Evaluation of Convective Heat Transfer Coefficient of Herbs Dried in a Mixed Mode Solar Dryer

D.V.N.Lakshmi and Dr. Apurba Layek
Department of Mechanical Engineering
NIT Durgapur, Durgapur, West Bengal, India
lakshmiratan2311@gmail.com

Prof. Palanisamy Muthukumar*
Department of Mechanical Engineering,
Indian Institute of Technology Guwahati
Guwahati, India
pmkumar@iitg.ac.in

Abstract—A mixed mode forced convection solar dryer (MFSCD) integrated with double pass counterflow solar air heaters was developed in-house for drying of high valued Moringa Oleifera and Stevia rebaudiana leaves. Experiments were carried out to evaluate the convective heat transfer coefficient of the samples in the developed solar dryer and under open sun drying (OSD). From the analysis, the average convective heat transfer coefficient of the leaves in the MFSCD are found to be 4.93 and 4.22 W/m²-K for Moringa and Stevia leaves and in OSD the average values are 1.31 and 1.25 W/m²-K, respectively. The efficiency of the mixed mode solar dryer was found to be 26.4 %. The proximate analysis for the protein and fiber content of the experimental samples concludes that the crude protein and crude fiber of solar dried samples are better than the sun-dried ones.

Index Terms— Dryer efficiency, heat transfer coefficient, mixed mode solar dryer, Moringa leaves, Stevia rebaudiana leaves.

I. INTRODUCTION

Ayurvedic medicines are having their own advantages since ancient times. Being extracted from natural resources, these products are having their importance in curing the diseases with minimal side effects. So, demand for medicinal herbs and spices are increasing steadily day by day. The reflex action is quite visible in the international market that with the trade value of around 826.7 million USD. India being dominated with diversified climate e.g. tropical, subtropical etc. and wrapped with hills and forests is a natural house for medicinal plants like Moringa, Stevia, Neem, Tulasi etc. Moringa Oleifera is the plant under focus due to its ability to cure many diseases. This tree can be cultivated with minimum maintenance. Moringa leaves are commonly known as drumstick leaves, it is a native plant of India, but it can grow in other tropical and subtropical regions also. This tree is known as magical tree. Every part of this tree has high medicinal values. Consumption of this leaves improves the malnutrition in the children. This leaves have high fiber, so it can be used as a dietary supplement. The anti-oxidant and phytochemical value of this leaves are higher [1]. India is largest producer of Moringa Oleifera in the world. Stevia is a natural sweetener and its sweetness is 300 times greater than the sugar. The plant is a native from America, but nowadays, it can be cultivated in all over the world. Stevia has many natural antioxidants that help lower blood pressure, cholesterol, and control diabetes [2]. The leaves are seasonal by nature and are highly perishable. So, drying is necessary for long-term storage of these herbs. Drying process is an old technique for storing grains, herbs and spices. The product spreads on floor and exposed directly solar radiation known as open sun drying (OSD). This is a common practice in most of tropical countries. The disadvantages in this technique are degradation of product quality, chances of mixing of insects and decrement of nutritional values due to direct exposure to sunlight.

Drying process consumes a lot of energy, it accounts for 15 % of total world energy consumption for drying of agricultural products, medicines, etc. Industrial dryers consume high-cost fossil fuels which cannot be afforded by small-scale farmers. So, renewable energy-based dryers are adopted due to their low cost and less GWP. Solar energy-based dryers are the promising solution for drying of medicinal herbs and spices. The construction and operation of these dryers are simple and can be easily operated in remote areas. Gulcimen et al. [3] developed a solar air heater with fins for drying of sweet basil. The experiments were carried out by varying the mass flow rates and found that the flow rate affects the drying rate. The maximum efficiency was found at a flow rate of 0.033kg/s. Labed et al. [4] developed two different collectors and compared their performance. The collector with finned obstacle and double-pass solar collector was found better than the single pass collector it was integrated with a solar dryer and used for drying of henna leaves. Mghazli et al. [5] studied the drying kinetics of rosemary leaves in a solar dryer. It was operated under indirect forced convection mode (IFSCD). The experiments were performed at four different temperatures and two mass flow rates. Thin layer drying kinetic models were applied and found that Midilli Kucuk model was the best. A multi-pass solar air
heater with sensible heat storage for drying of Roselle was developed by Kareem et al. [6]. The dryer performance was studied in terms of the collector, pick up and exergy efficiencies. Lakshmi et al. [7] developed two types of solar dryers (mixed and indirect type) and the drying behavior of Moringa leaves was studied in two solar dryers. The performance of both the dryers were compared and found that MFSCD was better. Rabha et al. [8] studied the drying behavior of ghost chili in IFSCD. The experimental moisture ratio fitted to the drying kinetic models available in the literature and found that Midilli Kucuk model was best-suited model for drying of ghost chili. Lakshmi et al. [9] investigated the drying behavior of black turmeric in a MFSCD solar dryer. The dryer was integrated with a thermal energy storage device to have a continuous thermal effect even after sunset. Lakshmi et al. studied the drying kinetics of bitter gourd in a mixed mode solar dryer with and without thermal energy storage [10]. The drying kinetics models applied to the experimental moisture ratio and found that Midilli Kucuk model was found best solar dried samples and logarithmic model was for OSD samples.

