International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878, Volume-8 Issue-3, September 2019

Optimization of Solar Dryer using Taguchi Method

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Abstract: ***Solar dryers are one of most efficient devices for drying food and other products. These devices are eco-friendly and need solar energy for their operation and which is available freely and abundantly at almost every place. These are simple devices which do not need use any fossil fuel for their operation, which are expensive, exhaustive in nature and are not eco friendly. Several fresh food products and other items are dried for preservation and utilization for longer period of time. In recent times, with the development in this technology, the solar dryers are becoming well equipped with efficiency increasing add-ons which give higher performance. Several experimental studies have been carried out to mitigate the time consumption and increasing the productivity of solar dryers. Optimization of solar dryers is done to increase their workability increasing accuracy and reducing drying time and cost investment. In order to optimize the complete setup several techniques could be used to get the optimum results. In the present work Taguchi optimization technique was applied for experimental analysis of solar dryer which was used to dry potatoes. The results thus obtained showed the best configuration comprising air velocity, air flow and humidity required to dry potatoes.***

Keywords: Taguchi Method, Optimization, Solar Dryers, Preservation, Efficiency

I. INTRODUCTION

The 2019 edition of the report by Food and Agriculture Association of United Nations indicated that an estimated 9.2% of the world's population (around 700 million people) was suffered from severe food uncertainty in 2018, signifying lowering the quantity of food consumed. In addition to this around 17.2% of the world population (around 1.3 billion people) experienced irregular access to nourishing and adequate food making it a total of 26.4% (around 2 billion people) of the world's population which experienced combination of moderate and severe levels of food insecurity. One of the main reasons of this struggle for healthy, nutritional and proper quantity of food is the loss of food due to post harvesting. With the ever increasing world's population, which is assumed to be around 10 billion by the next 30 years and with the older techniques of food preservation, it will even become worse. In such scenario drying of food items to keep them for a longer period of time & also to mitigate the loss of food items post harvesting, drying of food items using solar dryer can be a feasible solution to fight this challenging problem. The process of drying or dehydrating is one of the crucial processes carried out amongst the food industries. Dehydrating lowers the moisture content present in the food items which results in extension of the shelf life comprising the dried products which have much more life compared to the fresh food items (Majdi & Esfahani, 2018) [1]. Certain chemical as well as physical changes occur during drying which are complex in nature and evaluating them is also complex since they are dependent on several factors such as temperature, content of moisture present, and time consumed etc. The drying process involves a keen track of moisture content which is being altered under the direction of radiation of sun. This factor determines that how much the food item is dehydrated (Padmanaban & Palani, 2017) [2]. Several products of cultivation are comprised of very high content of moisture and hence they are prone to perish at a faster rate in nature. Loss of moisture or water in addition with consideration of decaying factors are few of the elements which are responsible for loss of such products of about 30-40% in developing nations based mainly in tropics as well as sub-tropic areas. These losses are due to non-sufficient storage facilities, mishandling while transportation etc. (Sharma, Garg, & Kumar, 2018)[3]. On the other hand it can be said that, solar based dryers in the nations which are still developing are capable of declining losses associated with the crops and improve the standards as well as quality of products that are dried. (Aghaie, Rahimi, & Akbarzadeh, 2015) [4].

II. OPTIMIZATION OF SOLAR DRYERS

Optimization of solar dryers refers to the process of finding out the optimum set of values amongst all the available operational parameters of solar dryer. Various optimizations techniques have been used for optimization of a solar dryer such as (ANN), Genetic Algorithm (GA), Response Surface Methodology (RSM) Particle Swarm Optimization (PSO) and Taguchi method. These optimization techniques model the different solar drying processes and their equipments to predict the optimal set of values which gives the best results. With growing technology, solar dryers are developed with modern designs that have maximum performance and efficiency in working.

Manuscript published on 30 September 2019
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Parameters such as drying time should be kept under consideration so as to obtain higher efficiency in short span of time (Chen, Chung, Wang, & Huang, 2011) [5]. This enables us to get the optimum configuration of parameters used in solar dryers which have higher accuracy in results compared to that of traditional or ongoing methods which take longer span of time.

