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A Mathematical Model and Experimental Analysis of Solar Dryer

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Abstract-*In many countries of the world, the use of solar thermal systems in the agricultural area to conserve vegetables, fruits, coffee and other crops has shown to be practical, economical and the responsible approach environmentally. Solar heating systems to dry food and other crops can improve the quality of the product, while reducing wasted produce and traditional fuels—thus improving the quality of life, however the availability of good information is lacking in many of the countries where solar food processing systems are most needed. Solar food dryers are available in a range of size and design and are used for drying various food products. It is found that various types of driers are available to suit the needs of farmers. Therefore, selection of dryers for a particular application is largely a decision based on what is available and the types of dryers currently used widely. A comprehensive review of the various designs, details of construction and operational principles of the wide variety of practically realized designs of solar-energy drying systems reported previously is presented. Compare the open solar drying with the solar dryer technology, drying analysis considering some standard model and error analysis for the particular model for solar dryer and open dryer system.*

Keywords-*Solar Dryer, Drying, Types of dryer, Drying model*

1) Introduction

Drying using the sun under the open sky for preserving food and agricultural crops has been practiced since ancient times. However, this process has many disadvantages: spoilt products due to rain, wind, moisture and dust; loss of produce due to birds and animals; deterioration in the harvested crops due to decomposition, insect attacks and fungi, etc. Further, the process is labour intensive, time consuming and requires a large area for spreading the produce out to dry. Artificial mechanical drying, a relatively recent development, is energy intensive and expensive, and ultimately increases the product cost.

Solar drying is often differentiated from ‘‘Sun Drying’’ by the use of equipment to collect the sun’s radiation in order to harness the radiative energy for drying applications. Solar food dryer improves upon the traditional open-air sun system in five important ways:

It is faster. Foods can be dried in a shorter period of time. Solar food dryers enhance drying times in two ways. Firstly, the translucent, or transparent, glazing over the collection area traps heat inside the dryer, raising the temperature of the air. Secondly, the flexibility of enlarging the solar collection area allows for greater collection of the sun’s energy.

It is more efficient. Since foodstuffs can be dried more quickly, less will be lost to spoilage immediately after harvest. This is especially true of products that require immediate drying such as freshly harvested grain with high moisture content. In this way, a larger percentage of food will be available for human consumption. Also, less of the harvest will be lost to marauding animals and insects since the food products are in safely enclosed compartments.

It is hygienic. Since foodstuffs are dried in a controlled environment, they are less likely to be contaminated by pests, and can be stored with less likelihood of the growth of toxic fungi.

It is healthier. Drying foods at optimum temperatures and in a shorter amount of time enables them to retain more of their nutritional value such as vitamin C. An added bonus is that foods will look and taste better, which enhances their marketability and hence provides better financial returns for the farmers.

It is cheap. Using freely available solar energy instead of conventional fuels to dry products, or using a cheap supplementary supply of solar heat, so reducing conventional fuel demand can result in significant cost savings.

Drying help in reducing the moisture content to a level below which deterioration does not occur and the product can be stored for a definite period. Different crops have different level of safe moisture content.

2) PHYSICS OF SOLAR DRYING:

Heat by convection and radiation to Surface of product

Goes to interior of product

- Increase in temperature
- Formation of water vapor

Evaporation of moisture from Surface.

Drying can be accelerated by

- Increasing flow rate of air,
- Increasing temperature of drying air.

Initial Drying- Surface drying, later on drying depends on type of materials.

Hygroscopic- Grains, fruit, food stuff have residual moisture.

2.1 Type of Solar Drying

Solar dryers can broadly be categorized into direct, indirect and specialized solar dryers. Direct solar dryers have the material to be dried placed in an enclosure, with a transparent cover on it. Heat is generated by absorption of solar radiation on the product itself as well as on the internal surfaces of the drying chamber. In indirect solar dryers, solar radiation is not directly incident on the material to be dried. Air is heated in a solar collector and then ducted to the drying chamber to dry the product. Specialized dryers are normally designed with a specific product in mind and may include hybrid systems where other forms of energy are also used although indirect dryers are less compact when compared to direct solar dryers, they are generally more efficient. Hybrid solar systems allow for faster rate of drying by using other sources of heat energy to supplement solar heat. The three modes of drying are:

i. Open Sun Drying,
ii. Direct Solar Drying,
iii. Indirect Solar Drying in the presence of solar energy.

