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Design, Construction and Evaluation of a Fan Speed Controller in a Forced Convection Solar Dryer to Optimize the Overall Energy Efficiency

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ABSTRACT

To increase agricultural crops' quality and to minimize losses in the final product and used energy during the drying process, major drying system parameters should be continuously controlled. Precise control of such parameters is attained by using automatic control systems. To optimize the overall dryer efficiency in a forced convective solar dryer, a controller was designed, constructed and evaluated. The dryer fan speed was chosen to be the controlled variable. Based upon the mathematical relations and a monitoring of the air inlet temperature to the collector, the air outlet temperature from the collector and the air outlet temperature from the drying chamber, the dryer efficiency was determined. Using the dryer control program the current and the optimized dryer efficiencies were calculated, compared and the fan speed changed accordingly to maintain the optimized efficiency. Experiments were carried out in three replications (in three days) with the results showing that the system was capable of controlling the fan speed to obtain the optimum efficiency. The dryer equipped with the designed control system worked with its highest efficiency throughout the day. Statistical analysis showed that the control system highly improved the dryer efficiency throughout its operation at a 1% probability level.

Keywords: Automatic control system, Fan speed, Forced-convection, Optimum efficiency, Solar dryer.

INTRODUCTION

Drying, as a post-harvest processing step is an important task to preserve agricultural products for future use. Properties of the dried products are in close relationship with the dryer working conditions and also with the control of system parameters during the drying process. The basic parameters of the system should be controlled and adjusted on the basis of calculated and designed properties of the system to improve the quality of dried agricultural products and as well to minimize the energy loss. Nybrant (1989) developed and tested an adaptive controller on a laboratory concurrent-flow dryer. Experiments were carried out in which either the final grain temperature or the approximate maximum grain temperature was taken as the controlled variable. In the experiments, very accurate control of the temperatures was obtained. Moreira and Bakker-Arkema (1990) developed an adaptive controller, based on a continuously updated linear control for a continuous-flow grain dryer. The system consisted of a linear model, a control algorithm, an on-line moisturemeter, a tachometer and a microcomputer. The control system was tested during two drying seasons on two

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commercial cross-flow maize dryers. The average outlet moisture content was controlled to be within ±0.3% of the set-point during two drying seasons. Bruce and McFarlane (1992) designed a feedback-plus-feed forward controller using a computer simulation which was tested on a laboratory-scale mixed-flow grain dryer. The contribution from the feed forward term led to a more appropriate control as compared to that of feedback alone, but the accuracy of the feed forward control was limited by systematic errors in measurements of the input moisture.

Rodriguez *et al.* (1996) controlled the final moisture content of the product to obtain a high quality product and as well to increase the dryer productivity. From among all the input process variables, two were chosen as control ones, namely: the drum speed, and the steam pressure. These variables were employed to keep the average final moisture content Xf^* constant. 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. Local complementary heating power was applied to correct the local heterogeneity of Xf to obtain $Xf= Xf^*$ at every point across the drum.

Fuller and Charters (1997) made use of a microprocessor system to control the exhaust fan in a solar tunnel dryer. Using the measured air relative humidity inside and outside the dryer, an appropriate decision was made on whether to activate the exhaust fan or not. Using a two stage control algorithm, fan operating time was reduced by 67% as compared to continuous fan operation and by 34% if a light sensitive switch had been provided to control the fan. Reduced fan operation also optimized the drying air temperatures in the dryer.

Temple *et al.* (2000) studied the robustness of controllers for fluidized bed tea drying. The controller was developed based on the dryer model to establish a range of controller settings giving minimal Integral of Squared Error while maintaining adequate gain. These settings were found to be suitable for the whole range of the conditions tested. A simplification to the inferential controller, using gains only rather than complete transfer functions in the inferential estimator, was shown to be justified.

Qiang Liu and Bakker-Arkema (2001) presented a model-predictive control system for cross flow dryers. Simulation tests on a virtual dryer showed that the controller performed properly over a wide range of drying conditions. Results on a commercial cross flow corn dryer, showed excellent accuracy and stability.

Temple and van Boxtel (2001) presented a control system on a laboratory batch fluid-bed dryer to stop drying when the process was complete. The control system required only the initial weight of the sample as an input to the controller. The system then took full control, using only inlet and exhaust temperature measurements. A simulation model was employed to explore the operating region of the dryer, and how the various disturbances affect the drying time. The algorithm was tested in practice and found to be significantly more effective than the manual system used previously.

