes the model's fit estimations on the empirical data in various treatments along with the statistical comparison of the degradation kinetic constants (k). In terms of the kinetic constant (k), the difference between the studied temperatures

(70, 75, and 80°C) was statistically significant (P<0.05) and the vitamin degradation kinetic constant (k) was found elevated with the increase in temperature. Joshi et al. (2011) reported that the use of Vitamin C, for its protection against polyphenols oxidation, as the major reason behind ascorbic acid oxidation under high temperature conditions. In the present study, the vitamin content of the sample was found almost similar in shorter times at various temperatures (Figure 12-in 30 minutes). Thus, the use of high temperature and short time (HTST), meanwhile accelerating the enzyme degradation and annihilation of oxidative enzymes can be appropriate in preserving the product quality. Therefore, it was found that the proper thickness for quickly blanching and the lower dependency of vitamin degradation to temperature was the thickness of 5 mm. These results are in compliance with what was found by Uddin *et al*., 2001; Chua *et al*., 2003; Timoumi *et al*., 2007; Wu *et al*., 2010; Kaya *et al*., 2010; and, Mrad *et al*., 2012.

**Table 4. Vitamin C degradation model fit estimations over the experimental data obtained from various treatments**

| Thickness | Temperature (°C) | k ($min^{-1}$) | Adj.$R^2$ | RMSE |
|---|---|---|---|---|
| **5** | 70 | $-0.001275^{Ca}$ | 0.9758 | 0.01237 |
| | 75 | $-0.001606^{Ba}$ | 0.9944 | 0.006606 |
| | 80 | $-0.002122^{Aa}$ | 0.9977 | 0.004916 |
| **9** | 70 | $-0.001152^{Cb}$ | 0.9981 | 0.005043 |
| | 75 | $-0.001533^{Bb}$ | 0.9953 | 0.008689 |
| | 80 | $-0.00196^{Ab}$ | 0.9933 | 0.01191 |
| **13** | 70 | $-0.0011^{Cb}$ | 0.9967 | 0.007898 |
| | 75 | $-0.00149^{Bb}$ | 0.9953 | 0.0105 |
| | 80 | $-0.001900^{Ab}$ | 0.989 | 0.01757 |

*Capital letters denote the comparisons between the test temperatures and the small letters denote the comparisons between the slices' thicknesses; similar letters denote the absence of significant difference (P<0.05)

**Temperature separation for blanching and dehydration**

The appropriate temperature for blanching operation was evaluated 80°C. For dehydration operation, the temperature of 70°C was evaluated to be more appropriate than 75°C. In this regard, Zhu et al. (2010) observed significantly higher enzyme transfer rates at 80°C during infrared radiation. They considered the most appropriate temperature at 75°C and a thickness of 5 mm. Table 5 shows the appropriate time classification for each step of the process and the changing pattern of radiation temperature based on the maximum time required for blanching. Thus, the undesired quality effects can be prevented by the gradual reduction of the surface temperature during irradiation. Also, blanching speed would be increased by high temperature heating in a short time (HTST). Nowak and Lewicki (2004) had argued that the effect of infrared energy on apple slices is increased when the water was removed from the product during heating. Thus, a reduction in surface temperature can have the desired effect in this regard.

**Table 5- Appropriate time and temperature separation for each blanching and dehydration operation**

| Time (min) | 0-15 | 15-30 | 30-45 | 45-60 | 60-75 |
|---|---|---|---|---|---|
| **Main process** | blanching | Blanching-dehydration | dehydration | dehydration | dehydration |
| **Temperature (°C)** | 80 | 75 | 70 | 70 | 70 |

**Response analysis in simulation**

Figure 13 shows the step response diagram in simulation. As seen, the first-order transfer function (Figure 13a) caused a more desired response than the second order transfer function (Figure 13b). In fact, increasing the order of the transfer function caused an increase in the response speed. However, this was done by increasing the cost of oscillations and reducing the stability, which is not desirable. In the output response of the simulation model, recorded by the first-order transfer function, there is almost no overshoot and the time to achieve steady state is 20.55 seconds. In output response derived from second-order transfer function, to achieve steady state after 37 seconds is possible, and the sharp drop of response is seen after achieving the response value equal to one. In this regard, Coeyman and Bowles (1996) stated that the fuzzy temperature controller reduces the rate of overshoot to the minimum level.