Optimization of solar dryer can be done by various different methods such as linear regression, Genetic algorithm, Grey relational analysis and Taguchi method etc. (Bakari, Minja, & Njau, 2014) [6].

III. LITERATURE REVIEW OF OPTIMIZATION TECHNIQUES

In the year 2014 Dalvand et al. [7] performed solar based drying and used agricultural products for drying which was based on their moisture contents. A new method was proposed for drying which included the application of Electro Hydro Dynamic (EHD) which was connected to a PV unit. Voltage in the range 6-15 kV was penetrated in the system which was used for drying the product in the solar chamber. The complete experiment was optimized further, by using Response Surface Method (RSM) which resulted in reduction of cost as well as time. In the year 2019 Verma et al. [8] in their study presented a study on Solar collector efficiency as this efficiency can contribute a lot in the field of solar powered systems. With the increase in use of solar based applications various researches are still going on in this direction. In this research study a method of space heating was introduced using a solar coupled heat pump (SCHP) system. For the study purpose Indian climatic conditions were considered for the boundary selections. Various parameters of the solar unit were optimized with the help of Taguchi method as an optimization technique. Five different parameters were varied to find the optimum results from the study. Further in the study COP and efficiency of overall system is calculated and optimized parameters were evaluated. For the Taguchi analysis higher the better factor was used for the selection of optimum parameter in L27 matrix. From the study it was depicted that COP of the system varied from 38% to 61% and 1.9 % to 3.01% respectively. Based on the observation variation in results was seen due to the variation of working parameters. With the use and adoption of Taguchi method overall efficiency and COP of complete SCHP system improved i.e. 5.7% and 4.3% respectively. In the year 2019 Liu et al. [9] presented his study based on the investigation of performance seen in a hybrid system comprising of a phase change material with ventilated Trombe wall. In this study overall parameters of particular hybrid system were optimized to have the optimum values for further functioning with these systems. This study was an experimental study based on numerical calculations where a L9 matrix was built using the Taguchi optimization factor. Nine different models with different range of parameters were used in this particular study. From the analysis graphs of S/N ratio and ANOVA analysis were designed. Main parameters for the variation of results were considered as mass flow rate, cooling water temperature at inlet and thickness of PCM. Optimum values for the system were obtained as 1 kg/s for mass flow rate, 0.6 m for diameter of pipe and 15 °C for temperature and 20mm for PCM thickness for the highest QE of 20,700 kWh. In the year 2018 Osodo et al. [10] presented his study on a solar dryer by varying various design and working parameters. For the study purpose author used a variety of grains for which the thickness of layer was varied. In the boundary conditions different experimental parameters such as drying velocity, moisture content and temperature were considered. For the output parameters moisture removal rate and temperature were used for depicting the optimal results from this study. Optimum results of the study are identified using Taguchi method where values of ANOVA and LSD Were calculated to find the desired output of the study. In the experimental analysis a setup of 0.5 m x 0.5 m x 1.0 m dimension is used for the experimental work. The Taguchi method utilized in this study proposed that a combination of grain layer thickness and air velocity were 0.04 m and 0.34 m/s respectively for identifying the efficiency of drying. Optimum results of velocity were obtained at 0.410.41 m/s for temperature 45°C was found to be the optimum result. From the study shortest time to dry the grains was identified which was the major concern of this study. In 2018 Shamiq et al. [11] in their study proposed an optimum solution for the solar energy based spray dryer using Nano capsulated vitamin D3. For the study and optimization of parameters author utilized the Taguchi method and used different parameters such as moisture content, solubility, porosity, color, and powder yield from the apparatus. Further after performing the experimental study these parameters were optimized to provide an optimum solution in the form of highest yield of power and inlet temperature. Different Powders were produced in the experimental study by utilizing 2% WPC, 3% MS, and 25% MD respectively. Study depicted the highest value of yield as almost 96% from the overall study. In 2018 Jafari et al [12] in their study presented a novel model of solar air dryer which constituted of a drying chamber, collector and blower and some other components to make a complete setup. Different trays were used for the drying of material used for the study in which the hot air was circulated to record the drying time. From the overall study efficiency of drying rate of system, initial and final values for the moisture contents were recorded in the system. For the analysis green peas were used as the material for drying. The efficiency of overall system was estimated on the parameters of drying time and other parameters such as moisture content. From the study it was suggested that humidity and temperature played an important role in drying of food items and overall system efficiency also depends on these parameters.