In solar drying, convective heat transfer has an important role in removing the moisture from the product. The solar dryer design depends on the value of heat transfer coefficient and it varies with change in the temperature difference between the product and air. Anwar and Tiwari [11] measured h, (convective heat transfer coefficient) for six different crops dried in open sun drying. They found the value of ‘h’ depends on the product moisture and temperature. Jain [12] studied the drying behavior of two types of fish species, such as prawn and carp (chelwa). They found that convective heat and mass transfer coefficients depend on the moisture evaporation during drying. Anil Kumar and Tiwari [13] developed a thermal model to evaluate the temperature of jaggery. They compared it with the experimental data obtained from natural convection mode and observed a good agreement in them. The thermal behavior of Tinospora cordifolia (herb), Curcuma longa L. and Zingiber officinale (spices) were investigated by Jayshree Prasad [14] in open sun drying conditions. The convective heat transfer coefficient of the herbs under OSD was found 3.9, 3.4 and 3.2 W/m²-K, respectively. Prakash and Kumar [15] estimated the convective heat transfer coefficient of greenhouse dryer under covered and uncovered floor and reported that the convective heat transfer coefficient for covered floor dryer is 3.1 times more than the uncovered floor dryer. S. K. Sansaniwal et al. [16] studied the drying kinetics of zinger rhizomes in an indirect natural and forced convection drying. Calculated the values of constants C and n using linear regression analysis and found that the heat transfer coefficient was more for solar dried samples. Literature survey reveals that different types of dryers have been designed and tested for drying of various agricultural products, vegetables and fruits. Most of the works reported in the literature are focused on evaluating the convective heat transfer coefficient in solar greenhouse dryers. There was no study on evaluating the convective heat transfer coefficient of Stevia and Moringa Oleifera leaves drying in a mixed mode forced convection solar dryer reported in the literature. Therefore, the main objective of the present work is to develop a mixed mode solar dryer (MFSCD) for drying of herbs (Moringa and Stevia) and to estimate the convective heat transfer coefficient for OSD and MFSCD. Quality analysis (color and proximate analysis) of the dried leaves are also carried out.

II. EXPERIMENTAL SETUP

In the present work, the experimental set up consists of double pass solar air heaters (DPSCSAH) integrated with MFSCD. The schematic of a solar dryer is shown in “Fig. 1”. Two similar double pass counterflow solar air heaters are connected in series and entrenched to the dryer. The dimensions of two heaters are 2 m (L) X 1 m (W) X 0.02m (D). Two heaters are mounted at 25° to the south to maximize the solar radiation intensity. The absorber plate (1 mm GI) integrated with horizontal fins (to enhance heat transfer) is placed inside the SAH. The drying chamber is made up of mild steel having an effective drying area of 1.6 m². Six trays are placed inside the drying chamber and the trays are loaded manually. The drying is a batch process. Fresh Moringa leaves (6 kg) are placed on six trays in single layer. Temperatures at different locations e.g. inlet and outlet of solar air heater, inlet and outlet of dryer were noted with T type thermocouple (accuracy ± 0.2°C). Solar radiation intensity was measured with the pyrometer (accuracy ± W/m²). A data acquisition system connected with the thermocouples and pyranometer recorded the data. The weights of the samples are measured at 30 min interval to determine the moisture removal rate (Accuracy ± 0.01 g). The hygrometer was used to measure the relative humidity (RH) in the drying chamber and ambient condition.

