Simulation and control of fan speed in a solar dryer for optimization of energy efficiency

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Abstract: In a forced convection solar dryer, the dryer efficiency is continuously changing during the drying process due to changes of solar radiation and temperature. So, it is important to use a control system to optimize energy efficiency based on changing drying factors. For this reason, a controller was designed, simulated and evaluated. In this research, fan speed was simulated and controlled based on changing system variables accordingly to maintain the optimized efficiency. Fan speed was simulated by SIMULINK toolbar of MATLAB software. The dryer efficiency was determined by considering the mathematical relations and monitoring the air temperature in 3 positions: inlet and outlet of collector and outlet of drying chamber. All experiments were carried out in three replications. The current and optimized dryer efficiencies were calculated by using the control program. Results showed that the simulated model was capable of modeling fan speed. So, statistical analysis showed that the control system highly improved the dryer efficiency throughout its operation at probability level of 1%.

Keywords: control system, efficiency, fan speed, simulation, solar dryer

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1 Introduction

Drying and dehydration of fresh fruits and vegetables is one of the most energy-intensive processes in the food industry and a promising method of reducing postharvest losses. Improving energy efficiency by only 1% could result as 10% increase in profits (Dattatreya and Samuel, 2006).

Nowadays, optimization of solar systems is used to reduce system total cost, increase life cycle savings and improve thermal efficiency. It is very demanding for optimal utilization of solar resources to meet the energy demands (Sharma and Siddhartha, 2012). Some researches are carried out to improve dryer operation by controlling dryer parameters.

Bruce and McFarlane (1992) designed a feedback-plus-feed forward controller using a computer simulation for a mixed-flow grain dryer. Results showed that the feed forward term had much better control in comparison with feedback alone but the accuracy of the feed forward control was limited by systematic errors in measurements of the input moisture.

Rodriguez, Vasseur and Countois (1996) controlled the final moisture content of the product in order to increase the dryer productivity. Two variables were chosen to be controlled: the drum speed and the steam pressure. Results showed that classic control was not sufficient enough to eliminate some process perturbations. Therefore, the setup was modified by adding an actuator, in this case an inductive electric heater.

Fuller and Charters (1997) controlled the exhaust fan in a solar tunnel dryer. Activation of exhaust fan was

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made using the measured air relative humidity inside and outside the dryer. Fan operating time was reduced by 67% in comparison with continuous fan operation. Reduced fan operation also optimized the drying air temperatures in the dryer.

Stefanoviand and Staki (2000) investigated the effects of control parameters on a dryer system by the help of computer simulation.

Didriksen (2001) developed a dynamic model for sugar beet rotary dyer. Traditional control systems were compared with predictive control by simulation.

Temple and Van Boxtel (2001) investigated a control system on a laboratory tea fluid-bed dryer. A simulation model was used by MATLAB software. This model explored the operating region of the dryer, and various disturbances affect the drying time. Results showed that the control system was significantly better than the manual system used previously.

Srzednicki et al (2005) developed a control system for rice drying. They used a dryer simulation program for investigating the effects of control parameters on each other and optimizing drying process. They obtained similar results for laboratory and simulated data

Smitabhindua et al (2007) investigated banana solar dryer operation by a simulated model. The model was confirmed by comparing simulated and real data and it was possible to optimize the dryer parameters by this model.

Boulemtafes-Boukadoum and Benzaoui (2011) investigated energy and energy analysis of a mint solar dryer. They estimated useful energy received by the heater and that was really used during drying. So, they estimated the energy losses during the drying process.

2 Materials and methods

The experimental dryer (Figure 1) is a forced convection solar dryer for drying leafy vegetables (Soheili et al., 2006). Hot air in this dryer is provided by forced convection through an air solar collector.

The dryer has 2 main parts: fined-flat collector and dryer chamber. The area of collector is 1.83 m^2. The dryer chamber has an axial tube fan and two sliding trays with a total area of 1 m^2. An axial tube fan with 12 cm in diameter, 210 m^3/h flow, 2,300 rpm, 38 W, 220 V, 50 Hz-AC (Soheili et al., 2006).