IV. METHODOLOGY

In the present work experimental approach was carried out in drying potatoes as product in a solar dryer. The complete study was carried out from 9:00 am to 6:00 pm and the results were noted down for every hour of interval. A total of 10 kg of fresh potatoes were placed on the trays of the dryer chamber. Readings were noted down by the help of appropriate measuring devices for temperature, humidity, air flow, etc inside the chamber every hour.

Based on the readings obtained Taguchi Optimization technique was applied in the experiment to get the optimum configuration of input parameters for effective drying. Design procedure as suggested by Hossain and Hossain [13] was used for the calculating various parameters as follows.

(i) MOISTURE TO BE REMOVED (M_r)

$$M_r = \frac{M_p \times (M_i - M_f)}{(100 - M_f)} \text{------(i)}$$

Where,

M_r = Moisture to be removed in kg
M_p = Weight of the product in kg
M_i = Initial moisture content in %
M_f = Final moisture content in %

(ii) **DRYING BED SURFACE AREA PRESSURE (P)**

$$P = 0.00308\, g\, (T_i - T_{am})\, h \text{------(ii)}$$

Where,

P = Surface area pressure in Pa
g = Acceleration due to gravity
T_i= Temperature inside the dryer
T_{am} = Ambient Temperature in
h = Pressure Head

(iii) **ENERGY REQUIRED FOR EVAPORATION (E)**

$$E = M_r \times h_{fg} \text{------(iii)}$$

Where,
h_{fg} = Latent heat of vaporization

(iv) **AREA OF COLLECTOR**

$$A_c = \frac{E}{S_r \times \eta} \text{------(iv)}$$

Where,

S_r = Insolation value at Bhopal, MJ/M²/day
η = Efficiency of the collector

(v) **HEAT ENERGY GAIN FOR COLLECTOR (Q)**

$$Q = C_P M_P (T_C - T_{am}) + h_{fg} M_{wf} \text{------(v)}$$

Where

C_p = Specific heat capacity of potatoes
M_p = Initial weight of potatoes in kg
T_c = Collector temperature in
T_{am} = Ambient temperature in
h_{fg} = Heat of evaporation
M_{wf} = Final weight of weight potatoes

(vi) **DRYING RATE (D_r)**

$$D_r = \frac{dM}{dt} \text{------(vi)}$$

Where,

t = Drying time available

(vii) **MASS FLOW RATE (M_a)**

$$M_a = \frac{D_r}{(W_{a2} - W_{a1}) \times 3600} \text{------(vii)}$$

Where,

W_{a2} = Humidity Ratio after drying
W_{a1} = Humidity Ratio before drying

(viii) **VOLUMETRIC AIR FLOW RATE (V_{af})**

$$V_{af} = \frac{M_a}{\rho_a} \text{------(viii)}$$

Where,
M_a = Mass of air needed for drying.
ρ_a = Density of air

(ix) **VENT AREA (A_v)**

$$A_v = \frac{V_{af}}{V_w} \text{------(ix)}$$

Where,

V_{af} = Volumetric Air flow rate in m³/s.
V_w = Wind Speed in m/s. (For Bhopal it is 3.5 m/s)

(x) **VENT DIAMETER (D_v)**

$$D_v = \sqrt{(\pi \times A_v)/4} \text{------(x)}$$

(xi) **DRYING AREA (A_d)**

$$A_d = \frac{\text{Mass of potatoes to be dried } (M_p)}{\text{Spreading Density } (\rho_s)} \text{------(xi)}$$

Where ,
M_p = Mass of Potatoes to be dried
ρ_s = Spreading Density of air

(xii) **AREA OF EACH TRAY (A_t)**

$$\text{Area of each tray } A_t = \frac{A_d}{N_t} \text{------(xii)}$$

Assuming that Number of Tray (N_t) =4

(xiii) WIDTH OF EACH TRAY (W_t)

$$\text{Width of each tray } (W_t) = \frac{A_t}{L_t} \text{------(xiii)}$$

The table below shows the parameters evaluated for drying process.