Nabil *et al.* (2005) used a linear state space dynamic model to describe drying in continuous fluidized bed dryers. The estimation technique based on Kalman filter design was used to provide state estimates for an optimal state feedback control system. The filter showed acceptable performance in reducing the noise of the system and in converging to the actual states, from incorrect initial states. Also, feedback controller state showed an acceptable performance in tracking set point changes when using either actual states or estimated ones.

Arjona *et al.* (2005) developed and tested a control system based on PID (Proportional plus Integral plus Derivative) controller on an industrial dryer to control the outlet production moisture where the energy use efficiency should be minimized.

Mehdizadeh and Zomorrodian (2009) compared a thin layer solar drying method with a sun drying one of paddy with their effects on quality characteristics of two varieties of rice. They used a mixed-mode solar dryer. Results indicated more appropriate characteristics for solar drying in comparison with those in sun drying method.

Since the dryer efficiency is continuously changing during the drying process due to hourly changes of solar radiation and temperature, the application of a system to maintain overall efficiency in optimum level, based on the changing drying factors seems to be indispensable. Maximization of the dryer efficiency will lead to a minimization of the fan electric energy consumption. Therefore, the objective of this research was to control the fan speed in a forced convection solar dryer to maintain the optimum overall dryer energy use efficiency.

MATERIALS AND METHODS

The experimental dryer (Figure 1) is a forced convection solar dryer designed and constructed to dry leafy vegetables (Soheili Mehdizade *et al.,* 2006). In this pilot solar dryer, hot air is provided by forced convection through an air solar collector. The product final moisture content reaches about 12%.

Two main parts of the dryer are fined-flat collector and dryer chamber. The area of collector is 1.83 m^2 and its absorber surface is covered with a Nextel dark paint. The dryer chamber has an axial tube fan and two sliding trays with a total area of 1 m^2. The net type trays are made up of aluminum strings. An axial tube fan of 12 cm diameter, 210 m^3 h^{-1} flow, 220 V, 50 Hz-AC, 2,300 rpm, 38 W, with static pressure of 8 mm WC was employed (Soheili Mehdizade *et al.,* 2006).

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

The optimum air speed in the fan outlet was found by partially differentiating the energy efficiency equation relative to outlet air flow speed and equating it to zero. To measure temperature, temperature sensors (SMT 160-30) were installed in the collector inlet (T_1 as ambient temperature), collector outlet (T_2) and in the dry chamber exit (T_3). Determination of the current speed is obtained through two infra-red transmitter

Figure 1. Experimental forced convection solar dryer.

and receiver sensors. The sensors were located in either side of the fan vanes and opposite to each other. The experimental fan consists of six vanes, with the six passes of the vanes in front of the fan being considered as one revolution.

The experiments all were carried out in three replications from 9 am to 5 pm in the city of Karaj in July with an average ambient temperature of 39°C during the experimental hours, a total daily solar radiation of 26.288 MJ m^{-2} and a monthly average air relative humidity of 39% (Anon., 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 precision of 0.1 m s^{-1} was applied to measure the air speed of the fan outlet. A program was written in Visual Basic 6.0 to control the speed of the fan. 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, receival and sending of information from/to RS-232 port becomes possible.

To determine the trend of moisture change with and without automatic control system, the method of oven was applied. Three samples of mint were taken from three parts of the tray in one hour intervals. Samples were put in three different small containers and after being weighed, were dried in 103°C for 24 hours. The experiment continued reach the desired final moisture content of 12% (Soheili *et al.,* 2006). The experimental data were analyzed using SPSS 12.0 statistical software.

Calculations

The general efficiency of a convective solar dryer is shown by Equation (1) (Augustus *et al.,* 2002):

$$E = \frac{M_w . L}{I_t . A_c + E_f} \tag{1}$$

E: Current dryer efficiency (decimal);

M_w: Evaporated moisture mass of the product (kg);

L: Specific latent heat of water vaporization (kJ kg^{-1});

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.

In the Collector Total Solar Radiation Energy Calculation

The solar radiation energy on the collector area is equal to the absorbed heat energy in it (Duffie & Beckman., 1991):

$$\sum I_t A_c = \sum \frac{Q_{co}}{E_c} \tag{2}$$

$I_t.A_c$: Total solar radiation energy on the collector area (kJ);

Q_{co}: Absorbed heat energy by collector (kJ),

E_c: Collector efficiency. 40% for this solar drier (Soheili Mehdizade *et al.,* 2006).