Figure 1 Experimental forced convection solar dryer

A controller was simulated, constructed and evaluated to change fan speed to optimize dryer energy efficiency. The mathematical equations to describe relationship between the dryer efficiency and the outlet air flow speed were derived.

To measure temperature, the temperature sensors (SMT 160-30) were installed in the collector inlet (T_1), collector outlet (T_2) and in the dry chamber exit (T_3). Determination of fan current speed is obtained through two infra-red transmitter and receiver sensors that located in both sides of the fan vanes.

All experiments were carried out in three replications from 9 am to 5 pm in July with an average ambient temperature of 39°C and the monthly average of air relative humidity of 39% (Anonymous, 2009). In each replication, 5 kg of mint (with initial moisture content of about 80%) was dried in the dryer. A digital hotwire anemometer with a precision of 0.1 m/s was used to measure the air speed of the fan outlet. A program was written in Visual Basic 6.0 to control the fan speed. A feedback control system was designed to reduce errors. To link the user to the hardware, an ActiveX control was programmed and installed on the computer being executable in Visual Basic 6.0. Using "Mscomm" control, receiving and sending information from/to RS-232 port become possible. To model fan speed, the system was simulated in SIMULINK part of MATLAB software. To evaluate the simulated model, real and simulated data were compared. Experiments data were analyzed using SPSS 12.0 statistical software.

2.1 Calculation of dryer efficiency

The general efficiency of a convective solar dryer is shown by Equation (1) (Augustus Leon, Kumar and Bhattacharya, 2002):

$$E = \frac{M_w L}{I_t A_c + E_f} \quad (1)$$

where, E: current dryer efficiency, decimal; M_w: evaporated moisture mass of the product, kg; L: specific latent heat of water vaporization, kJ/kg; I_t: solar radiation energy per collecting area, kJ/m^2; A_C: collector area, m^2; E_f: fan energy, kJ.

As the aim of using automatic control system is to change the fan speed to optimize the dryer efficiency, it is necessary to formulate a relationship in which the efficiency of the dryer is subjected to the fan speed as a controlled variable.

2.1.1 Total solar radiation energy calculation in the collector

The quantity of solar radiation energy in collector area is equal to the absorbed heat energy in it (Duffie and Beckman, 1991):

$$\sum I_t A_c = \sum \frac{Q_{co}}{E_c} \quad (2)$$

where, $I_t.A_c$: total solar radiation energy in collector area, kJ; Q_{co}: absorbed heat energy by collector, kJ; E_c: collector efficiency. 40% for this solar drier (Soheili Mehdizadeh et al., 2006)

Based on energy balance equation (Soheili Mehdizadeh et al., 2006):

$$Q_{co} = MC_p(T_2 - T_1) \quad (3)$$

where, M: air mass (mixed of dry and wet air), kg; C_p: air specific heat, at 1 atmosphere pressure, 1.006 kJ/ (kg K); T_2: air temperature at the collector exit, K; T_1: air temperature at the collector entrance, K

By flow continuity law, the air volume transit from collector is equal to:

$$V_c A_c t = V_1 A_f t \quad (4)$$

where, t: time, s; V_c: air velocity in collector, m/s; A_c: area of collector, 1.83 m^2; V_1: air velocity in the fan outlet, m/s; A_f: fan area, m^2.

The total absorbed heat energy by collector is equal to:

$$Q_{co} = \frac{PnV_1 A_f tC_p(T_2 - T_1)}{RT_1} \quad (5)$$

where, P: ambient pressure, Pa; n: air molecular weight, kg/kmol; R: universal gas constant, 8134.4 J/(kmol·K)

With putting Equation (5) into Equation (2), the total solar radiation energy in the collector area is equal to:

$$\sum I_t A_c = \frac{PnV_1 A_f tC_p(T_2 - T_1)}{E_c RT_1} \quad (6)$$

2.1.2 Calculation of necessary energy for product moisture evaporation

Based on energy balance equation, the necessary energy for evaporation of product moisture is equal to:

$$Q_{out} = M_w L = MC_p(T_2 - T_3) \quad (7)$$

where, T_3: air temperature at the dryer chamber exit, K.