The working principle of these modes mainly depends upon the method of solar-energy collection and its conversion to useful thermal energy. Different types of solar dryer are shown in figure 1, 2, 3 & 4.

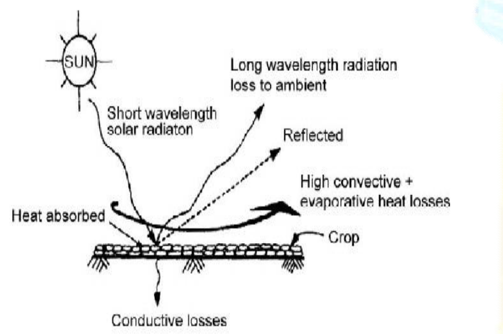

Fig. 1. Working Principle of Open Sun Drying

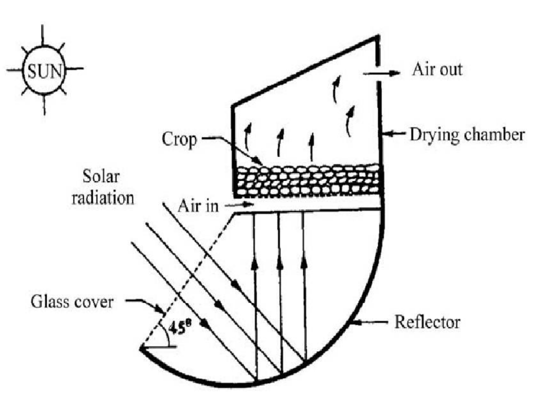

Fig. 2. Direct Solar Drying

2.2 *Analysis of Drying*

Simplified drying models have been used to quantify drying kinetics of various grains and some seeds. Three common models are as follows:

The Henderson Pabis model

$$MR = \frac{M - M_e}{M_i - M_e} = a.\exp(-kt)$$

The Page model

$$MR = \frac{M - M_e}{M_i - M_e} = a.\exp(-kt^N)$$

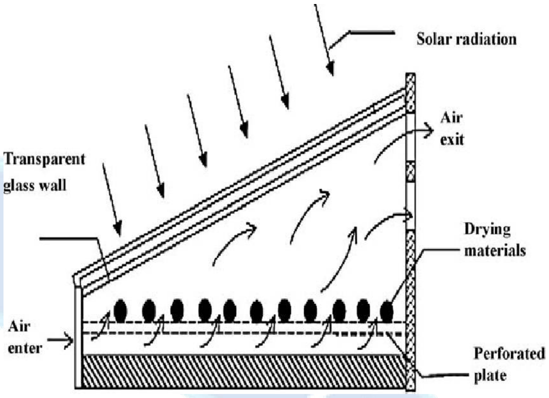

Fig. 3. Reverse Absorber Cabinet Dryer

The Lewis model

$$MR = \frac{M - M_e}{M_i - M_e} = \exp(-kt)$$

The empirical constants for the thin-layer drying models were determined experimentally from normalized drying curves at different temperatures. Normalized from of Lewis and Henderson Pabis equation is

$$\ln(MR) = -kt + 1$$
$$\ln(MR) = -kt + a$$

Where the drying constants k and a are determined from the slope and intercept, respectively, of the ln (MR) vs. time curve. But for Lewis intercept set as 1.

The form of the normalized Page equation is

$$\ln[-\ln(MR)] = \ln(k) + N\ln(t)$$

Value of constant k and N can find from the interception and slope of the ln (ln (MR)) vs. ln (t) curve, respectively.