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

$$Q_{co} = M.C_p(T_2 - T_1) \tag{3}$$

M: Air mass (mixed dry and wet air), (kg);

C_p: Air specific heat, at 1 atmospheric pressure (1.006 Kj kg^{-1} K);

T_2: Air temperature at the collector exit (K),

T_1: Air temperature at the collector entrance (K).

$$M = \rho.V \tag{4}$$

ρ: Air density at mean collector or drying chamber temperature (kg m^{-3}),

V: Transit air volume at collector (m^3).

Air density is equal to (Holman, 1980):

$$\rho = \frac{P.n}{R.T} \qquad (5)$$

P: Ambient pressure (Pa)
n: Air molecular weight (kg $kmol^{-1}$)
R: Universal gas constant (8134.4 J $kmol^{-1}$ K^{-1})
T: Ambient temperature (here is T_1), (K)

From ASHRAE Equation, P is equal to (Anon., 2006):

$$P = 101.325\left(1 - 2.25577.10^{-5}.Z\right)^{5.2559} \qquad (6)$$

Z: height from sea level (for Karaj city is 1312.5 m) (Anon., 2009)

Air molecular weight was found to be 46.97 kg $kmol^{-1}$ by considering dry and wet air molecular weights (ASHRAE, 2006).

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

$$V_c.A_c.t = V_1.A_f.t \qquad (7)$$

t: Time (s);
V_c: Air velocity in collector (m s^{-1});
A_c: Area of collector (1.83 m^2);
V_1: Air velocity in the fan outlet (m s^{-1}),
A_f: Fan area (m^2).

Inserting Equations (4-7) into Equation (3) the total absorbed heat energy by collector is equal to:

$$Q_{co} = \frac{P.n.V_1.A_f.t.C_p\left(T_2 - T_1\right)}{RT_1} \qquad (8)$$

Through an insertion of Equation (8) into Equation (2), the total solar radiation energy in the collector area would be equal to:

$$\sum I_t.A_c = \frac{P.n.V_1.A_f.t.C_p\left(T_2 - T_1\right)}{E_c.R.T_1} \qquad (9)$$

Calculation of Necessary Energy for Product Moisture Evaporation

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

$$Q_{out} = M_w.L = M.C_p\left(T_2 - T_3\right) \qquad (10)$$

T_3: Air temperature at the dryer chamber exit (K).

Similar to that in equations for calculating Q_{co} by inserting M from Equations (4-7) into Equation (10), the necessary energy for product moisture evaporation would be equal to:

$$Q_{out} = \frac{2.P.n.V_1.A_f.t.C_p\left(T_2 - T_3\right)}{R\left(T_2 + T_3\right)} \qquad (11)$$

Here T in Equation (5) is the chamber temperature that is equal to an average of T_2 and T_3.

Fan Electric Energy Calculation

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

$$E_f = \frac{P_w.t}{E_E.E_m} \text{ Where:} \qquad (12)$$

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:

$$P_w = 9.81Q.Tp \text{ Where:} \qquad (13)$$

Tp: Total pressure (mm WC),
Q: Air flow (m^3 s^{-1}).

$$Tp = Sp + Vp \qquad (14)$$

Sp: Static pressure (mm WC),
Vp: Velocity pressure (mm WC).

Velocity pressure is calculated from (Bleier, 1998):

$$Vp = 0.051\rho.V_1^{\,2} \qquad (15)$$

Static pressure is not constant. So, an equation was obtained for the static pressure based on such variables as T_3 and V_1 (Bagheri, 2006; ASAE, 2000):

$$Sp = \left[\left(\frac{2.22L_0.V_1^{\,2}}{\ln\left(1 + 0.116V_1\right)}\right) + \left(\frac{3.72*10^{-6}.P.n.V_1^{\,2}}{RT_3}\right)\right] \qquad (16)$$

L_o: Product thickness on tray (m).

