An Approach to Formulate Mathematical Model for Solar Drying for Green Drying of Herbs

S.M. Mowade[a*], Dr. G.K. Awari [b], Dr. M.P.Singh[c], Dr. C.N. Sakhale[d]

[a*]*Research Scholar & Asstt. Professor, Madhukarrao Pandav College of Engineering, Bhandara, India*
[b]*Professor & Principal, Tulsiram Gaikwad Patil College of Engineering, Nagpur, India*
[c] *Professor & Principal,Priyadarshini College of Engineering, Nagpur, India*
[c]*Associate Professor and Head PG, Mechanical Engg. Deptt.,Priyadarshini College of Engineering, Nagpu, India*

***Abstract*- The objectives of this research work is to carry out "Studies on drying characteristics, effectiveness and evolution of solar dryers for green drying of stevia leaves and other selected herbs of central India. This paper presents an overall idea of estimation of time required, mass of air flow, total quantity of drying, Percentage of moisture removal, Convective heat and mass transfer coefficient from crop to air and Heat energy required for drying Green crop by using solar drying process. The overview of dimensional analysis to formulate an approximate generalized experimental data based model for Solar drying process by the method of design of experiments.**

Keywords—***Solar Dryer, Green Drying, Convective heat transfer, Dimension Analysis, Test Plan***

I. INTRODUCTION

Drying is a vital and critical operation in any industrial/Agro Industrial process requiring substantial conventional energy. India spends annually around 1.80 Million KL of furnace oil its equivalent for meeting 60% of thermal energy for processing the end products India, with an average solar radiation potential of 4-7 kWh/m2/day , has huge potential to utilize solar energy as alternate source of energy. The central India city Nagpur having higher solar radiation rate of 5.8 kWh/m2/day. with nearly 300 clear days and summer temperature close to 48 degree C has been declared as a solar city by Govt. of India. As per department of AYUSH, Govt of India sources, around 40% of India forest products including herbs are soured from central India in and around Nagpur including the Satpura Hills. Also the Satpura Hills area is being considered to be declared as a Biotech Zone amongst other Natural herbs, the region quite suitable to grow stevia, the Natural Herbal sweetener. These herbs, being perishable in nature need to be dried as primary post harvest system Few Green Herbs of importance in central India along with their benefits considered for the study. This paper highlights the studies on stevia.

Stevia the herb known as alternate to suger without side effect, giving steviol and steviocides , the natural Herbal Sweetner grown well in semi-humid subtropical on 200-400 meters above sea level, with 1500-1800 mm of rain temperature extremes of minus 6 deg C to plus 43 Deg C . The mature perennial plant survives to 5 years and can be larger, up to 1.8 m with up to 20 branches per plant Nagpur Region is ideal for Stevia cultivation.

II. SOLAR DRYING OPERATION

Solar drying systems present an attractive option to sun drying. Such system can be quite compact and suitable for small farmers in the region or quite large and of industrial design solar drying systems can be classified as direct or indirect and where airflow may be natural or forced convection. For industrial applications or drying on large estates, mixed mode dryers which utilize solar energy and conventional fuels as well as forced convection are recommended. For the small formers of the region, property designed simple solar cabinets will be recommended. Solar Drying will now be viewed as a standalone process for the production of storable, primary green herbs in the region. Drying will be also be considered in integrated, food processing operations, with technology and entrepreneurship combined to create successful business that will create many entrepreneurs in the suicide hit/drought hit areas of Nagpur.

Crop drying is the process of removing water from food by circulating hot air through it, Hot air is required to vaporize the moisture contained by the solid, and air flow is necessary to remove the vapour. For effective drying air should be hot, dry and moving and moisture must migrate from within the product to the product's surface, as this is where the moisture exchange with the air occurs. There two stages in a typical drying process:

- The first state is the removal of surface moisture.
- The second stage is the removal of 'internal moisture' form within the solid material.

The drying process is therefore divided into a "constant rate" period and a "falling rate" period. During the constant rate drying period, the surface of the material is still wet and the rate of drying is governed by evaporation of free moisture from the product's surface or near surface areas. The rate of drying is dependent on the vapor pressure difference between surface and the air. Drying air temperature, air velocity and shape and size of the drying particles can significantly affect the drying rate[5],[6].

All most all the natural products including selected herbs for the studies like Stevia amongst other herbs need to be dried Green to retain their actives for better effectives. Hence there is a big demand for dryers to produce dried material that will remain green after drying. The market size being huge and with good availability of solar radiations, solar dryers could emerge as cost effective and energy efficient alternative for such applications. The objectives of this research work is to carry out "Studies on drying characteristics, effectiveness and evolution of solar dryers for green drying of stevia leaves and other selected herbs of central India.

III. DESIGN OF EXPERIMENTAL SET-UP

The solar dryer with box-type absorber collector was constructed using the materials that are easily obtainable from the local market.

Fig. 1 shows a section of the solar crop dryer.