Similar to equations for calculating Q_{co}, the necessary energy for product moisture evaporation is equal to:

$$Q_{out} = \frac{2PnV_1 A_f tC_p(T_2 - T_3)}{R(T_2 + T_3)} \quad (8)$$

2.1.3 Fan electric energy calculation

The fan electric energy is (Morey and Gustafson., 1978):

$$E_f = \frac{P_w t}{E_E E_m} \quad (9)$$

where, E_f : fan energy, kJ; P_w: power of fan outlet air, W; t: time, s; E_E: electromotor electric efficiency, %; E_m: impeller mechanical efficiency, %

The power of outlet air from fan (Bleier, 1998) is:

$$P_w = 9.81QTp \quad (10)$$

where, Tp: total pressure, mmWC; Q: air flow, m^3/s.

$$Tp = Sp + Vp \quad (11)$$

where, Sp: static pressure, mmWC; Vp: velocity pressure, mmWC.

Velocity pressure calculates from (Bleier, 1998):

$$Vp = 0.051\rho V_1^2 \quad (12)$$

where, L_o: product thickness on tray, m.

Fan electric energy is equal to:

$$E_f = \left(\frac{9.81tV_1 A_f}{1000E_E E_m}\right)\left(S_p + 0.051\frac{pnV_1^2}{RT_2}\right) \quad (13)$$

2.1.4 Optimum dryer efficiency calculation

Putting Equations (6), (8) and (13) into Equation (1), the energy efficiency equation is obtained based on air speed in the fan outlet (V_1). The optimum air speed in the fan outlet was found by partially differentiating equation of energy efficiency relative to V_0 and equating to 0.

$$\frac{\partial E}{\partial V_o} = 0 \Rightarrow V_o = \frac{220 L_0 R T_2}{Pn} \quad (14)$$

where, V_o: optimum air speed in the fan outlet, m/s.

2.1.5 Relation between air speed in the fan outlet and fan speed

To measure the air speed of the fan outlet, a digital hotwire anemometer with precision of 0.1 m/s was used. A program was written in Visual Basic 6.0 to control the speed of the fan. The calibration equation with high coefficient of determination (R^2=0.99) was found for the fan speed. Figure 2 shows the variation of the fan outlet air speed with the fan speed.

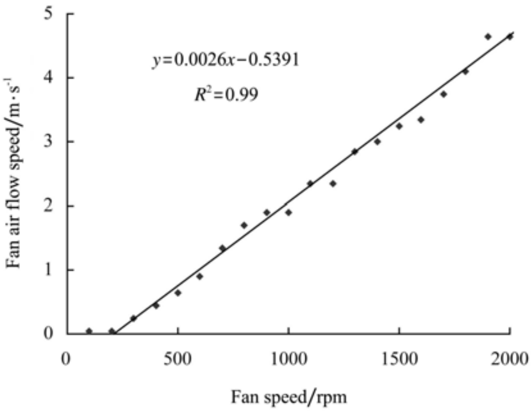

Figure 2 Variation of the fan outlet air speed with the fan speed

2.2 Automatic control system

The automatic control system consists of two micro controllers of ATMEGA 8535-16PI, five volt regulator, two crystals of 16 MHz, an IC MAX 232 as an interface between RS-232 port and micro controller, an infra-red rays receiver (TSOP1738) and transmitter (TSAL6400) sensors,, an opto-coupler (to convert signals), a triac (to direct current when reached to a specified value), a 9 volt adaptor and digital temperature sensors (SMT 160-30).

A feedback control system was designed to reduce error between the optimum and current optimum fan speeds (Figure 3).