Inserting Equations (13-16) into Equation (12), fan electric energy would be equal to:

$$E_f=\left(\frac{9.81t.V_1.A_f}{1000E_E.E_m}\right)\left(Sp+0.051\frac{p.n.V_1^2}{R.T_2}\right) \quad (17)$$

Dryer Efficiency Calculation Based on Air Speed in the Fan Outlet

Through an Equations (9), (11) and (17) in Equation (1), the energy efficiency equation is obtained, based upon air speed in the fan outlet (V_1):

$$E=\frac{\dfrac{2P.A_f.C_p.n(T_2-T_3)}{R(T_2+T_3)}}{\dfrac{P.A_f.C_p.n(T_2-T_1)}{E_c.RT_1}+\dfrac{9.81A_f}{1000E_E.E_m}\left(\dfrac{2.22L_o.V_1^2}{\ln(1+0.116V_1)}+\dfrac{3.72*10^{-6}P.n.V_1^2}{RT_3}+\dfrac{0.051P.n.V_1^2}{RT_2}\right)} \quad (18)$$

Optimum Dryer Efficiency Calculations

Equation (18) shows the relationship between the dryer efficiency and the outlet air flow speed. The dryer optimum efficiency (E_o) can be determined by substituting the optimum air speed in the fan outlet (V_o) into Equation (18). The optimum air speed in the fan outlet was found by partially differentiating Eq. (18) relative to V_o and equating it to zero.

$$\frac{\partial E}{\partial V_o}=0\Rightarrow V_o=\frac{220L_0.R.T_2}{P.n} \quad (19)$$

V_o: Optimum air speed in the fan outlet ($m\ s^{-1}$)

Relationship between Air Speed in the Fan Outlet and Fan Speed

To formulate the relationship of dryer efficiency as based on the fan speed, the relationship between the fan speed and the outlet air speed from the fan had to be known. A digital hotwire anemometer with a precision of 0.1 $m\ s^{-1}$ was employed to measure the air speed at the fan outlet. A program was written in Visual Basic 6.0 to control the speed of the fan. Ignoring the first few seconds to maintain a steady condition, the calibration equation with a high coefficient of determination (R^2= 0.994) was found for the fan speed (n_o) and for the fan outlet air speed (V_o):

$$n_o=-61.324\ V_o^2+823.1V_o-677.7 \quad (20)$$

n_o= Optimum fan speed (rpm),
V_o= Optimum air speed in the fan outlet ($m\ s^{-1}$).

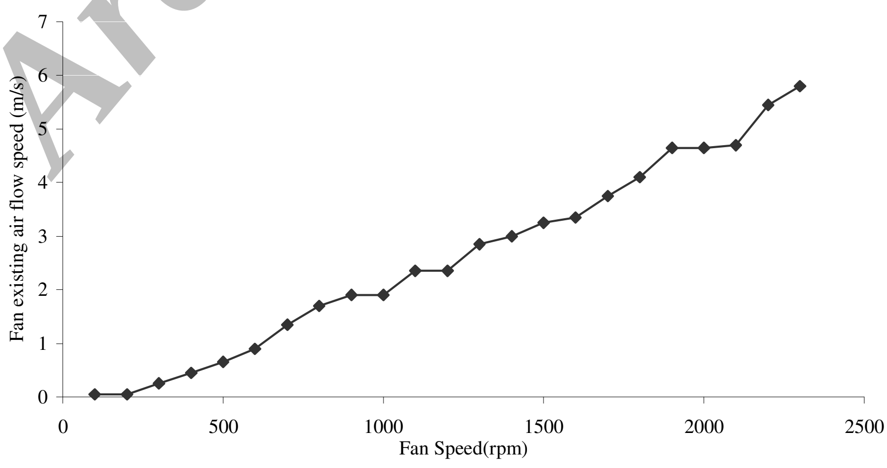

Figure 2. Variation of the fan outlet air speed with the change in fan speed.

Figure 2 shows the variation of the fan outlet air speed *vs.* fan speed. Following the calculation of the optimum air speed in the fan outlet from Equation (19) and putting it into Equation (20), the optimum fan speed was calculated and the result sent to the control system to turn the fan speed into its optimum value.