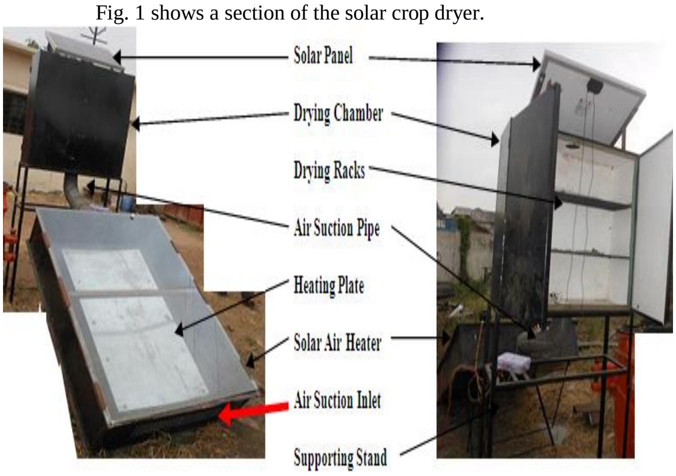

Fig. 1: Experimental Setup of Solar Dryer

The dryer has four main features namely: the box-type absorber solar air collector, Suction pipe with air suction blower, drying cabinet and drying racks with air exhaust blower and Solar panel for power supply of blowers

a) Collector (solar air heater)

The heat absorber (inner box) of the solar air heater was constructed using 2 mm thick galvanized plate, painted black, the surface facing sunlight was painted with black paint containing (5%) black chromium powder to increase its absorbing capability ([1]Duffie and Beckman, 1974). The solar collector is fitted with Copper plate installed on heighted studs. In experimentation this copper sheet can be replaced with aluminum, Stainless steel plate. The solar collector assembly consists of air flow channel enclosed by transparent cover (glazing). The glazing is a single layer of 6 mm thick transparent glass sheet. It has a surface area of 5ft by 4 ft and height of 1.5 ft (fig. 2).

b) Suction pipe with air suction blower

Two blowers are used in this mechanism. First blower is used for sucking hot air from solar air heater to the drying chamber cabinet through hosepipe insulated by cotton. Second blower is attached at top of drying chamber for extracting air from drying chamber. Here computer fan is used as blower (fig.3).

c) The drying cabinet and drying racks

The designing of the drying chamber depends on many factors such as the product to be dried, the required temperature and velocity of the air to dry food material, the quantity of the dried product and the relative humidity of the air passing over the food material[4]. The drying chamber houses two drying racks with meshed wire fitting as shown in Figure 1. Two trays of dimension (3ft x 1ft) were fabricated and stacked uniformly/evenly at distances (1ft) apart, for placing of material to be dried. The tray was made from an aluminum wire mesh attached to it. The drying chamber was also lined with foam insulation material 5 cm thick to prevent loss of heat (fig.3).

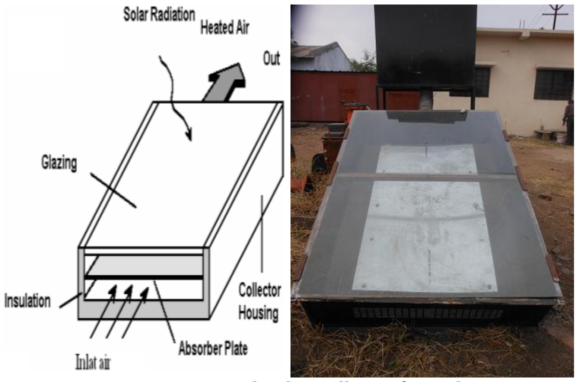

Fig. 2: Typical Solar Collector for air heating

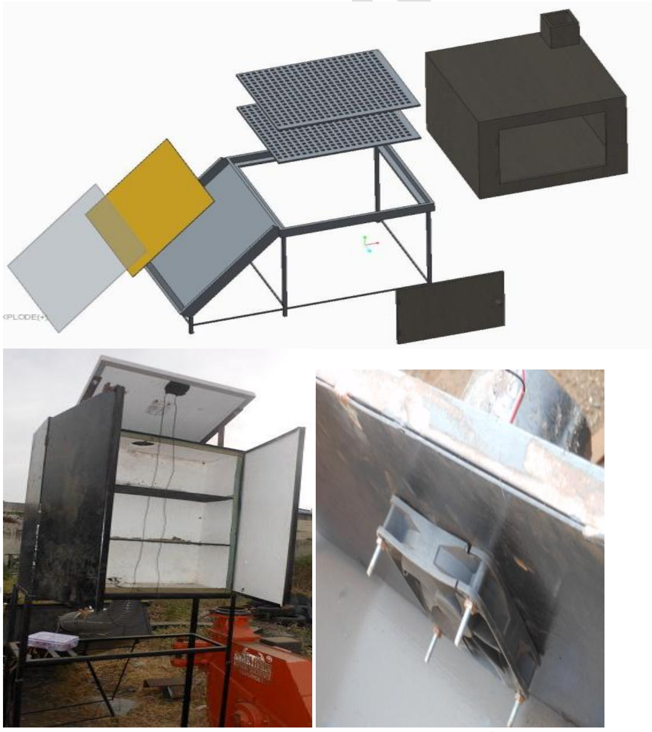

Fig. 3: Drying Cabinet with wire mesh racks, Blower for air extraction

IV. DRYING MECHANISM

In the process of drying, heat is necessary to evaporate moisture from the material and a flow of air helps in carrying away the evaporated moisture. There are two basic mechanisms involved in the drying process: 1) the migration of moisture from the interior of an individual material to the surface, and 2) the evaporation of moisture from the surface to the surrounding air. The drying of a product is a complex heat and mass transfer process which depends on external variables such as temperature, humidity and velocity of the air stream and internal variables which depend on parameters like surface characteristics (rough or smooth surface), chemical composition (sugars, starches, etc.), physical structure (porosity, density, etc.), and size and shape of product.

V. THE EXPERIMENTAL MEASUREMENTS

Three thermocouples have been positioned to measure the air temperature at the inlet and outlet portion of the air heater with accuracy of ±1. Another thermocouples have been placed on trays in order to measure the temperature of trays. Ambient temperature and humidity was also recorded during the course of experiments. The experiment was conducted at Nagpur, Center India (latitude 21°06’ N and Longitude 79°03’E) and the orientation of the solar collector has been fixed towards the south direction, inclined at an angle of 31°. The solar radiation on a horizontal and inclined surface has been recorded during the course of experiments with the help of solar meter. Air velocity or flow rate of air at the inlet position of the drying chamber was measured by anemometer (fig.4).