Ahuja and Kumar (2014) reported that the use of the fuzzy controller in the form of closed loop showed a zero percent of overshoot, in fact, had better performance than high-power control systems. Shakya et al. (2014) also reported that the fuzzy controller has a very small overshoot and has a faster response than other control methods. They stated that oscillatory responses can damage the system and the proper fuzzy controller does not show this dangerous oscillation during the unsteady period. Al Gizi et al. (2014) also stated that the appropriate fuzzy controller achieved a set point with a very small oscillation, which this oscillation is due to the initial speed of the system response.

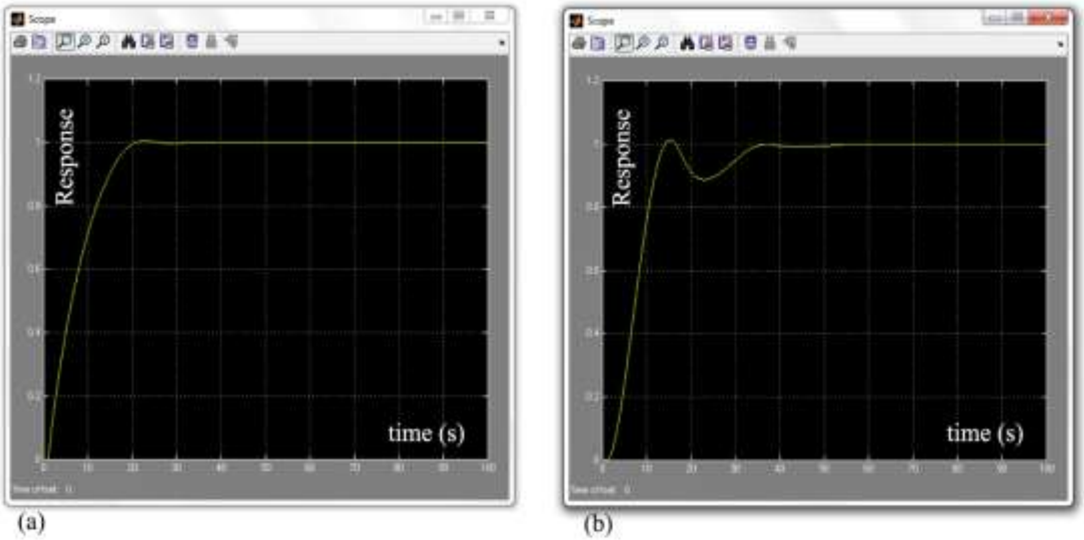


**Fig. 13. Step response diagram for the simulated model by recording the output by the first-order transfer function (a) and the second-order transfer function (b)**

Figure 14 shows the diagram of error (e) versus the response time for the first order transfer function and the second order transfer function. As seen, the first order function leads to faster achieving the zero error level in steady form. While the second order function leads to achieving the zero level earlier, but this state is not steady. Pirrello et al. (2001) observed a similar error process for the fuzzy controller of the rotatory drying process. Figure 15 shows the diagram of error variations (de) during the response time. The first order transfer function reduces the error variations to zero with more regular oscillations. Thus, based on Figure (16), the first-order transfer function would lead to achieve steady level of the command difference (du) faster.

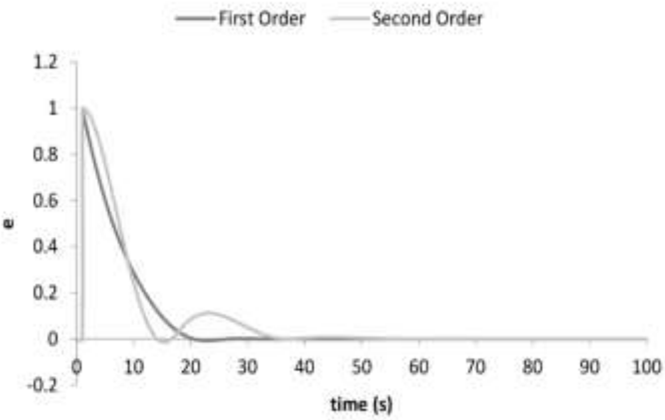


**Fig. 14. Diagram of error (e) versus response time for first order transfer function and second order transfer function**