Automatic Control System Hardware

The automatic control system of the fan speed consists of: two micro controllers of ATMEGA 8535-16PI (programming language of micro controller is C and compiler code Vision of AVR), L7805cv 5 volt regulator for supplying the voltage in the working range of sensors), 2 crystals of 16 MHz to produce signals, an IC MAX 232 as an interface between the micro controller and the RS-232 port, an infra-red rays receiver (TSOP1738) and transmitter (TSAL6400) sensors for counting the fan vanes, an opto-coupler to convert signals, a triac to direct current when reached to a specified value, a 9 volt adaptor for supplying power to the system and digital temperature sensors (SMT 160-30). Because of long distances among the collector input, the collector output and the air exit from the dryer chamber where temperatures should be determined, digital temperature sensors were employed. These sensors guarantee the transfer of data with high accuracy and minimum error that could arise due to long wires connected to sensors. A capacitor, a covered wire of two layers to eliminate noises, some needed sockets and a resistor to eliminate noise and to decrease sensitivity, as well as a 9 pin connector were used.

Automatic Control System Software

The algorithm of the control system of the fan speed includes the following steps:

- Calculating the optimum fan speed and applying it to fan
- Calculating the optimum efficiency, based on optimum fan speed
- A feedback control system to reduce error

Determination of the current speed is obtained through two infra-red rays as sender and receiver sensors. The infra-red transmitter and receiver sensors were located in either side of the fan vanes and opposite to each other. The tested fan consists of six vanes. A set of six passes of the vanes in front of the fan is considered as one revolution. A feedback control system was designed to reduce the error between the practical and mathematical optimum fan speeds and practical and mathematical optimum dryer efficiencies (Figure 3).

Changing the fan speed is made possible by changing the fan input voltage from 0 to 220 V. The current speed as well as its variation from the optimum speed are calculated for the fan speed to reach the optimum speed. The micro controller program includes three essential parts, operating simultaneously. The main part controls the serial port input and executes the computer orders. The second part calculates

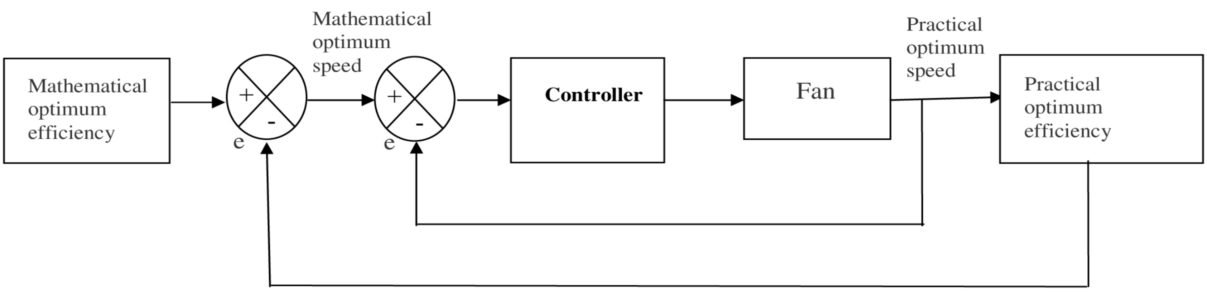

Figure 3. The block diagram of fan speed control system.

the temperatures and makes it available as a function in the program. The third part controls the fan speed in the vicinity of the input value.

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 becomes possible. In the final stage, the program is linked to the control hardware. The program is coded according to the steps shown in Figure 4. In this program, the optimized efficiency (E_o) and the current efficiency (E) of the dryer are calculated and compared. If the obtained values are not the same, the speed on which the current efficiency becomes optimized is calculated and the speed control system is applied to change the current speed to the optimized one (Figure 4).

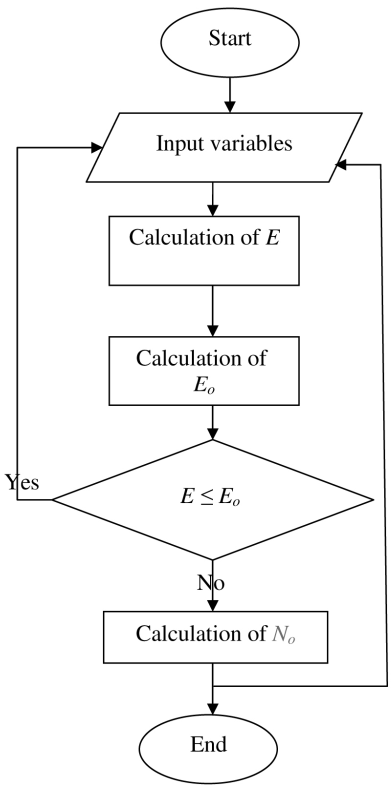

Figure 4. Efficiency calculation flowchart.