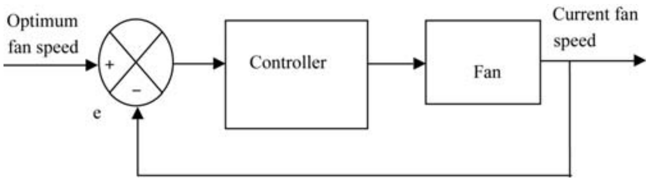

Figure 3 Block diagram of fan speed control system

2.3 Fan Simulation

To investigate the controller's behavior, fan was simulated by SIMULINK part of MATLAB7 software. Figure 4 shows fan simulation block diagram by MATLAB Software. System input is optimum engine speed and system output is real engine speed. Fan engine specifications are: armature resistance: 10 Ω, Engine torque constant: 3.56 N m/A (K_i) and Back EMF constant: 9.55 Vs (K_b).

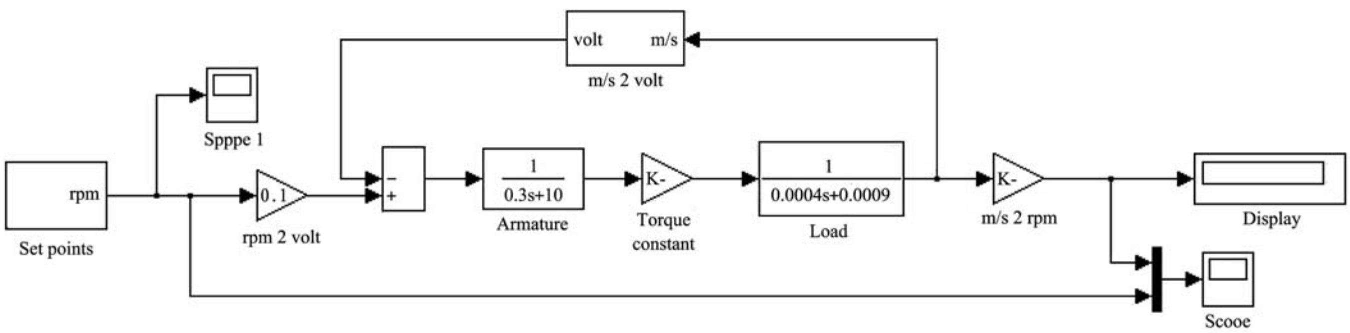

Figure 4 Fan simulation block diagram by MATLAB Software

3 Results and discussion

3.1 Evaluation of simulated model for fan speed

To evaluate simulated model, simulated and real fan speed data were compared. Figure 5 shows the relation between simulated and real fan speeds. Results showed that there is no difference between simulated and real fan speed with high coefficient of determination (R^2=0.9998). It shows that the simulated model is useful to predict control system behavior. A paired-mean test was carried out by Excel software to compare simulated model data with real data. Results showed that at the probability level of 5% there is no significant difference between real and simulated fan speeds. So results showed the simulated model is useful for modeling fan speed control system.

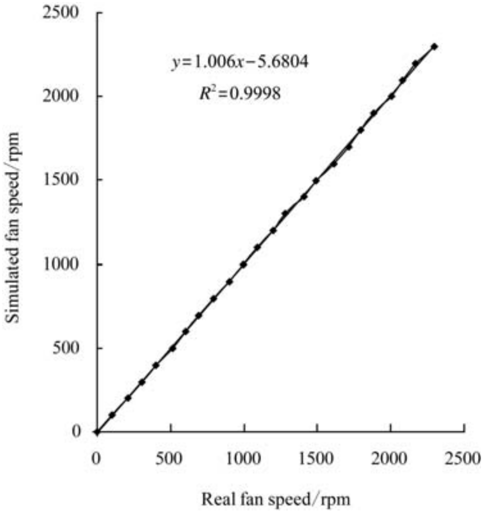

Figure 5 Comparison of real and simulated fan speed

So, to evaluate simulated model, the fan speed of 1700 rpm was imported to the system as an input. Figure 6 shows the behavior of system to input speed. This model shows that the system is capable of maintaining fan speed around the optimum value after 0.3 s. Variation of fan speed around the optimum level is because of friction and inertia engine effects.

Figure 6 shows the response of system to input speed (as an example: 1700 rpm).