The goodness of fit for each model was evaluated based on regression analysis and relative percent error (PE). The predicted moisture ratio was compared to the experimental moisture ratio using root mean square error and chi square as shown in the following equations.

$$\mathrm{PE}(\%) = \frac{100}{n}\sum_{i=1}^{n}\frac{|M_{exp,i} - M_{predict,i}|}{M_{exp,i}}$$

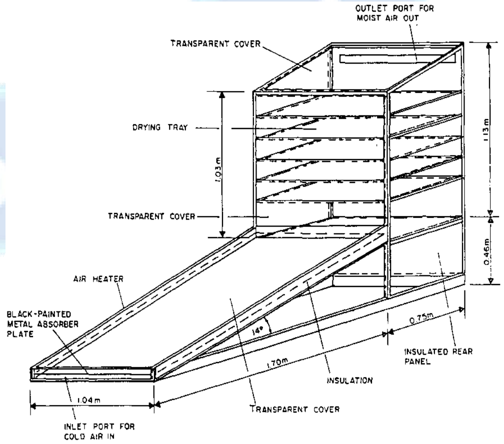

Fig. 4. Conventional Type Solar Dryer

Relative percent error (PE) compares the absolute differences between the predicted moisture contents with the experimental moisture contents throughout drying.The relative percent errors below 10% indicate good fit.

3). Experiment On Solar Dryer Using Grapes Food and Comparison Between Open And Solar Dryer:

Experimental setup shown in Fig. 5 is used for the experiment purpose and grapes used as a food material for the drying purpose.

Fig. 5. Experimental Setup

4). RESULTS & DISCUSSION

In the figure 6, pieces of graves after the drying by using open sun drying system and in the figure 7, pieces of graves are showed after moisture removed using the solar dryer system.

Fig.6. Open Sun Drying

Fig.7. Solar Drying

By comparing the experimental data in showed in table 1 & 2, it is easy to evaluate the performance of both systems. Initially the moisture content is same for both the systems and during the experiments, the drying rate for the solar drying system is much better than the open sun drying system in the equal time and the product is also saved from the rain, wind, birds etc in the Solar drying system which is not possible in the open sun drying system. Figure 8 & 9 shown the graphs are also presented in the paper in between the moisture content and drying rate with time.

Table 1: Initial and final moisture content and drying rate of moisture removed by using the open sun drying system.

Time	**Open Drying**			
	Total Moisture	**(%) Moisture**	**Moisture removed (%)**	**Drying rate (gram/h)**
0h	100	76.0	0	0
2h	83	71.084337	-7.8947	8.5
4h	76	68.421053	-10.5263	3.5
6h	72	66.666667	-12.2807	2
8h	70	65.714286	-13.5338	1
10h	69	65.217391	-14.1876	0.5
12h	68.5	64.963504	-14.8606	0.25

Table 2: Initial and final moisture content and drying rate of moisture removed by using the Open solar drying system.

Time	**Solar Drying**			
	Total Moisture	**(%) Moisture**	**Moisture removed (%)**	**Drying rate (gram/h)**
0h	100	76.0	0	0
2h	83	68.0	-10.526	12.5
4h	76	63.6363	-16.267	4.5
6h	72	60.0	-21.052	3
8h	70	57.1428	-24.812	2
10h	69	55.1401	-27.447	1.25
12h	68.5	53.8461	-29.149	0.75

4.1 Drying Analysis

As mentioned above, for drying analysis, two methods are used and the results are showed in the form of graphs.

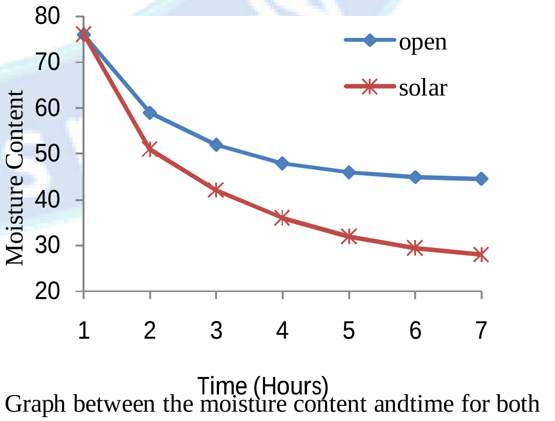

Fig.8. Graph between the moisture content andtime for both system.