RESULTS AND DISCUSSION

Comparison of the Real and Nominal Fan Speeds

To determine the accuracy level and flexibility of the automatic control system, an experiment was conducted. In this experiment, nominal and real speeds produced by the controller were compared. Figure 5 shows the relationship between real and nominal speeds. Results showed that there is no difference between nominal and real fan speed with high coefficient of determination (R^2= 0.9998). This shows that the automatic control system is accurate enough to provide the required fan speed for further experiments.

Temperature Variation during the Experiment

Figure 6 showed the average of temperatures' variations with time during the experiments. Results indicated that air temperature at the collector entrance (T_1), air temperature at the collector exit (T_2) and air temperature at the dryer chamber exit (T_3) were initially increased and then decreased. T_2 and T_3 temperatures changed based on T_1 changes. As the collector inlet air temperature (environment temperature) decreases (increases) the collector outlet air temperature and dryer chamber outlet air temperature decreases (increases), accordingly.

T_1 depends on solar radiation when in a summery day it is increased from morning (9 am) to afternoon (3 pm) and then decreased afterwards. Also, the difference between exiting air temperature from the collector (T_2) and the exiting air temperature from the drying chamber (T_3) is a function of the product moisture content. Results showed that at the beginning of the drying process, since the initial moisture content of the product and the rate of vaporization from the surface of

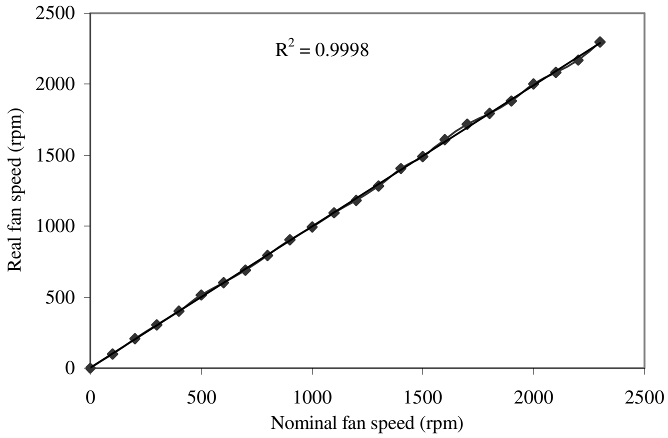

Figure 5. Comparison of nominal and real fan speed.

the product is high, the difference between T_2 and T_3 is also high (Figure 6). As drying process advances, due to lower moisture content of the product, and changes of solar radiation this difference tends to decrease. The results showed that the average of *T1, T2* and *T3* in three replications were 39°C, 58.8°C and 46.8°C , respectively.

Current and Optimized Efficiencies

To compare the optimized efficiency (E_o) and current efficiency (E), the current efficiency was calculated based on the nominal fan speed, as there was no control over it. The optimized efficiency was determined by calculating V_o using Equation (19) and inserting the resultant into Equation (18). following a comparison of the optimized efficiency with the current one, the optimized speed corresponding to the optimized efficiency was calculated and applied to the fan (Figure 4).

Experiments were repeated in three replications in different days from 9 am to 5 pm. Figure 7 shows the average data. Results indicated that both current and optimized energy efficiencies were not fixed and they decreased during the drying process. This was due to the fact that the efficiency was dependent on temperatures, which in turn is subject to change during the experiments. The paired mean test was performed for current and optimized

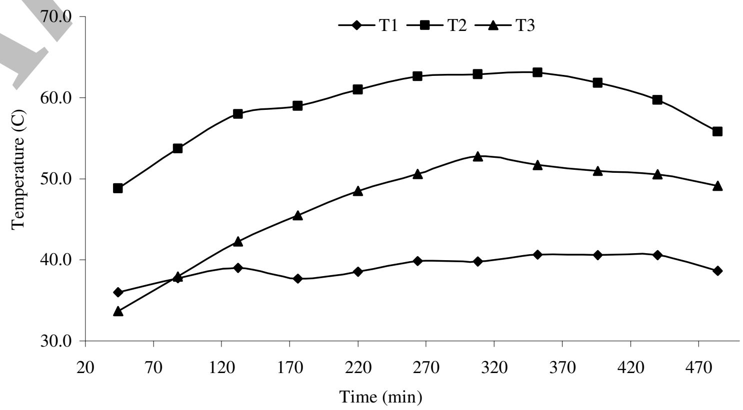

Figure6. The average temperature variations with time (in three replications).