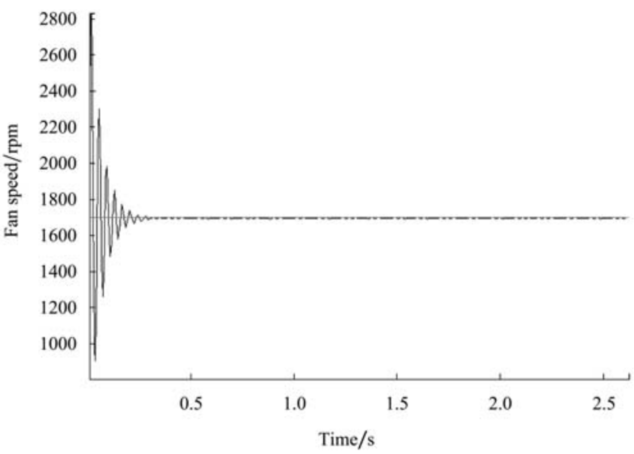

Figure 6 Response of system to 1700 rpm input

Figure 7 shows the response of simulated model to input speed in different speeds. In the experiment, different fan speeds between 0-2,300 rpm were applied to system. This situation is used when the controller is going to change fan speed and send order to the controller. So, fan speed is compared by optimum value and then order is sent to controller to decrease the errors. This figure shows dynamic response of the system to input speeds.

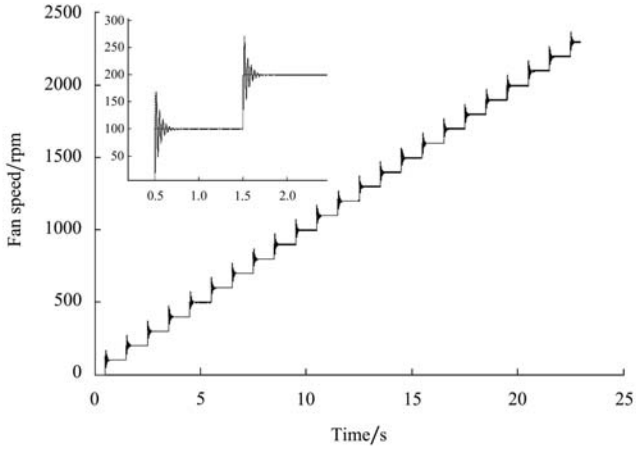

Figure 7 Simulated model responses to different speeds

3.3 Current and optimized efficiencies

Figure 8 shows the average data for current and optimized efficiencies. Results showed that both current and optimized energy efficiencies were changeable because the amount of efficiency was dependent on temperatures, which in turn, change during the experiments. The paired mean test was performed for current and optimized efficiencies. Results showed significant difference between two efficiencies at 1% probability level where optimized efficiency was significantly higher than that of the current one; since, the optimum fan speed was less than nominal fan speed leading to a decrease in fan electric energy and an increase in energy efficiency.

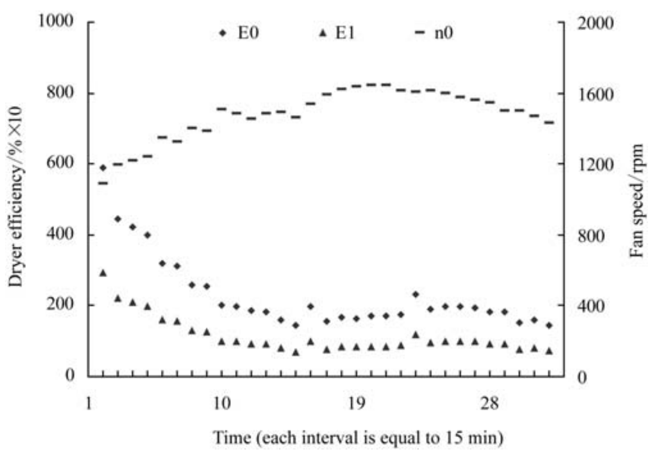

Figure 8 Efficiency and controlled fan speed variations with time

4 Conclusions

The results of testing the simulated model with real data showed that at the probability level of 5 percents there was no significant difference between real and simulated fan speeds. So, the simulated model was capable of predicting the control system behavior in real situations. Also, results showed that the control system could improve energy efficiency during the drying process.

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