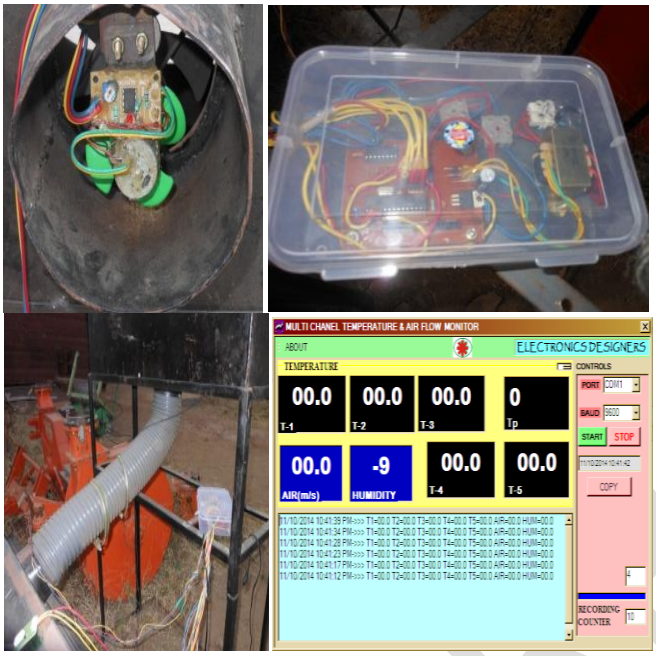

Fig. 4: Anemometer, Electronic Circuit along with thermocouples, humidifier and window of software for measurement of temperature, humidity and air velocity.

VI. DESIGN CALCULATIONS

The various parameters of solar drying process I s calculated using following relations

i) Mass of air flow (m_a)

Calculated using relation $(\boldsymbol{m_a}) = \left(\frac{Q}{C_{pa}.\Delta T}\right)$**….(1)**

Where Q is heat flow in watts, C_{pa} - Specific heat of air at temp. t_f in J/Kg°C, ΔT is Temperature gradient.

ii) Convective heat and mass transfer coefficient from crop to air (h)

h is Calculated using relation $(\boldsymbol{Nu}) = \{\frac{h.Dh}{K}\}$**….(2)**

Where Dh is hydraulic dia in m, and K is thermal Conductivity of heating medium in $W/m^{2o}C$.

iii) Heat energy required for drying crop (Q)

Q is Calculated using relation $(\boldsymbol{Q}) = \{\boldsymbol{h}.\boldsymbol{A_p}.(\boldsymbol{t_p} - \boldsymbol{t_\infty})\}$**….(3)**

Where Q is heat flow in watts, A_p- Cross section Area of heating plate, tp & $\boldsymbol{t_\infty}$is Temperature of plate and ambient in °C resp.

iv) Efficiency of heat collector plate (η_c)

η_c is Calculated using relation $(\boldsymbol{\eta_c}) = \{\frac{Q}{I.\ A_p}\}$**….(4)**

Where I is Solar heat flux in W/m^2.

I= Ig x Cos(θi) **….(5)**

Where, θi is the angle of incident.

Calculation for global heat flux (Ig)

(ω) =(h-12) x15**….(6)**

ω is Hour angle and h is time

Declination (δ)

This is the angle between the sun’s direction and the equatorial plane and is given by [3]Forson et al. (2007) as,

δ = 23.45 sin [0.9863 (284 + n)] **….(7)**

Where (n) is the day in the year which varies from n = 1 to n = 365.

Optimum collector slope (β)

The optimum collector slope, β, is determined from

β = δ + φ **….(8)**

Where (δ) is the angle of declination. For Nagpur β slope angle is 31.1^o

and (φ)= $21.1\ ^o$ is the latitude of the location.

Cos (θi)= Sin δ .sin (φ – β) + Cos δ. Cos ω. Cos(φ – β) **….(9)**

Length of the day

The length of the day is given by [2] Henry et al. (1999) as:

N = (2/15) cos-1(-tanφtanδ) **….(10)**

v) % moisture Content (PMC)

PMC is calculated using relation (%MC) = $\left(\frac{M_{ci}-M_{co}}{M_{ci}}\right)$. **….(11)**

Where, Mci= mass of crop sample before drying and Mco = mass of crop sample after drying.

VII. NEED FOR FORMULATING GENERALIZED EXPERIMENTAL DATA BASED MODELS

In view of forgoing it is obvious that one will have to decide what should be the maximum heat generated, % of moisture and maximum efficiency to the system for getting appropriate quality of drying herbs in minimum time. By knowing this one can establish herb drying properties. This would be possible if one can have a quantitative relationship amongst various dependent and independent variables of the system. This relationship would be known as the mathematical model of this solar drying operation. It is well known that such a model for the solar drying cannot be formulated applying logic [9]. The only option with which one is left is to formulate an experimental data based model. Hence, in this investigation it is decided to formulate such an experimental data based model. In this approach all the independent variable are varied over a widest possible range, a response data is collected and an analytical relationship is established. Once such a relationship is established then the technique of optimization can be applied to deduce the values of independent variables at which the necessary responses can be minimized or maximized. In fact determination of such values of independent variables is always the puzzle for the operator because it is a complex phenomenon of interaction of various independent variables and dependant variables shown in table 1. It is well known that mathematical modeling of any drying operation is possible by applying methodology of experimentation [7]. The same is adopted in the present work.