Table 1: Calculated data & Parameter Estimation

S. N.	Parameter		Equation	Symbol	Value
1	Moisture to be removed from potatoes		(i)	M_r	7.01 kg
2	Final moisture of potatoes			M_i	13%
3	Pressure throughout the drying bed		(ii)	P	0.335 Pa
4	Energy Requirement for Evaporation		(iii)	E	16824 KJ
5	Collector	Area	(iv)	A_c	3.3 m^2
		Length		L_c	2.2 m
		Width	Assumed	W_c	1.5 m
6	Collector useful heat energy gain		(v)	Q	8553 KJ
7	Drying rate & average drying rate		(vi)	D_r	0.701 kg
8	Airflow rate	Mass flow rate	(vii)	M_a	0.1 kg/s
		Volumetric air flow rate	(viii)	Vaf	0.09 m^3/s
9	Vent Area	Vent Area	(ix)	A_v	0.03 m^2
		Vent Diameter	(x)	D_v	0.15 m
10	Dryer	Drying Area	(xi)	A_d	2.5 m^2
		Number of Tray	Assumed	N_t	4
		Area of Each tray	(xii)	A_t	0.625 m^2
		Length of tray	Assumed	L_t	1.5 m
		Width of each tray	(xiii)	W_t	0.42 m

V. TAGUCHI OPTIMIZATION TECHNIQUE

Taguchi is a method which involves three phases: structure of outline, ideology behind input parameters, and framework of resistance. Taguchi is a technique which is used as measurable planning so as to optimize and improve the quality of any entity, Chen et al., 2011 [5]. The method of Taguchi comprises included formation of orthogonal arrays to observe complete parameters with some of the input parameters. The result outcomes obtained from the trials are transformed in to form of signal to noise (s/n) ratios. The S/N ratio has two categories i.e. smaller the better and higher the better,Tasirin, Puspasari, Xing, Yaakob, & Ghani, 2013 [14]. The equations for calculating **larger the better** S/N ratio is given below:-

$$(S/N)\ Ratio\ = -10\log\frac{1}{n}\sum_{i=1}^{n} 1/yi^2$$

Here,

y = observed response value and
n = number of replications.

Smaller the better is used where smaller value is desired.

$$(S/N)\ Ratio\ = -10\log\frac{1}{n}\sum_{i=1}^{n} yi^2$$

Here,

y = observed response value and
n = number of replications.

In the present work Taguchi L9 orthogonal array matrix was implemented based on parameters of Humidity, air flow and air velocity and the output parameter was kept as solar radiation.

VI. RESULT AND DISCUSSION

Table 2: Readings obtained in the experiment

Time	Ambient Temp. (^0C)	Ambient Relative Humidity (%)	Upper Tray Temp. (^0C)	Lower Tray Temp. (^0C)	Exhaust Temp. (^0C)	Exhaust Relative Humidity	Air Velocity (m/s)	Air Flow (m^3/s)	Solar Radiation (W/m^2)
9:00 am	30.3	80.3	41.3	37.2	38.2	62.3	1.1	14.5	150.4
10:00 am	31.4	79.5	43.7	37	38.5	60.6	2.12	28.9	161.2
11:00 am	32.5	73.1	50.2	41.4	43.3	52.6	2.45	34.5	180.4
12:00 pm	34.9	68.2	48.6	45.1	49.5	40.5	3.01	40.4	236.22
1:00 pm	35.5	62.4	59	51.9	53	36.2	2.8	39.3	210.15
2:00 pm	37.3	59.4	58.5	51.6	53.6	33.9	2.6	33.5	226.19
3:00 pm	36.1	63.4	49.6	47.5	45.9	47.5	1.5	18.6	196.5
4:00 pm	33.2	55.4	52.9	45.8	47.6	40.1	2.53	33.7	164.4
5:00 pm	31.3	62.7	44	41.9	41.8	50.3	1.43	19.2	150.3
6:00 pm	30.2	76	35.9	36.5	33.8	74.1	1.1	1.45	110.8
Mean	33.0	68.04	48.37	43.59	44.5	49.8	2.06	26.4	178.6