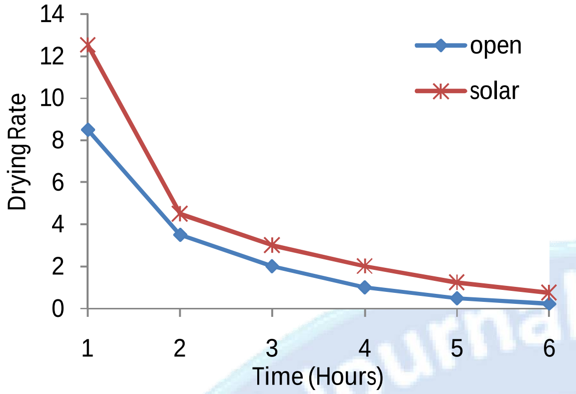

Fig. 9. Graph between the drying rates with time for both systems.

Two standard model Henderson Pabis model and Page model, we going to use for the drying analysis.

Model 1

Henderson Pabis model

$$MR= ae^{(-kt)}$$

Normalized form

$$\ln(MR)=-kt +\ln(a)$$

With that we can find out the value of k and a by using the MR (moisture removal)

For open drying

y= -0.027x-.2536 k= 0.027, a= .7760

Now

MR= $ae^{(-kt)}$

For Solar Drying

y=-.0597x-.3406 k=0.0597, a= 0.7143

Now

MR= $ae^{(-kt)}$

4.2Comparison between Experimental Value and Model 1 Value

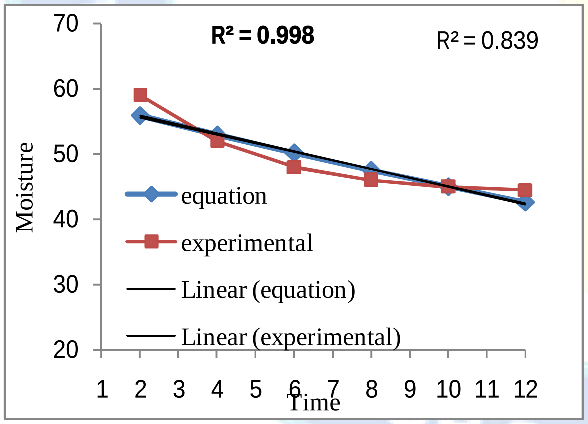

Fig: 10. Moisture vs. Time (Open)

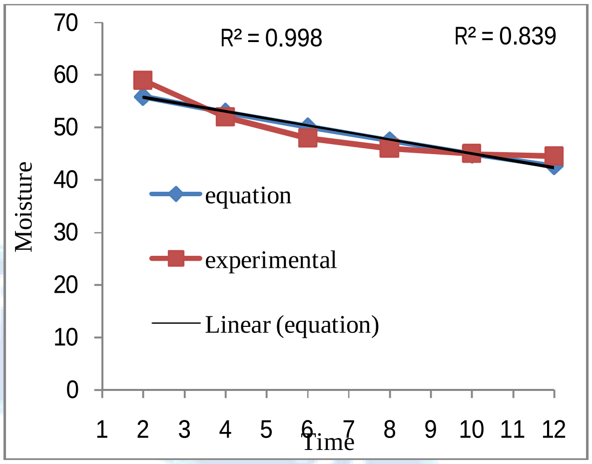

Fig: 11. Moisture vs. Time (Solar)

MODEL 2

Page model

$$MR = e^{(-kt^N)}$$

Normalized form

$$\ln(-\ln MR) = \ln k + N \ln t$$

With that we can find out the value of k and n by using the MR (moisture removal)