Table 1. Dependent and Independent variable For solar drying Operation

S. N.	Variables	Symbol	Unit	$M^0L^0T^0\theta^0$	Dependant/ Independent	Variable/Constant
01	Mass of crop after drying	M_{Co}	Kg	M	Dependant	Response Variable
02	Time required for drying crop	t_d	Sec	T	Dependant	Response Variable
03	Mass of air flow	m_a	Kg/S	MT^{-1}	Dependant	Response Variable
04	Convective heat and mass transfer coefficient from crop to air	h	W/m² °C	$MT^{-3}\theta^{-1}$	Dependant	Response Variable
05	Heat energy required for drying crop	Q	W	ML^2T^{-3}	Dependant	Response Variable
06	Efficiency of heat collector plate	η_c	%	$M^0L^0T^0\theta^0$		
07	% moisture Content	PMC	%	$M^0L^0T^0\theta^0$	Dependant	Response Variable
1	Velocity of air	v_a	m/s	LT^{-1}	Independent	Variable
2	Ambient Temperature	$t\infty$	°C	$M^0L^0T^0\theta^1$	Independent	Variable
3	Temperature inside the heating Chamber	t_p	°C	$M^0L^0T^0\theta^1$	Independent	Variable
4	Temperature inside the drying chamber	t_b	°C	$M^0L^0T^0\theta^1$	Independent	Variable
5	Film Temperature $t_f = t_p + t\infty/2$	t_f	°C	$M^0L^0T^0\theta^1$	Independent	Variable
6	Relative Humidity	H	%	$M^0L^0T^0\theta^0$	Independent	Variable
7	Dynamic Viscosity of air at temp. t_f	μ_a	NS/m²	$ML^{-1}T^{-1}$	Independent	Variable
8	Thermal Conductivity of air at temp. t_f	K_a	W/m°C	$MLT^{-3}\theta^{-1}$	Independent	Variable
9	Specific heat of air at temp. t_f	C_{pa}	J/Kg°C	$L^2T^{-2}\theta^{-1}$	Independent	Variable
10	Density of air at temp. t_f	ρa	Kg/m³	ML^{-3}	Independent	Variable
11	Length of heating Plate	L_p	m	L	Independent	Variable
12	Width of heating Plate	B_p	m	L	Independent	Variable
13	Thickness of heating plate	T_p	m	L	Independent	Variable
14	Thermal Conductivity of heating Plate	K_P	W/m°C	$MLT^{-3}\theta^{-1}$	Independent	Variable
15	Specific heat of heating Plate	C_{pp}	J/Kg°C	$L^2T^{-2}\theta^{-1}$	Independent	Variable
16	Thermal diffusivity of heating Plate	α_p	m²/s	L^2T^{-1}	Independent	Variable
17	Specific Density of heating Plate	ρ_p	Kg/m³	ML^{-3}	Independent	Variable
18	Volume of heating Chamber	V_{hc}	m³	L^3	Independent	Variable
19	Volume of drying Chamber	V_{dc}	m³	L^3	Independent	Variable
20	Solar heat flux	I	W/m²	MT^{-3}	Independent	Variable
21	Angle of incident	θ	rad	--	Independent	Variable
22	Length of Day	N	--	--	Independent	Variable
23	Mass of crop before drying	M_{Ci}	Kg	M	Independent	Variable

VIII. BRIEF DESCRIPTION OF APPLICATION OF THEORY OF EXPERIMENTATION

The approach adopted for formulating generalized experimental model suggested by Hilbert Schenck Jr [9] is indicated below stepwise

1) Identification of independent, dependent and extraneous variables, 2) Reduction of independent variables adopting dimensional analysis, 3) Test planning comprising of determination of test envelope, test points, test sequence and experimentation plan, 4) Physical design of an experimental set up, 5) Execution of experimentation, 6) Purification of experimentation data, 7) Formulation of the model.8)Model optimization.

IX. EXPERIMENTAL PROCEDURES

For Solar drying of various types of herbs, six to seven types of herbs should be selected and at dried using three different (copper, Aluminum & Steel) heat collecting plate of air heating chamber in various months of the year. The reading should be noted for forced and natural draft circulation. Based on the data experimental plan can be decided to calculate test plan. Based on the collected data mathematical model can be formulated using Buckingham's π– theorem. The procedure to establish mathematical model is as follows:

A. *Formulation of Approximate Generalized Experimental Data Base Model By Dimensional Analysis*

As per dimensional analysis [8], **Mass of crop after drying (M_{Co})**
was written in the function form as :-

$\mathbf{M_{Co}}$ =f(v_a, $t\infty$, t_p, t_b, t_f, H, μ_a, K_a, C_{pa}, ρ_a, L_p, B_p, T_p, K_P, C_{pp}, α_p, ρ_p, V_{hc}, V_{dc}, I, ϴ, N, M_{Ci}) … (12)