RESULTS FOR TAGUCHI APPROACH

The results for optimization were calibrated on humidity, air flow, velocity of air and solar radiation. The very initial phase signal to noise table was created. The criterion selected in this approach was larger the better. The results were calculated by ANOVA approach (Analysis of Variance).

Table 3: S/N table for Optimization

S.N.	Ambient Relative Humidity	Air Velocity	Air Flow	Solar Radiation	S/N Ratio
1	73.1	2.45	34.5	180.4	45.12473
2	73.1	2.8	39.3	203.45	46.16915
3	73.1	1.5	18.6	184.56	45.32275
4	62.4	2.45	34.5	187.58	45.46373
5	62.4	2.8	39.3	210.15	46.45059
6	62.4	1.5	18.6	198.5	45.95521
7	63.4	2.45	34.5	195.3	45.81404
8	63.4	2.8	39.3	201.54	46.08723
9	63.4	1.5	18.6	196.5	45.86725

Response Table for Signal to Noise Ratios

Larger is better

Table 4: Rank Table

Level	Ambient Relative Humidity	Air Velocity	Air Flow
1	45.96	45.72	45.72
2	45.92	45.47	45.47
3	45.54	46.24	46.24
Delta	0.42	0.77	0.77
Rank	3	1.5	1.5

ANALYSIS OF VARIANCE (ANOVA)

Table 5: Result from ANOVA

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Ambient Relative Humidity	2	156.0	21.24%	156.0	77.99	2.85	0.170
Air Velocity	2	468.9	63.84%	468.9	234.47	8.56	0.036
Error	4	109.6	14.92%	109.6	27.40		
Total	8	734.5	100.00%				

Where,

DF - Degrees of freedom, SeqSS - sum of squares,MS - mean squares (Variance),

F-ratio of variance of a source to variance of error, $P < 0.05$ - determines significance of a factor at 95% confidence level.