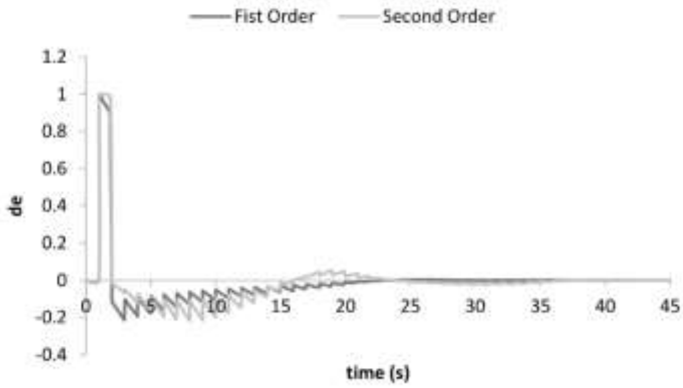


**Fig. 15. Diagram of error variations (de) during response time for first order transfer function and second order transfer function**

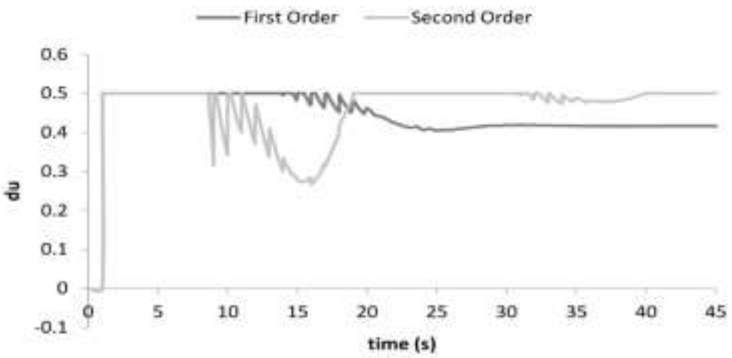


**Fig. 16. Diagram of command difference (du) during the response time for the first order transfer function and the second order transfer function**

**Efficiency of simulation**

Table 6 illustrates the simulation evaluation indices with the first order transfer function and the second order transfer function. In general, the first order transfer function has a desired state compared to the second order transfer model. The index of (ISE) for the first order transfer function was 0.760 times than that of the second-order transfer function. Alghannam (2012) considered the index of (IAE) appropriate to evaluate the computer simulation efficiency, which for the first-order transfer; it was seen 0.821 times than that of the second-order function. According to the ITAE index, it can be seen that in the long term implementation of controller, the error rate of the model simulated with the first order transfer function is 0.589 of the error resulting from the second-order transfer function. According to Al Gizi et al. (2014), the simulation results indicate the validity of the fuzzy model, since fuzzy rules test shows high sensitivity to system error to achieve the zero error level. The proposed model also provides acceptable computational efficiency to maintain a system steady state error close to zero. In this regard, the steady state error ($e_{ss}$) of the first order function is closer to zero.

**Table 6- Analysis of the efficiency of the simulated controller model with the output of different transfer functions**

| **Transfer function** | **Simulation evaluation index** | | | |
|---|---|---|---|---|
| | ISE | IAE | ITAE | $e_{ss}$ |
| **First order** | 3.718 | 6.485 | 39.944 | $-7.78\times10^{-12}$ |
| **second order** | 4.891 | 7.898 | 67.805 | $3.19\times10^{-7}$ |

**Conclusion**

In this study, the appropriate temperatures for infrared irradiation with intermittent heating method were separated based on the qualitative changes of apple slices in terms of deactivation of polyphenol oxidase (PPO) enzyme and vitamin C degradation. Accordingly, the temperature of 80°C was selected for blanching operation, and then, dehydration at 70°C was considered appropriate. The fuzzy temperature controller was set at target temperature to reduce the overshoot and it was implemented in the simulation environment. The results of the simulation with the first order transfer function confirmed the fuzzy rules, since they cause to achieve zero steady state error (ess). The application of fuzzy temperature controller in the irradiation with intermittent heating can be used as smart processing system in the food industry.

**References**


Acevedo, N. C., Briones, V., Buera, P., & Aguilera, J. M. (2008). Microstructure affects the rate of chemical, physical and color changes during storage of dried apple discs. *Journal of Food Engineering*, 85(2), 222-231.