![Figure 1. A Schematic of MFSCD with counterflow double pass solar air heaters.](image)

III. DRYING ANALYSIS

Using the Eq. 1 the shrinkage moisture ratio of the product is calculated.

$$\text{MR} = \frac{X_f}{X_o}$$

The mass of water evaporated from the product is calculated by employing Eq. 2. Here mwr is the mass of the water removed and mi is mass of the product loaded in the dryer. Primary and final moisture contents of the product are $X_i$ and $X_f$ respectively on wet basis.
\[ m_{av} = \frac{m(X_i - X_f)}{100 - X_f} \]  

The effective moisture diffusivity is evaluated from Fick’s second law of diffusion.

\[ \frac{\partial}{\partial t} (MR) = D_{eff} \times \nabla^2 MR \]  

where, Deff is effective diffusivity (m2/s).

Eq. 3 is simplified as the following

\[ MR = \frac{8}{\pi^2} \exp \left( -\frac{\pi^2 D_{eff} t}{4L^2} \right) \]  

Effective diffusivity is estimated by plotting a graph between \( \ln (MR) \) vs time. From the slope of this equation effective diffusivity can be estimated.

\[ \ln (MR) = \ln \left( \frac{8}{\pi^2} \right) - \left( \frac{\pi^2 D_{eff} t}{4L^2} \right) \]  

\[ D_{eff} = \frac{\text{slope} \times 4L^2}{\pi^2} \]  

Energy input to the dryer is calculated by using Eq. 6, where, \( A_1, A_2 \) and \( Ad \) are areas of solar air heaters and dryer, \( I \) is the average solar radiation intensity and \( BP \) is power consumed by the blower.

\[ E_{MFCSD} = \left[ (A_1 + A_2 + A_d) \times I + BP \right] \times t_{MFCSD} \]  

The overall dryer efficiency is determined using Eq. 7. It is the ratio of amount of energy required to remove moisture from the product and energy input to the dryer.

\[ \eta_{MFCSD} = \frac{m_h \times I_{MFCSD}}{E_{MFCSD}} \]  

A. Evaluation of convective heat transfer coefficient:

Heat transfer plays a vital role in designing the efficient solar dryer. In convective solar dryer, the convection is dominant one compared to the other modes of heat transfer. The convective heat transfer coefficient is also important to evaluate the performance of the dryer and this value, mainly depends on product type, moisture content, shape, size and drying time. The rate of heat utilized to evaporate the moisture (Qe) is given as,

\[ Q_e = 0.016 \frac{K_{humid \ air} \times Nu}{L} [P(T_{ri}) - \gamma P(T_{ri})] \]  

where, \( P(T_{ri}) \) and \( P(T_{is}) \) are partial vapor pressure of air at the product surface and air just above the product surface and \( \gamma \) is relative humidity of air. The convective heat transfer coefficient \( hc \) is given as

\[ h_c = \frac{K_{humid \ air} \times Nu}{L} \]  

where \( K_{humid \ air} \) is the thermal conductivity of humid air, \( Nu \) is the Nusselt number and \( L \) is the characteristic dimension. The value of \( hc \) is substituted in Eq. 8.

The moisture evaporated (Mev) is determined by the following equation

\[ M_{ev} = \frac{Q_e}{h_{fg}} A_i t \]  

The \( h_{fg} \) represents the latent heat of vaporization, at is area of tray, and \( t \) is the time interval.

From Eq. 11

\[ M_{ev} = 0.016 \frac{K_{humid \ air} Nu}{h_{fg} L} [P(T_{ri}) - \gamma P(T_{ri})] A_i t \]  

Eq. 12 can be simplified as

\[ M_{ev} = Nu \times Z \]  

where, \( Nu = C (Re. Pr)^n \) for forced convection; \( Nu = C (Gr. Pr)^n \) for natural convection

\[ Nu = \frac{m_{es}}{Z} = C \ (Re. Pr)^n ; Nu = \frac{m_{es}}{Z} = C \ (Gr. Pr)^n \]  

\[ \ln Nu = n \ln (Re \ Pr) + \ln C \]  

\[ \ln Nu = n \ln (Gr. Pr) + \ln C \]  

Above equation \( Y = \ln \left( \frac{M_{ev}}{Z} \right) \), \( m = n \), \( X = \ln (Re. Pr), C_o = \ln C \).