By selecting Mass (M), Length(L), Time (T) and Temperature (ϴ) as the basic dimensions, the basic dimensions of the forgoing quantities were mentioned in table 1:
According to the Buckingham's - theorem, (n- m) number of dimensionless groups are forms. In this case n is 23 and m=4, so π_1 to π_{19}dimensionless groups were formed. By choosing 'L_p', 'v_a', 'K_a' and 'μ_a' as a repeating variable, nineteen π terms were developed as follows:

$$\left(\frac{v_a.M_{co}}{L_p{}^2.\mu_a}\right) = f\left\{\begin{array}{c}\left(\frac{K_a.t_\infty}{v_a^2.\mu_a}\right)\left(\frac{K_a.t_p}{v_a^2.\mu_a}\right)\left(\frac{K_a.t_b}{v_a^2.\mu_a}\right)\left(\frac{K_a.t_f}{v_a^2.\mu_a}\right)(H)\left(\frac{\mu_a.C_{Pa}}{K_a}\right)\\ \left(\frac{\mu_a.C_{Pp}}{K_a}\right)\left(\frac{\rho_a.v_a.L_a}{\mu_a}\right)\left(\frac{\rho_p.v_a.L_a}{\mu_a}\right)\\ \left(\frac{K_p}{K_a}\right)\left(\frac{B_p}{L_a}\right)\left(\frac{T_p}{L_a}\right)\left(\frac{V_{hc}}{L_a{}^3}\right)\left(\frac{V_{dc}}{L_a{}^3}\right)\left(\frac{I.L_p}{\mu_a.v_a{}^2}\right)\\ \left(\frac{\alpha_p}{L_p.v_a}\right)\left(\frac{v_a.M_{ci}}{L_p{}^2.\mu_a}\right)(\Theta i)(N)\end{array}\right\} \quad ..(13)$$

B. Reduction of independent variables/dimensional analysis

When n (no. of variables) is large, even by applying Buckingham's π theorem number of π terms will not be reduced significantly than number of all independent variables. Thus, much reduction in number of variables is not achieved. It is evident that, if we take the product of the π terms it will also be dimensionless number and hence a π term. This property is used to achieve further reduction of the number of variables. Thus few π terms are formed by logically taking the product of few other π terms and final mathematical equations are given below:

i) Mass of crop after drying ($\mathbf{M_{co}}$) : Measured with calibrated with weighing device.

$$(\pi_{01}) = f\left\{\begin{array}{c}(\pi_{01})(\pi_{02})(\pi_{03})(\pi_{04})(\pi_{05})\\(\pi_{06})(\pi_{07})(\pi_{08})(\pi_{09})(\pi_{10})(\pi_{11})\end{array}\right\}$$

$$\left(\frac{v_a.M_{co}}{L_p{}^2.\mu_a}\right) = f\left\{\begin{array}{c}\left(\frac{K_a{}^4.t_\infty.t_p.t_b.t_f}{v_a{}^8.\mu_a{}^4}\right)(H)\left(\frac{\mu_a{}^2.C_{Pa}.C_{Pp}}{K_a{}^2}\right)\\ \left(\frac{v_a{}^2L_p{}^2.\ \rho_a.\ \rho_p}{\mu_a{}^2}\right)\left(\frac{K_p}{K_a}\right)\left(\frac{B_p.T_p}{L_a}\right)\\ \left(\frac{V_{hc}.V_{dc}}{L_a{}^6}\right)\left(\frac{I.L_p}{\mu_a.v_a{}^2}\right)\left(\frac{\alpha_p}{L_p.v_a}\right)\\ \left(\frac{v_a.M_{ci}}{L_p{}^2.\mu_a}\right)(\Theta i.N)\end{array}\right\}$$

$$M_{co} = K_1\frac{L_p{}^2.\mu_a}{v_a}\left\{\begin{array}{c}\left(\frac{K_a{}^4.t_\infty.t_p.t_b.t_f}{v_a{}^8.\mu_a{}^4}\right)^{a1}(H)^{b1}\\ \left(\frac{\mu_a{}^2.C_{Pa}.C_{Pp}}{K_a{}^2}\right)^{c1}\left(\frac{v_a{}^2L_p{}^2.\rho_a.\rho_p}{\mu_a{}^2}\right)^{d1}\\ \left(\frac{K_p}{K_a}\right)^{e1}\left(\frac{B_p.T_p}{L_a}\right)^{f1}\left(\frac{V_{hc}.V_{dc}}{L_a{}^6}\right)^{g1}\left(\frac{I.L_p}{\mu_a.v_a{}^2}\right)^{h1}\left(\frac{\alpha_p}{L_p.v_a}\right)^{i1}\\ \left(\frac{v_a.M_{ci}}{L_p{}^2.\mu_a}\right)^{j1}(\Theta i.N)^{k1}\end{array}\right\}$$

(14)

ii) Time required for drying crop- *t_d*

$$(\pi_{02}) = f\left\{\begin{array}{c}(\pi_{01})(\pi_{02})(\pi_{03})(\pi_{04})\\(\pi_{05})(\pi_{06})(\pi_{07})(\pi_{08})(\pi_{09})(\pi_{10})(\pi_{11})\end{array}\right\}$$

$$\left(\frac{v_a.t_d}{L_a}\right) = f\left\{\begin{array}{c}\left(\frac{K_a{}^4.t_\infty.t_p.t_b.t_f}{v_a{}^8.\mu_a{}^4}\right)(H)\left(\frac{\mu_a{}^2.C_{Pa}.C_{Pp}}{K_a{}^2}\right)\\ \left(\frac{v_a{}^2L_p{}^2.\ \rho_a.\ \rho_p}{\mu_a{}^2}\right)\left(\frac{K_p}{K_a}\right)\left(\frac{B_p.T_p}{L_a}\right)\\ \left(\frac{V_{hc}.V_{dc}}{L_a{}^6}\right)\left(\frac{I.L_p}{\mu_a.v_a{}^2}\right)\left(\frac{\alpha_p}{L_p.v_a}\right)\left(\frac{v_a.M_{ci}}{L_p{}^2.\mu_a}\right)(\Theta i.N)\end{array}\right\}$$