Aguilar, R., Muñoz, V., & Callero, Y. (2012). Control application using fuzzy logic: Design of a fuzzy temperature controller. *Fuzzy Inference System-Theory and Applications*: InTech.

Ahuja, R. K., & Kumar, R. (2014). Design and Simulation of Fuzzy Logic Controller based Switched-Mode Power Supply. International *Journal of Electrical Engineering*, 2(5), 16-21.

Al Gizi, A. J., Mustafa, M., & Jebur, H. H. (2014). A novel design of high-sensitive fuzzy PID controller. *Applied Soft Computing*, 24, 794-805.

Alghannam, A. R. O. (2012). Design of a Simple Fuzzy Logic Control for Food Processing. Trends in Vital *Food and Control Engineering*: InTech.

AOAC. (2000). Official methods of analysis. 17th ed., Association of Official Analytical Chemists. Washington, DC, Unites States.

Berk, P., Rakun, J., Vindis, P., Stajnko, D., & Lakota, M. (2010). Temperature loop structure with fuzzy and classical controllers. *DAAAM International scientific book*, 117-128.

Birle, S., Hussein, M., & Becker, T. (2013). Fuzzy logic control and soft sensing applications in food and beverage processes. *Food Control*, 29(1), 254-269.

Brown, R., Rothwell, T., & Davidson, V. (2001). A fuzzy controller for infrared roasting of cereal grain. Canadian *Biosystems Engineering*, 43, 3.9-3.16.

Chua, K., Mujumdar, A., & Chou, S. (2003). Intermittent drying of bioproducts—an overview. *Bioresource Technology*, 90(3), 285-295.

Coeyman, B., & Bowles, J. (1996). Fuzzy logic applied to reboiler temperature control. Paper presented at the Fuzzy Systems, 1996, Proceedings of the Fifth IEEE International Conference on.

Cuccurullo, G., Giordano, L., Albanese, D., Cinquanta, L., & Di Matteo, M. (2012). Infrared thermography assisted control for apples microwave drying. *Journal of Food Engineering,* 112(4), 319-325.

Doymaz, İ. (2010). Effect of citric acid and blanching pre-treatments on drying and rehydration of Amasya red apples. *Food and Bioproducts Processing*, 88(2), 124-132.

Guillaume, S., & Charnomordic, B. (2001). Knowledge discovery for control purposes in food industry databases. *Fuzzy Sets and Systems*, 122(3), 487-497.

Jaturonglumlert, S., & Kiatsiriroat, T. (2010). Heat and mass transfer in combined convective and far-infrared drying of fruit leather. *Journal of Food Engineering*, 100(2), 254-260.

Jun, S., Krishnamurthy, K., Irudayaraj, J., and Demirci, A. (2010). Fundamentals and Theory of Infrared Radiation. In: Pan, Z., and Atungulu, G. G. (Eds.), Infrared Heating for Food and Agricultural Processing, CRC Press, pp. 1-18.

Kaya, A., Aydın, O., & Kolaylı, S. (2010). Effect of different drying conditions on the vitamin C (ascorbic acid) content of Hayward kiwifruits (*Actinidia deliciosa* Planch). *Food and Bioproducts Processing*, 88(2), 165-173.

Lao, S., Choy, K. L., Ho, G. T., Yam, R. C., Tsim, Y., & Poon, T. (2012). Achieving quality assurance functionality in the food industry using a hybrid case-based reasoning and fuzzy logic approach. *Expert Systems with Applications*, 39(5), 5251-5261.

Lee, M.-K., Kim, Y.-M., Kim, N.-Y., Kim, G.-N., Kim, S.-H., Bang, K.-S., & Park, I. (2002). Prevention of browning in potato with a heat-treated onion extract. Bioscience, *Biotechnology, and Biochemistry*, 66(4), 856-858.

Li, Z., Raghavan, G. V., & Wang, N. (2010). Carrot volatiles monitoring and control in microwave drying. *LWT-Food Science and Technology*, 43(2), 291-297.

Linko, S., & Linko, P. (1998). Developments in monitoring and control of food processes. *Food and Bioproducts Processing*, 76(3), 127-137.

Liu, Y., Zhu, W., Luo, L., Li, X., & Yu, H. (2014). A mathematical model for vacuum far-infrared drying of potato slices. *Drying Technology*, 32(2), 180-189.