Eq. 15 becomes \( Y = m \ X + C \) a linear equation. The constants in the linear equation are evaluated with linear regression analysis.

\[ n = \frac{N \sum XY - \sum X \sum Y}{N \sum X^2 - (\sum X)^2} \]  

\[ \ln C = \frac{\sum X^2 \sum Y - \sum XY \sum X}{N \sum X^2 - (\sum X)^2} \]  

IV. RESULTS AND DISCUSSION

The experiments were performed in a developed dryer for drying of Moringa Oleifera and Stevia rebaudiana leaves. The fresh leaves were collected from local farm and pre-processed before actual drying. The pre-processing includes separation of the leaves from the stem, washing in free flow water and removal of water particles from the surface by wrapping in tissue paper. The experimental set up was run around 1 h to attain a steady state before the actual placement of leaves in the drying chamber. Hourly variation of solar radiation intensity, dryer inlet and exit temperature, product temperature at sample tray are presented in “Fig.2”. The maximum solar radiation intensity was measured as 690 W/m2. The average intensity was found as 458.5 W/m2. The difference between dryer inlet and outlet temperatures were high during the initial
drying hours. At the end stage of drying, the difference decreases as the product does not consume much energy at the end stage of drying. The maximum product temperature was measured as 50.8°C. The average RH inside the dryer was 24.3 % and ambient conditions 64.4 %.

In both the experiments (MFSCD and OSD), Moringa Oleifera leaves was dried from having a moisture content of 81.2 % w.b to 6.2 % (w.b). Similarly, Stevia leaves were dried from 83.5% to 7.1 % (w.b) under MFSCD and OSD conditions. The dryer was loaded with 6 kg of Moringa and they are placed equally in all the trays. To evaluate the drying behavior a sample amount of 100 g leaves was placed inside the dryer as well as in open sun. At the initial phase of drying, the diffusion process takes place in a rapid manner, so a constant drying process is not feasible. From “Fig.3” it was observed that the drying has taken place in the falling rate period for both the leaves. To attain the desired moisture content the product takes more time in OSD. The drying time for Moringa leaves under OSD condition was 9 h, and in MFSCD took only 4 h. The drying time of 55% can be saved by the developed dryer compared to OSD. Similarly, the Stevia leaves (6 kg) were dried in the solar dryer took 6 h and under open sun the drying, it was 15 h. At all drying conditions, effective moisture diffusivity of the herbs was estimated by plotting a graph between ln (MR) vs drying time (shown in Fig.4.) The effective moisture diffusivity of the samples was estimated using Eq.5.

![Figure 2. Variation of ambient temperature and radiation intensity with drying time.](image)

![Figure 3. Variation of moisture content with drying time.](image)

![Figure 4. Effect of mode of drying on diffusion coefficient for Moringa and Stevia](image)

<table>
<thead>
<tr>
<th>Mode of Drying</th>
<th>$D_{eff} (m^2/s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFSCD (Moringa)</td>
<td>$2.84 \times 10^{-10}$</td>
</tr>
<tr>
<td>MFSCD (Stevia)</td>
<td>$1.42 \times 10^{-10}$</td>
</tr>
<tr>
<td>OSD (Moringa)</td>
<td>$0.86 \times 10^{-11}$</td>
</tr>
<tr>
<td>OSD (Stevia)</td>
<td>$1.91 \times 10^{-11}$</td>
</tr>
</tbody>
</table>

TABLE I: VALUES OF EFFECTIVE MOISTURE DIFFUSIVITY OF MORINGA AND STEVIA LEAVES UNDER TWO DRYING CONDITIONS
The overall efficiency of a dryer depends on the initial moisture content, drying temperature, relative humidity, and structure of the product. The mass of water removed from the product was calculated by using Eq. 2. The latent heat of vaporization was found to be 2.71 MJ/kg (estimated at average dryer temperature). The average solar radiation intensity was obtained as 458.5 W/m² and the dryer efficiency was found to be 26.4 %.

Similarly, the dryer efficiency was estimated for stevia leaves drying and found that the overall dryer efficiency was found to be 23.8 %.

The value of ‘h’ evaluated by using the values of C and n is given in Table 2.

<table>
<thead>
<tr>
<th>Mode of Drying</th>
<th>C</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFSCD (Moringa)</td>
<td>1.12</td>
<td>0.14</td>
</tr>
<tr>
<td>MFSCD (Stevia)</td>
<td>1.42</td>
<td>0.12</td>
</tr>
<tr>
<td>OSD (Moringa)</td>
<td>0.86</td>
<td>0.08</td>
</tr>
<tr>
<td>OSD (Stevia)</td>
<td>0.78</td>
<td>0.07</td>
</tr>
</tbody>
</table>

The heat transfer coefficient value depends on C and n; the value of heat transfer coefficients under forced and open sun drying condition is shown in “Fig. 5”.