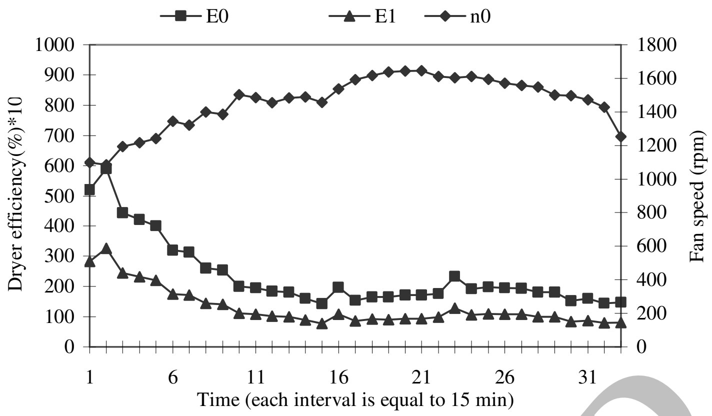

Figure 7. Efficiency and controlled fan speed variations with time.

efficiencies. Results indicated a significant difference between the two efficiencies at 1% probability where optimized efficiency was significantly higher than the current one. Since, the optimum fan speed was less than the nominal one, it led to a decrease in fan electrical energy use up and an increase in energy efficiency.

Product Moisture Content Measurement

The moisture of each sample was determined based on the wet basis using the following equation (Zomorrodian and Dadashzadeh., 2009; Singh., 2009):

$$M_{wb} = \frac{W_w - W_d}{W_w} \text{ Where:} \qquad (21$$

M_{wb}= Moisture content (w.b.), (%);
Ww= Wet weight (g),
W_d= Dried weight (g).

Figure 8 shows the drying trend of the mint when equipped with and when without controller. Paired samples' test was carried out for the two conditions, the

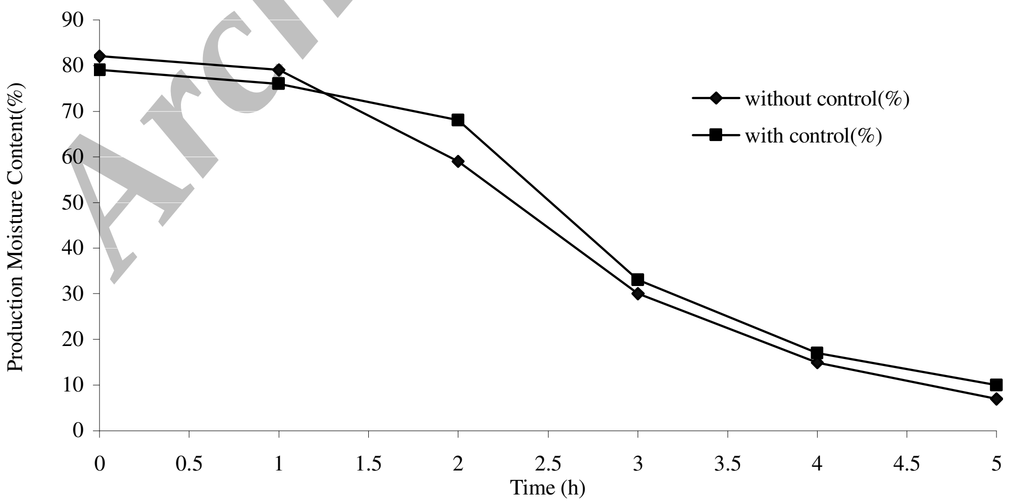

Figure 8. Variation of drying trend of mint with and without control system.

results showing that there was no significant difference observed in terms of moisture change either with or without using the control system. The reason for lack of moisture difference of the product with and without control system in the dryer is due to the fact that the controlled speed was near the nominal fan speed. If the dryer had been equipped with a fan with higher nominal speeds, the difference could have been significant. At least, one can conclude that in the controlled situation, by maintaining higher efficiency, less electrical energy is consumed, since, in uncontrolled situation, the fan is constantly working at its highest nominal speed.

CONCLUSIONS

To optimize the overall energy efficiency in a forced convection solar dryer, a control system was designed, constructed and evaluated. Results showed that T_1, T_2 and T_3 were not fixed and changed during the experiments. Also, results showed that, the energy efficiency of a solar dryer was not fixed. The paired mean test results showed significant differences between the current and optimized efficiencies at 1% probability level with the optimized energy efficiency being higher than the current efficiencies.