Liu, Z., & Li, H.-X. (2005). A probabilistic fuzzy logic system for modeling and control. IEEE *Transactions on Fuzzy Systems*, 13(6), 848-859.

Luz, G. R., dos Santos Conceição, W. A., de Matos Jorge, L. M., Paraíso, P. R., & Andrade, C. M. G. (2010). Dynamic modeling and control of soybean meal drying in a direct rotary dryer. *Food and Bioproducts Processing*, 88(2), 90-98.

Maskan, M. (2001). Kinetics of colour change of kiwifruits during hot air and microwave drying. *Journal of Food Engineering*, 48(2), 169-175.

Menlik, T., Özdemir, M. B., & Kirmaci, V. (2010). Determination of freeze-drying behaviors of apples by artificial neural network. Expert Systems with Applications, 37(12), 7669-7677.

Mittal, G. S. (1996). Process controls in the food industry: Problems and solutions. *Food science and technology, Marcel Dekker*, Inc., 1-12.

Mrad, N. D., Boudhrioua, N., Kechaou, N., Courtois, F., & Bonazzi, C. (2012). Influence of air drying temperature on kinetics, physicochemical properties, total phenolic content and ascorbic acid of pears. *Food and Bioproducts Processing*, 90(3), 433-441.

Nowak, D., & Lewicki, P. P. (2004). Infrared drying of apple slices. *Innovative Food Science & Emerging Technologies*, 5(3), 353-360.

Octavia, N., Maung, M. M., & Tun, H. M. (2014). Performance Evaluation of Fuzzy Logic Controller in Water Bath Temperature Control System. International Journal of Science, *Engineering and Technology Research*, 3(6), 1623-1629.

Odetunji, O. A., & Kehinde, O. O. (2005). Computer simulation of fuzzy control system for gari fermentation plant. *Journal of Food Engineering*, 68(2), 197-207.

Perrot, N., Ioannou, I., Allais, I., Curt, C., Hossenlopp, J., & Trystram, G. (2006). Fuzzy concepts applied to food product quality control: A review. *Fuzzy Sets and Systems*, 157(9), 1145-1154.

Pirrello, L., Yliniemi, L., & Leiviskä, K. (2001). Development of a Fuzzy Logic Controller for a Rotary Dryer with Self-Tuning of Scaling Factor: University of Oulu.

Romani, S., Rocculi, P., Mendoza, F., & Dalla Rosa, M. (2009). Image characterization of potato chip appearance during frying. *Journal of Food Engineering*, 93(4), 487-494.

Rywotycki, R. (2002). The effect of fat temperature on heat energy consumption during frying of food. *Journal of Food Engineering*, 54(3), 257-261.

Shakya, R., Rajanwal, K., Patel, S., & Dinkar, S. (2014). Design and Simulation of PD, PID and Fuzzy Logic Controller for Industrial Application. *International Journal of Information and Computation Technology*, 4(4), 363-368.

Sharma, D. (2011). Designing and modeling fuzzy control Systems. *International Journal of Computer Applications*, 16(1), 46-53.

Singh, K., Mishra, A., & Mishra, H. (2012). Fuzzy analysis of sensory attributes of bread prepared from millet-based composite flours. *LWT-Food Science and Technology*, 48(2), 276-282.

Sivanandam, S., Sumathi, S., & Deepa, S. (2007). Introduction to fuzzy logic using MATLAB (Vol. 1): Springer.

Sturm, B., Vega, A.-M. N., & Hofacker, W. C. (2014). Influence of process control strategies on drying kinetics, colour and shrinkage of air dried apples. *Applied Thermal Engineering*, 62(2), 455-460.

Timoumi, S., Mihoubi, D., & Zagrouba, F. (2007). Shrinkage, vitamin C degradation and aroma losses during infra-red drying of apple slices. *LWT- Food Science and Technology*, 40(9), 1648-1654.

Trystram, G. (2012). Modelling of food and food processes. Journal of Food Engineering, 110(2), 269-277.

Uddin, M., Hawlader, M., & Zhou, L. (2001). Kinetics of ascorbic acid degradation in dried kiwifruits during storage. *Drying Technology*, 19(2), 437-446.

Vaishnav, S., & Khan, Z. (2007). Design and performance of PID and fuzzy logic controller with smaller rule set for higher order system. Paper presented at the Proceedings of the World Congress on Engineering and Computer Science.