Higher heat transfer coefficient causes to higher drying rate. The average heat values for Moringa leaves in MFSCD and OSD were 4.22 ± 0.19 W/m²-K and 1.31 ± 0.045 W/m²-K, respectively. The average convective heat transfer coefficient value for stevia leaves dried in a solar dryer and open sun drying were 4.93 ± 0.21 W/m²-K and 1.25 ± 0.051 W/m²-K, respectively.

**Quality analysis:** The quality analyses of the leaves have been carried out as per the methods adopted by Lakshmi et al.,[8]. Color is critical quality attribute of a product. In the present study, the color index was measured with the help of hunter colorimeter. “Figs 6 and 7” show the color variation of solar and open sun-dried Moringa-oleifera and stevia leaf samples. Bright green color of the fresh leaves changes to yellow during the course of drying. In open sun drying, drying periods is quite long. The direct exposure of leaves to sun radiation renders the leaves to be less green and more yellowish. In different drying methods, the change in color is due to the high temperatures, oxidation and non-enzymatic reactions.

<table>
<thead>
<tr>
<th>Leaves</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh</td>
<td>34.4</td>
<td>-11.6</td>
<td>21.8</td>
</tr>
<tr>
<td>Solar</td>
<td>33.9</td>
<td>-10.9</td>
<td>13.8</td>
</tr>
<tr>
<td>Open sun</td>
<td>30.4</td>
<td>-9.56</td>
<td>6.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Leaves</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh</td>
<td>35.6</td>
<td>-8.4</td>
<td>22.5</td>
</tr>
</tbody>
</table>
TABLE IV. PROXIMATE ANALYSIS OF MORINGA OLEIFERA LEAVES IN DIFFERENT DRYING CONDITION

<table>
<thead>
<tr>
<th>Table  Name</th>
<th>Crude Protein</th>
<th>Ash</th>
<th>Crude Fiber</th>
<th>NFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh Moringa</td>
<td>6.7 ± 0.11</td>
<td>1.9 ± 0.08</td>
<td>1.71 ± 0.23</td>
<td>12.5 ± 0.23</td>
</tr>
<tr>
<td>Solar Dryer (Moringa)</td>
<td>31.69±0.90</td>
<td>10.62±0.20</td>
<td>21.87±1.07</td>
<td>43.64±1.33</td>
</tr>
<tr>
<td>Open Sun Drying (Moringa)</td>
<td>27.09±0.08</td>
<td>6.24±0.76</td>
<td>17.84±0.34</td>
<td>34.64±1.74</td>
</tr>
</tbody>
</table>

Proximate analyses of the leaves were carried out by adopting AOAC method. The proximate analysis of Moringa-Oleifera leaves are shown in Table 4. Drying technique affects the quality of the products. It is observed that the fiber content of the solar dried samples is high as compared to fresh and open sun-dried samples. The crude protein, crude fiber and carbohydrate of solar dried samples are also higher compared to sun drying samples.

V. CONCLUSIONS

A mixed mode solar dryer has been developed and tested for drying of high-value Moringa Oleifera and Stevia leaves. From the experimental studies the conclusions drawn are listed below:

1. The moisture content of the Moringa leaves reduces from initial moisture content 81.2 % to final 6.2 % in 4 h and 9 h in the developed dryer and open sun drying respectively. The stevia leaves were dried from initial moisture content 83.5% to final 7.1% in 6 h and 15 h in the solar dryer and OSD. This indicates the effectiveness of the developed solar dryer.

2. The overall efficiency of the dryer was estimated as 26.4 % for Moringa leaves. Similarly, the dryer efficiency was estimated 23.8% for stevia leaves.

3. The average convective heat transfer coefficient of solar dried Moringa and Stevia leaves were estimated as 4.22 and 4.93 W/m²·K.

4. The effective moisture diffusivity of the solar dried samples (Moringa and Stevia) was obtained 2.84 × 10⁻¹⁰ and 1.42x 10⁻¹⁰ m²/s. For OSD the effective moisture diffusivity in the range of 10⁻¹¹ m²/s, respectively.

5. The color retention of the solar dryer samples is better than the samples of the OSD.

6. From the proximate analysis, it is observed that the protein, crude fiber and carbohydrates of the open sun drying samples are low as compared to the solar drying. This indicates that the developed solar dryer helps in retention of many qualities of the products during and after drying.

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