For Open Drying

y=0.4235x-1.6047, k= 0.2009, N= 0.4235

Now

$$MR = e^{(-kt^N)}$$

For Solar Drying

y=0.522x-1.2571, k= 0.2844, N= 0.522

Now

$$MR = e^{(-kt^N)}$$

4.3 Comparison between Experimental Value and Model 2 Value

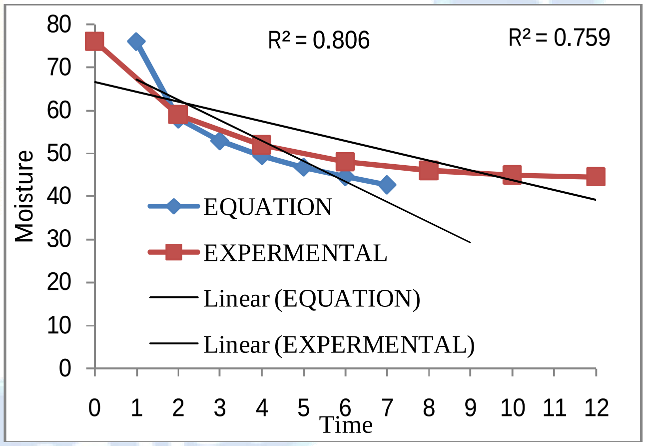

Fig: 12. Moisture vs. Time (open)

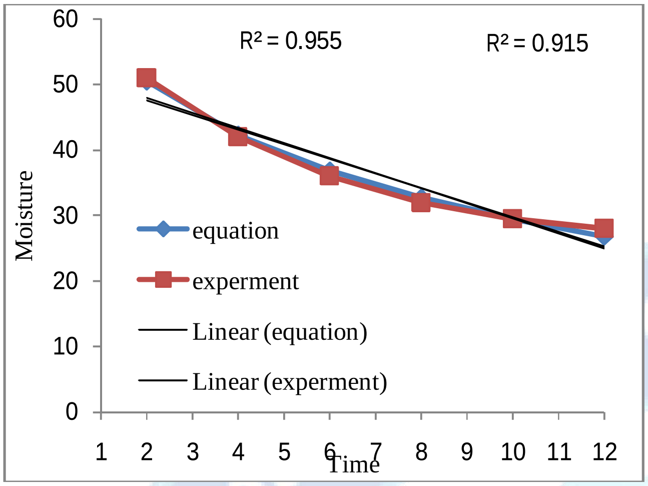

Fig: 13. Moisture vs. Time (Solar)

4.4 *Error Analysis*

For solar dryer, relative percentage error

$$PE(\%) = \frac{100}{n}\sum_{i=1}^{n}\frac{M\exp,i - Mpredict,i}{M\exp,i}$$

PE below 10% indicate good fit
For model 1
PE= 4.07%
For model 2
PE = .034%

- By comparing the two models Henderson Pabis and page model, the well suited model for our experiment results is model 2(page model).
- Also percentage error of Model 2 is very small as compare to the model 1.

With the given analysis we can say that Model 2(Page model) is best suited model for our experimental result.

V. CONCLUSIONS

Present work is focused on the available solar dryer's systems. Experimental performance of solar dryer using grapes food is done and reached at two conclusions which are as follows

1. The efficiency of open solar dryer for drying the grapes is 41.5% and for solar dryer, efficiency is upto 63.15% as per the experimental calculation, so it is advisable to use the solar dryer for the drying of agricultural crops.
2. By calculating the relative percentage error of moisture removal for two different models, I got relative percentage error for Page model as 0.034%, which is very less as compare to 4.07% for Henderson Pabis model. Therefore, Page model is best suited for calculating the moisture removal of agriculture crops by using solar dryer.

NOMENCLATURE

w	Wet mass
d	Dry mass
∝	Absorptivity
τ	Transmittivity
ρ	Reflectivity
M	Mass
C	Specific heat
h	Convective heat transfer coefficient
I	Solar radiation
V	Volume
T	Temperature
U	heat transfer coefficient
W	Width
MR	Moisture Removal
t	Time

SUBSCRIPTS

c	Crop
ch	chamber
rc	radiation heat transfer
cc	convection heat transfer
ec	evaporation heat transfer
s	side wall
a	Ambient
p	Absorber plate
f	fluid
pf	plate to fluid
rpc	absorber plate to crop
fc	fluid to crop
b	fluid to ambient
fo	flow out
fi	flow in
e	equilibrium
i	initial

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