$$t_d = K_2\frac{L_a}{v_a}\left\{\begin{array}{c}\left(\frac{K_a{}^4.t_\infty.t_p.t_b.t_f}{v_a{}^8.\mu_a{}^4}\right)^{a2}(H)^{b2}\\ \left(\frac{\mu_a{}^2.C_{Pa}.C_{Pp}}{K_a{}^2}\right)^{c2}\left(\frac{v_a{}^2L_p{}^2.\ \rho_a.\ \rho_p}{\mu_a{}^2}\right)^{d2}\\ \left(\frac{K_p}{K_a}\right)^{e2}\left(\frac{B_p.T_p}{L_a}\right)^{f2}\left(\frac{V_{hc}.V_{dc}}{L_a{}^6}\right)^{g2}\left(\frac{I.L_p}{\mu_a.v_a{}^2}\right)^{h2}\\ \left(\frac{\alpha_p}{L_p.v_a}\right)^{i2}\left(\frac{v_a.M_{ci}}{L_p{}^2.\mu_a}\right)^{j2}(\Theta i.N)^{k2}\end{array}\right\}$$

.....(15)

iii) Mass of air flow ($\mathbf{m_a}$)

$$(\pi_{03}) = f\left\{\begin{array}{c}(\pi_{01})(\pi_{02})(\pi_{03})(\pi_{04})(\pi_{05})\\(\pi_{06})(\pi_{07})(\pi_{08})(\pi_{09})(\pi_{10})(\pi_{11})\end{array}\right\}$$

$$\left(\frac{m_a}{L_a.\mu_a}\right) = f\left\{\begin{array}{c}\left(\frac{K_a{}^4.t_\infty.t_p.t_b.t_f}{v_a{}^8.\mu_a{}^4}\right)(H)\left(\frac{\mu_a{}^2.C_{Pa}.C_{Pp}}{K_a{}^2}\right)\\ \left(\frac{v_a{}^2L_p{}^2.\ \rho_a.\ \rho_p}{\mu_a{}^2}\right)\left(\frac{K_p}{K_a}\right)\left(\frac{B_p.T_p}{L_a}\right)\\ \left(\frac{V_{hc}.V_{dc}}{L_a{}^6}\right)\left(\frac{I.L_p}{\mu_a.v_a{}^2}\right)\left(\frac{\alpha_p}{L_p.v_a}\right)\left(\frac{v_a.M_{ci}}{L_p{}^2.\mu_a}\right)(\Theta i.N)\end{array}\right\}$$

$$m_a = K_3 . L_a . \mu_a \left\{ \begin{matrix} \left(\frac{K_a{}^4 . t_\infty . t_p . t_b . t_f}{v_a{}^8 . \mu_a{}^4}\right)^{a3} (H)^{b3} \\ \left(\frac{\mu_a{}^2 . C_{Pa} . C_{Pp}}{K_a{}^2}\right)^{c3} \left(\frac{v_a{}^2 L_p{}^2 . \rho_a . \rho_p}{\mu_a{}^2}\right)^{d3} \\ \left(\frac{K_p}{K_a}\right)^{e3} \left(\frac{B_p . T_p}{L_a}\right)^{f3} \left(\frac{V_{hc} . V_{dc}}{L_a{}^6}\right)^{g3} \\ \left(\frac{I . L_p}{\mu_a . v_a{}^2}\right)^{h3} \left(\frac{\alpha_p}{L_p . v_a}\right)^{i3} \left(\frac{v_a . M_{ci}}{L_p{}^2 . \mu_a}\right)^{j3} \\ (\theta i . N)^{k3} \end{matrix} \right\}$$

.....(16)

iv) Convective heat and mass transfer coefficient from crop to air (h)

$$(\pi_{04}) = f \left\{ \begin{matrix} (\pi_{01})(\pi_{02})(\pi_{03})(\pi_{04})(\pi_{05})(\pi_{06}) \\ (\pi_{07})(\pi_{08})(\pi_{09})(\pi_{10})(\pi_{11}) \end{matrix} \right\}$$

$$\left(\frac{L_p . h}{K_a}\right) = f \left\{ \begin{matrix} \left(\frac{K_a{}^4 . t_\infty . t_p . t_b . t_f}{v_a{}^8 . \mu_a{}^4}\right)(H)\left(\frac{\mu_a{}^2 . C_{Pa} . C_{Pp}}{K_a{}^2}\right) \\ \left(\frac{v_a{}^2 L_p{}^2 . \rho_a . \rho_p}{\mu_a{}^2}\right)\left(\frac{K_p}{K_a}\right)\left(\frac{B_p . T_p}{L_a}\right) \\ \left(\frac{V_{hc} . V_{dc}}{L_a{}^6}\right)\left(\frac{I . L_p}{\mu_a . v_a{}^2}\right)\left(\frac{\alpha_p}{L_p . v_a}\right)\left(\frac{v_a . M_{ci}}{L_p{}^2 . \mu_a}\right)(\theta i . N) \end{matrix} \right\}$$

$$(Nu) = f \left\{ \begin{matrix} \left(\frac{K_a{}^4 . t_\infty . t_p . t_b . t_f}{v_a{}^8 . \mu_a{}^4}\right)(H)\left(\frac{\mu_a{}^2 . C_{Pa} . C_{Pp}}{K_a{}^2}\right) \\ \left(\frac{v_a{}^2 L_p{}^2 . \rho_a . \rho_p}{\mu_a{}^2}\right)\left(\frac{K_p}{K_a}\right)\left(\frac{B_p . T_p}{L_a}\right)\left(\frac{V_{hc} . V_{dc}}{L_a{}^6}\right) \\ \left(\frac{I . L_p}{\mu_a . v_a{}^2}\right)\left(\frac{\alpha_p}{L_p . v_a}\right)\left(\frac{v_a . M_{ci}}{L_p{}^2 . \mu_a}\right)(\theta i . N) \end{matrix} \right\}$$