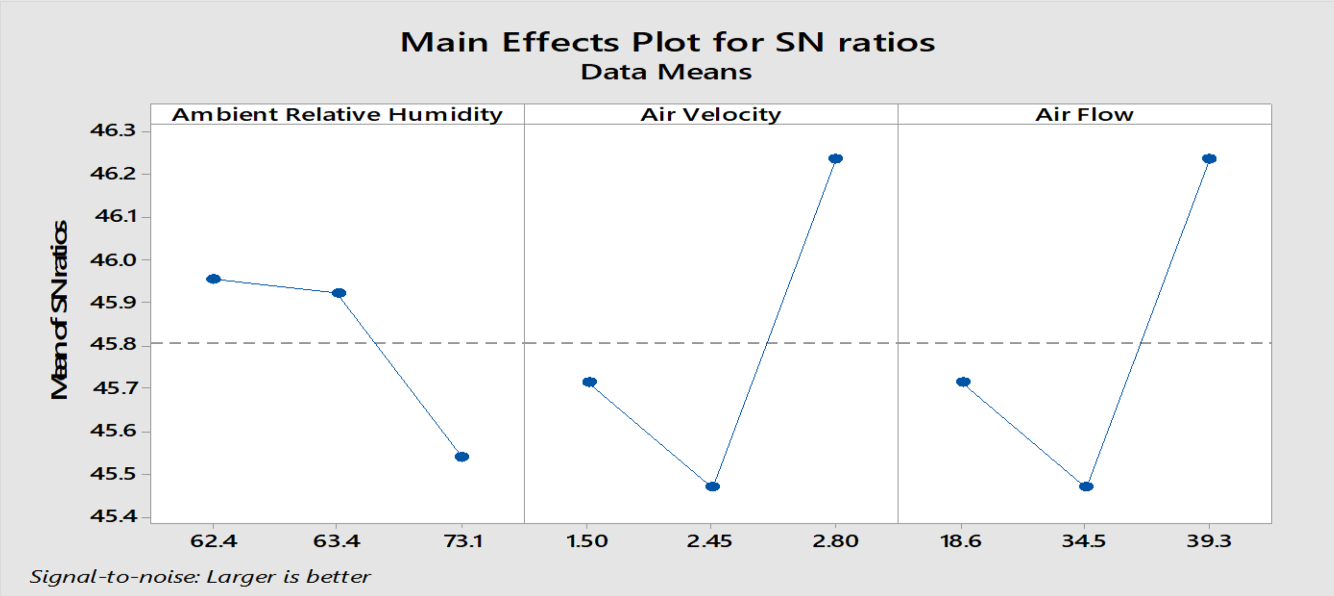

Fig 1: Response Graph for S/N Ratio

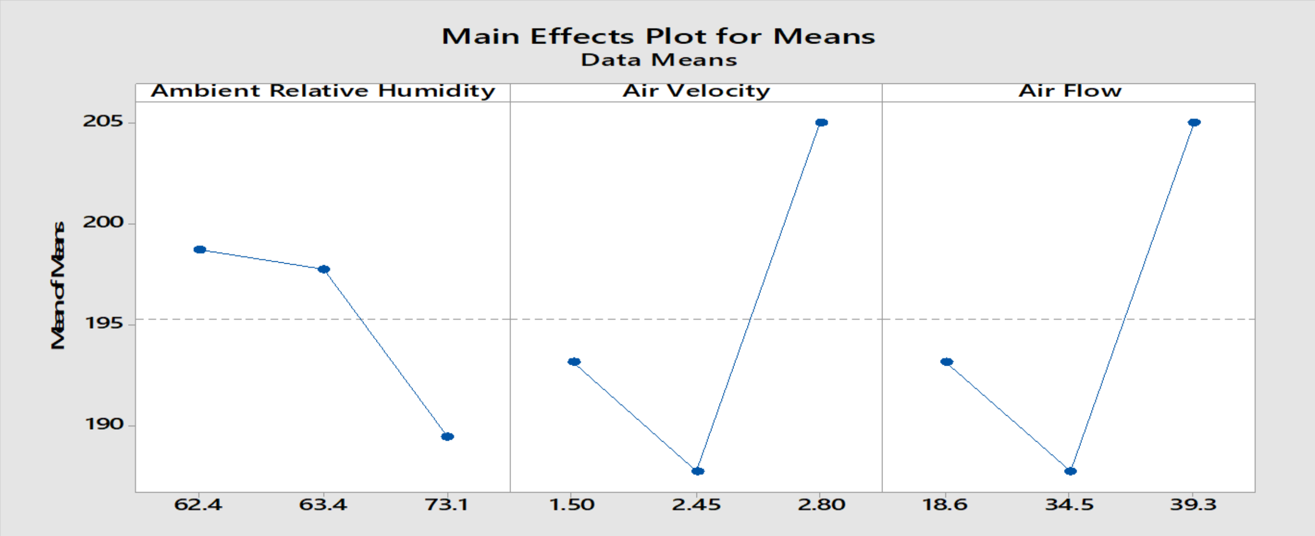

Fig 2: Response Graph for Mean of Means

VII. CONCLUSION

The experiment was successfully performed and hourly based readings were taken. The result showed that the maximum intensity of solar radiation is at 12.00 pm of about 236.72 W/m^2. Further the readings were optimized using Taguchi L9 orthogonal array to get optimum set of configuration for the performance of solar dryer. The required S/N ratio was established on the parameters of air flow, air velocity, and humidity. The graphs formed by the optimization technique showed that optimized result had values for air as 39.3 m^3/s, , value of air velocity as 2.8 m/s and the humidity as 62.4% at the time of 1.00 pm

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