The drying rate of mint in the current *vs.* optimized efficiency cases showed no significant difference, implying that if the dryer is equipped with the automatic control system, electric fan works at a lower speed, and the consumption of electric energy is lowered while the energy efficiency was being increased.

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Nomenclature

A_C: Collector area (m^2)
A_f: Fan area (m^2)
C_p: Air specific heat (KJ kg^{-1} K^{-1})
E: Current dryer efficiency (Decimal)
E_o: Optimum dryer efficiency based on V_o (Decimal)
E_c: Collector efficiency (Decimal)
E_E: Electromotor electric efficiency (Decimal)
E_f: Fan energy (KJ)
E_m: Impeller mechanical efficiency (Decimal)
I_t: Solar radiation energy per collecting area (KJ m^{-2})
L: Specific latent heat (KJ kg^{-1})
L_o: Product thickness on tray (m)
M: Air mass (Mixed of dry and wet air), (kg)
M_w: Evaporated moisture mass of the product (kg)
M_{wb}: Moisture content (w.b.), %
n: Air molecular weight (kg $kmol^{-1}$)
n_a: Dry air molecular weight (kg $kmol^{-1}$)
n_w: Wet air molecular weight (kg $kmol^{-1}$)
n_o: Optimum fan speed (rpm)
P: Ambient pressure (Pa)
P_w: Power of fan outlet air (W)
Q: Air flow (m^3 s^{-1})
Q_{co}: Absorbed heat energy by collector (KJ)
R: Universal gas constant (8134.4 J $kmol^{-1}$ K^{-1})
Sp: Static pressure (mm WC)
t: Time (s)
T: Ambient temperature (K)
T_1: Air temperature at the collector entrance (K)
T_2: Air temperature at the collector exit (K)
T_3: Air temperature at the dryer chamber exit (K)
Tp: Total pressure (mm WC)
V: Transit air volume at collector (m^3)
V_c: Air velocity in collector (m s^{-1})

Vp: Velocity pressure (mm WC)
V_1: Air speed in the fan outlet (m s^{-1})
V_o: Optimum air speed in the fan outlet (m s^{-1})
W_d: Dried weight (g)
Ww: Wet weight (g)
Z: Height (m)
ρ: Air density in ambient temperature (kg m^{-3})

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طراحی، ساخت و ارزیابی سیستم کنترل خودکار دور فن خشک کن خورشیدی همرفت اجباری به منظور بهینه سازی بازده انرژی

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چکیده

به منظور افزایش کیفیت محصولات خشک شده وکاهش ضایعات مرحله خشکاندن می باید پارامترهای اساسی سیستم به صورت مداوم در طول فرآیند خشک شدن کنترل گردند. کنترل دقیق چنین پارامترهایی با استفاده از سیستم های کنترل خودکار میسر است. از همین رو، به منظور بهینه سازی بازده انرژی در خشک کن های خورشیدی همرفت اجباری یک سیستم کنترل خودکار طراحی و ساخته شد. با استفاده از روابط ریاضی و پایش دمای هوای ورودی به جمع کننده، دمای هوای خروجی از جمع کننده و دمای هوای خروجی از محفظه خشک کن، بازده انرژی به دست آمد. با استفاده از برنامه نوشته شده، بازده های فعلی و بهینه خشک کن محاسبه شده و با هم مقایسه می شدند. در صورت برابر نبودن این دو بازده، دور فن به گونه ای تغییر می یافت تا بازده خشک کن در حد بهینه باقی بماند. به منظور ارزیابی سیستم کنترل خودکار، آزمایش هایی در۳ تکرار انجام شد و نتایج نشان داد که سیستم کنترل خودکار قادر است به خوبی دور فن را به دور کنترلی مورد نظر برای تامین بازده بهینه برساند. هم چنین با استفاده از این سیستم، بازده فعلی برابر با بازده بهینه خشک کن شده به طوری که در طول یک روز کاری خشک کن همواره با بازده بهینه،کار می کند. همچنین آزمون نمونه های جفتی برای دو بازده فعلی و بازده بهینه با توزیع t-student انجام شد و نتایج تجزیه و تحلیل های آماری نشان داد که در سطح ۱ درصد بازده بهینه به طور معنی داری بیشتر از بازده فعلی خشک کن است.