Where Nu is Nusselt Number

$$h = K_4 \frac{K_a}{L_a} \left\{ \begin{matrix} \left(\frac{K_a{}^4 . t_\infty . t_p . t_b . t_f}{v_a{}^8 . \mu_a{}^4}\right)^{a4} (H)^{b4} \left(\frac{\mu_a{}^2 . C_{Pa} . C_{Pp}}{K_a{}^2}\right)^{c4} \\ \left(\frac{v_a{}^2 L_p{}^2 . \rho_a . \rho_p}{\mu_a{}^2}\right)^{d4} \left(\frac{K_p}{K_a}\right)^{e4} \left(\frac{B_p . T_p}{L_a}\right)^{f4} \\ \left(\frac{V_{hc} . V_{dc}}{L_a{}^6}\right)^{g4} \left(\frac{I . L_p}{\mu_a . v_a{}^2}\right)^{h4} \left(\frac{\alpha_p}{L_p . v_a}\right)^{i4} \\ \left(\frac{v_a . M_{ci}}{L_p{}^2 . \mu_a}\right)^{j4} (\theta i . N)^{k4} \end{matrix} \right\}$$

.....(17)

v) Heat energy required for drying crop (Q)

$$(\pi_{05}) = f \left\{ \begin{matrix} (\pi_{01})(\pi_{02})(\pi_{03})(\pi_{04})(\pi_{05})(\pi_{06}) \\ (\pi_{07})(\pi_{08})(\pi_{09})(\pi_{10})(\pi_{11}) \end{matrix} \right\}$$

$$\left(\frac{Q}{L_a . v_a{}^2 . \mu_a}\right) = f \left\{ \begin{matrix} \left(\frac{K_a{}^4 . t_\infty . t_p . t_b . t_f}{v_a{}^8 . \mu_a{}^4}\right)(H)\left(\frac{\mu_a{}^2 . C_{Pa} . C_{Pp}}{K_a{}^2}\right) \\ \left(\frac{v_a{}^2 L_p{}^2 . \rho_a . \rho_p}{\mu_a{}^2}\right)\left(\frac{K_p}{K_a}\right)\left(\frac{B_p . T_p}{L_a}\right)\left(\frac{V_{hc} . V_{dc}}{L_a{}^6}\right) \\ \left(\frac{I . L_p}{\mu_a . v_a{}^2}\right)\left(\frac{\alpha_p}{L_p . v_a}\right)\left(\frac{v_a . M_{ci}}{L_p{}^2 . \mu_a}\right)(\theta i . N) \end{matrix} \right\}$$

$$Q = K_5 . L_a . v_a{}^2 . \mu_a \left\{ \begin{matrix} \left(\frac{K_a{}^4 . t_\infty . t_p . t_b . t_f}{v_a{}^8 . \mu_a{}^4}\right)^{a5} (H)^{b5} \\ \left(\frac{\mu_a{}^2 . C_{Pa} . C_{Pp}}{K_a{}^2}\right)^{c5} \left(\frac{v_a{}^2 L_p{}^2 . \rho_a . \rho_p}{\mu_a{}^2}\right)^{d5} \left(\frac{K_p}{K_a}\right)^{e5} \\ \left(\frac{B_p . T_p}{L_a}\right)^{f5} \left(\frac{V_{hc} . V_{dc}}{L_a{}^6}\right)^{g5} \left(\frac{I . L_p}{\mu_a . v_a{}^2}\right)^{h5} \\ \left(\frac{\alpha_p}{L_p . v_a}\right)^{i5} \left(\frac{v_a . M_{ci}}{L_p{}^2 . \mu_a}\right)^{j5} (\theta i . N)^{k4} \end{matrix} \right\}$$

.....(18)

vi) Efficiency of heat collector plate (ηc)

$$(\pi_{06}) = f \left\{ \begin{matrix} (\pi_{01})(\pi_{02})(\pi_{03})(\pi_{04})(\pi_{05}) \\ (\pi_{06})(\pi_{07})(\pi_{08})(\pi_{09})(\pi_{10})(\pi_{11}) \end{matrix} \right\}$$

$$(\eta_c) = f \left\{ \begin{matrix} \left(\frac{K_a{}^4 . t_\infty . t_p . t_b . t_f}{v_a{}^8 . \mu_a{}^4}\right)(H)\left(\frac{\mu_a{}^2 . C_{Pa} . C_{Pp}}{K_a{}^2}\right) \\ \left(\frac{v_a{}^2 L_p{}^2 . \rho_a . \rho_p}{\mu_a{}^2}\right)\left(\frac{K_p}{K_a}\right)\left(\frac{B_p . T_p}{L_a}\right)\left(\frac{V_{hc} . V_{dc}}{L_a{}^6}\right) \\ \left(\frac{I . L_p}{\mu_a . v_a{}^2}\right)\left(\frac{\alpha_p}{L_p . v_a}\right)\left(\frac{v_a . M_{ci}}{L_p{}^2 . \mu_a}\right)(\theta i . N) \end{matrix} \right\}$$

$$\eta_c = K_6 \left\{ \begin{matrix} \left(\frac{K_a{}^4 . t_\infty . t_p . t_b . t_f}{v_a{}^8 . \mu_a{}^4}\right)^{a6} (H)^{b6} \left(\frac{\mu_a{}^2 . C_{Pa} . C_{Pp}}{K_a{}^2}\right)^{c6} \\ \left(\frac{v_a{}^2 L_p{}^2 . \rho_a . \rho_p}{\mu_a{}^2}\right)^{d6} \left(\frac{K_p}{K_a}\right)^{e6} \left(\frac{B_p . T_p}{L_a}\right)^{f6} \\ \left(\frac{V_{hc} . V_{dc}}{L_a{}^6}\right)^{g6} \left(\frac{I . L_p}{\mu_a . v_a{}^2}\right)^{h6} \\ \left(\frac{\alpha_p}{L_p . v_a}\right)^{i6} \left(\frac{v_a . M_{ci}}{L_p{}^2 . \mu_a}\right)^{j6} (\theta i . N)^{k6} \end{matrix} \right\}$$