Vega, A.-M. N., Sturm, B., & Hofacker, W. (2016). Simulation of the convective drying process with automatic control of surface temperature. *Journal of Food Engineering*, 170, 16-23.

Velickova, E., Winkelhausen, E., & Kuzmanova, S. (2014). Physical and sensory properties of ready to eat apple chips produced by osmo-convective drying. *Journal of food science and technology*, 51(12), 3691-3701.

Wu, G.-C., Zhang, M., Mujumdar, A. S., & Wang, R. (2010). Effect of calcium ion and microwave power on structural and quality changes in drying of apple slices. *Drying Technology*, 28(4), 517-522.

Zhu, Y., & Pan, Z. (2009). Processing and quality characteristics of apple slices under simultaneous infrared dry-blanching and dehydration with continuous heating. *Journal of Food Engineering*, 90(4), 441-452. doi:http://dx.doi.org/10.1016/j.jfoodeng.2008.07.015

Zhu, Y., Pan, Z., McHugh, T. H., & Barrett, D. M. (2010). Processing and quality characteristics of apple slices processed under simultaneous infrared dry-blanching and dehydration with intermittent heating. *Journal of Food Engineering*, 97(1), 8-16.

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# شبیه‌سازی کنترل‌کننده فازی دما طی فرآیند بلانچینگ خشک و آبزدایی مادون قرمز برش‌های سیب با روش حرارت‌دهی متناوب

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## چکیده

در این مطالعه، حرارت‌دهی مرحله‌ای و کنترل‌کننده فازی دما طی پرتودهی مادون قرمز سیب با روش حرارت‌دهی متناوب طراحی شد. بدین منظور، فرآیند بلانچینگ خشک و آبزدایی همزمان برش‌های سیب در سه دمای ۷۰، ۷۵ و ۸۰ درجه سانتی‌گراد براساس غیرفعال‌سازی آنزیم پلی‌فنل اکسیداز یا PPO (شاخص سرعت بلانچینگ) و حفظ ویتامین C (شاخص ثبات کیفیت) مطالعه شد. نمونه‌ها از خشک‌کن مادون قرمز با فاصله زمانی ۲ دقیقه به‌منظور جداسازی اختصاصی زمان بلانچینگ خشک و آبزدایی برش‌های سیب، خارج شدند. برای تمامی دماها، فرآیند حرارتی تا زمان عدم تغییرات رنگ ناشی از معرف کاتکول ادامه یافت (کفایت بلانچینگ). در نهایت، کنترل‌کننده فازی دما با حلقه پسخور با مقایسه دو تابع انتقال مرتبه یک و مرتبه دو در نرم‌افزار MATLAB طراحی، شبیه‌سازی و اجرا گردید. کارایی شبیه‌سازی با استفاده از شاخص‌های انتگرال مربع خطا (ISE)، انتگرال قدر مطلق خطا (IAE) و انتگرال قدرمطلق خطا در زمان (ITAE) و خطای شرایط پایا ($e_{ss}$) بررسی شد. این پارامترها بایستی به صفر نزدیک باشند. نتایج نشان داد که دمای ۸۰ درجه سانتی‌گراد به مدت ۱۵ دقیقه برای عملیات بلانچینگ و دمای ۷۰ درجه سانتی‌گراد برای عملیات آبزدایی مناسب بود. نتایج شبیه‌سازی تایید کرد که مرتبه بالاتر تابع انتقال موجب پاسخ سریع‌تر شد، اما افزایش نوسانات و کاهش پایداری مطلوب نبود. برای تابع انتقال مرتبه یک، شاخص‌های کارایی شامل (ISE)، (IAE) و (ITAE) به‌ترتیب ۰/۷۶۰، ۰/۸۲۱ و ۰/۵۸۹ برابر تابع انتقال مرتبه دو محاسبه شد. شبیه‌سازی نشان‌دهنده اعتبار مدل کنترل فازی بود و کارایی محاسباتی قابل قبولی نشان داد؛ زیرا آزمون قوانین فازی طی شبیه‌سازی حساسیت بالایی به حفظ خطای پایای ($e_{ss}$) نزدیک به صفر نشان داد.

**واژه‌های کلیدی:** مادون قرمز، سیب، حرارت‌دهی متناوب، کنترل‌کننده فازی، شبیه‌سازی.

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