....(19)

vi) % moisture Content (PMC)

$$(\pi_{07}) = f \left\{ \begin{matrix} (\pi_{01})(\pi_{02})(\pi_{03})(\pi_{04}) \\ (\pi_{05})(\pi_{06})(\pi_{07})(\pi_{08})(\pi_{09})(\pi_{10})(\pi_{11}) \end{matrix} \right\}$$

$$(PMC) = f \left\{ \begin{matrix} \left(\frac{K_a{}^4 . t_\infty . t_p . t_b . t_f}{v_a{}^8 . \mu_a{}^4}\right)(H)\left(\frac{\mu_a{}^2 . C_{Pa} . C_{Pp}}{K_a{}^2}\right) \\ \left(\frac{v_a{}^2 L_p{}^2 . \rho_a . \rho_p}{\mu_a{}^2}\right)\left(\frac{K_p}{K_a}\right)\left(\frac{B_p . T_p}{L_a}\right)\left(\frac{V_{hc} . V_{dc}}{L_a{}^6}\right) \\ \left(\frac{I . L_p}{\mu_a . v_a{}^2}\right)\left(\frac{\alpha_p}{L_p . v_a}\right)\left(\frac{v_a . M_{ci}}{L_p{}^2 . \mu_a}\right)(\theta i . N) \end{matrix} \right\}$$

$$PMC = K_7 \left\{ \begin{array}{c} \left(\frac{K_a{}^4 . t_\infty . t_p . t_b . t_f}{v_a{}^8 . \mu_a{}^4}\right)^{a7} (H)^{b7} \\ \left(\frac{\mu_a{}^2 . C_{Pa} . C_{Pp}}{K_a{}^2}\right)^{c7} \left(\frac{v_a{}^2 L_p{}^2 . \ \rho_a . \ \rho_p}{\mu_a{}^2}\right)^{d7} \\ \left(\frac{K_p}{K_a}\right)^{e7} \left(\frac{B_p . T_p}{L_a}\right)^{f7} \left(\frac{V_{hc} . V_{dc}}{L_a{}^6}\right)^{g7} \\ \left(\frac{I . L_p}{\mu_a . v_a{}^2}\right)^{h7} \left(\frac{\alpha_p}{L_p . v_a}\right)^{i7} \left(\frac{v_a . M_{ci}}{L_p{}^2 . \mu_a}\right)^{j7} (\theta i . N)^{k7} \end{array} \right\}$$

.....(20)

The relationship between various parameters was unknown. The dependent parameter Π_{01} to Π_{07} were bear an intricate relationship with remaining terms (ie. π_1 to π_{11}) evaluated on the basis of experimentation. The true relationship is difficult to obtain. The possible relation may be linear, log linear, polynomial with n degrees, linear with products of independent πi terms. In this manner any complicated relationship can be evaluated and further investigated for error. Hence the relationship for M_{co} was formulated as:

$\pi_{01} = k_1 \times (\pi_1)^{a1} \times (\pi_2)^{b1} \times (\pi_3)^{c1} \times (\pi_4)^{d1} \times (\pi_5)^{e1} \times (\pi_6)^{f1} \times (\pi_7)^{g1} .... (\pi_{11})^{k1}$ ….(21)

Equation is modified as:

Obtaining log on both sides we get,

Log π_{01} = log k1+ $a_1$log π_1+ $b_1$log π_2+ $c_1$log π_3 + $d_1$log π_4 + $e_1$log π_5 + $f_1$log π_6 + $g_1$log π_7**….** $k_1$log π_{11} (22)

This linear relationship now can be viewed as the hyper plane in seven dimensional spaces. To simplify further let us replace log terms by capital alphabet terms implies,

Let, Z_1= log $\pi_{31,}$ K_1 = log k1, A = log $\pi_{1,}$ B = log $\pi_{2,}$ C = log $\pi_{3,}$ D = log π_4, E = log $\pi_{5,}$ F = log π_6 G = log π_7 ....K= log π_{11}

Putting the values in eqn. 7, the same can be written as

$Z_1 = K_1 + a_1 A + b_1 B + c_1 C + d_1 D + e_1 E + f_1 F + g_1 G$............. $k_1 K$.(23)

This is true linear relationship between A to K to reveal π_{01} to π_{07} .Applying the theories of regression analysis, the aim is to minimize the error Error (E) = Ye – Yc. Yc is the computed value of π_{01} using regression equation and Ye is the value of the same term obtained from experimental data with exactly the same values of π_1 ---- $\pi_{11.}$ Correlation and reliability were computed for model accuracy.

IX. CONCLUSION

Under this experimental investigation of thermal performance of solar air heater gives the temperature difference of atmospheric air and wooden box of solar air heater of near about 20 to 25 0C on a moderate sunny day. It is suitable air heater for producing hot air of space heating and agricultural drying applications. After establishment of test points and test envelopes mentioned in this paper, the mathematical model for Mass of crop after drying, Time required for drying crop, Mass of air flow, Convective heat and mass transfer coefficient from crop to air, Heat energy required for drying crop, Efficiency of heat collector plate, and % moisture Content for solar drying operation can be easily established.

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