Optimization of a Convective Air Flow Solar Food Dryer

Jonathan K. Russon
jonathan.trish@gmail.com

Michael L. Dunn
michael_dunn@byu.edu

Frost M. Steele
frost_steele@byu.edu

International Journal of Food Engineering

Volume 5, *Issue* 1 2009 *Article* 8

Optimization of a Convective Air Flow Solar Food Dryer

Jonathan K. Russon* Michael L. Dunn† Frost M. Steele‡

*Brigham Young University, jkr54@byu.edu
†Brigham Young University, michael_dunn@byu.edu
‡Brigham Young University, frost_steele@byu.edu

Optimization of a Convective Air Flow Solar Food Dryer

Jonathan K. Russon, Michael L. Dunn, and Frost M. Steele

Abstract

A solar food dryer, previously developed for personal and small community use, was the object of this optimization study. Based on previous research of convective solar food dehydrators, several dryer parameters were identified for this study. Chimney height and dryer product load were two factors tested in a central composite experimental design. Dryer product load was found to produce a maximum efficiency of the dryer when fifteen product-filled trays were inserted in the dryer. Maximum efficiency was observed at the maximum chimney height tested. Post-optimization configuration compared with pre-optimization configuration resulted in a 40% increase in final dry product production per hour of dehydration time.

KEYWORDS: solar food dehydration, convection flow

INTRODUCTION

The industrialization of the food industry has led to many important advances which have resulted in a general amelioration of food quality and quantity. Though beneficial to the commercial food industry, industrialization of processes tends to increase the starting costs of manufacture. During times of physical disaster and economic hardship, the ability to produce and preserve food can be a boon. Dehydration of food is a commonly accepted method of food preservation, which has over time been developed into a large scale precisely controlled industrial process. The mechanization of this process has made it far too large a financial investment to be considered a reasonable venture by any small holdings farmer. Rowe and Steele (2004) developed a small-scale solar dryer, based on other dryer models previously in existence, with the hope of increasing the feasibility of the dehydration of foods for individual and local market use and storage. This dryer, though effective at maintaining low costs of construction and operation, was not evaluated critically to optimize its efficiency, efficiency being described as the percentage of incident solar energy exchanged into heat and further utilized to dry the product. Therefore, a reading of 100% indicated a complete exchange of all incident solar energy into heat and complete moisture saturation of the air at the exit of the drying chamber.

Key factors governing a dryer's efficiency are: airflow through the dryer and the dryer's product load. Karim and Hawlader (2006) suggested that an air mass flow rate of 0.035 Kg/m^2s was optimal for drying of most agricultural products. El-Sebaii et al. (2002) indicated that an optimal temperature range for drying these same products was 45.5-55.5˚C. Leon et al. (2002) noted that an increase in airflow in a collector increased the efficiency of the conversion of solar energy into more usable forms of energy at the expense of a drop in air temperature. Madhlopa et al. (2002) related that increasing the height of an added chimney improved the thermosiphoning abilities of a solar dryer. Furthermore, as airflow in a convective air system is directly linked to the change in air density due to temperature, the thermosiphoning abilities of the dryer and airflow are proportional. Kurtbas and Durmuş (2004) indicated that an increase in surface roughness of collector material caused a pressure loss along the airflow line suggesting that airflow had been impeded with a consequential decrease in dryer efficiency. Karim and Hawlader (2004) found that a collector which consisted of angled metal of 60º improved the efficiency of the collector by 7-12% over a normal flat plate absorber. Jain and Jain (2004) showed that increasing the depth of the product, in the drying bed, increased the thermal efficiency of the dryer. This finding, however, was tempered by Madhlopa et al. (2002) who found that increasing the depth of the product in the dryer bed decreased the airflow rate and thus decreased the efficiency of the collector.

The objective of this research was to optimize the dryer, described by Rowe and Steele (2004), as to its efficiency utilizing the effect of an added chimney and modification of the dryer's product load.

MATERIALS AND METHODS

Experimental design

As the overall objective of the dryer, developed by Rowe and Steele (2004), was to allow average small holdings/subsistence farmers to dehydrate their own produce; optimization of this dryer resulting in construction and operation recommendations for the final user. A chimney and more shelving space were added to the dryer developed by Rowe and Steele (2004) in an effort to optimize the dryer's efficiency. The chimney was added to aid in the overall airflow and the increased shelving was to allow for the modification of the dryer's product load. The solar collector absorber material in the original design was changed from a flat fly-screen absorber to a 60º angled aluminum absorber based on the study by Karim and Hawlader (2004). This 60º angled metal absorber was constructed of aluminum foil forming a V-groove running the entire length of the collector frame. This collector was a significant improvement over the previous collector. It allowed increased energy absorbance due to multiple internal reflections of radiant energy. As light entered the collector and struck the absorber, energy was released into the absorber, the remainder of the energy reflected and due to the angling of the metal this reflected energy proceeded deeper into the collector to strike the absorber again and theoretically a third time prior to reflection back into the atmosphere. Secondarily, as the orientation of the V-groove extended the entire length of the collector, airflow was not impeded. Thirdly the surface of the aluminum foil was far less rough than the fly-screen absorber, which allowed for a higher airflow rate. Optimization of the dryer was accomplished using the central composite experimental design, as outlined in Figure 1, with the two variables studied being chimney height and number of product-filled trays. This design allowed for multiple variables and their interaction effects to be tested simultaneously. The tested chimney heights were 0mm, 234mm, 798mm, 1361mm, and 1595mm. These heights were derived through use of scaling factors of the central composite design and limited to maximum size by construction materials.

The numbers of filled trays inserted in the dryer were 0 trays, 3 trays, 10 trays, 17 trays, and 20 trays. These quantities of trays were evaluated after determining that a maximum of 20 trays could fit into the dryer.

DOI: 10.2202/1556-3758.1500

Two subsequent single variable experiments were conducted. The first directly tested the effect of the chimney by consistently using 15 trays while testing all of the chimney heights. The second experiment monitored the optimized dryer throughout an entire drying batch and compared it to the pre-optimized dryer.

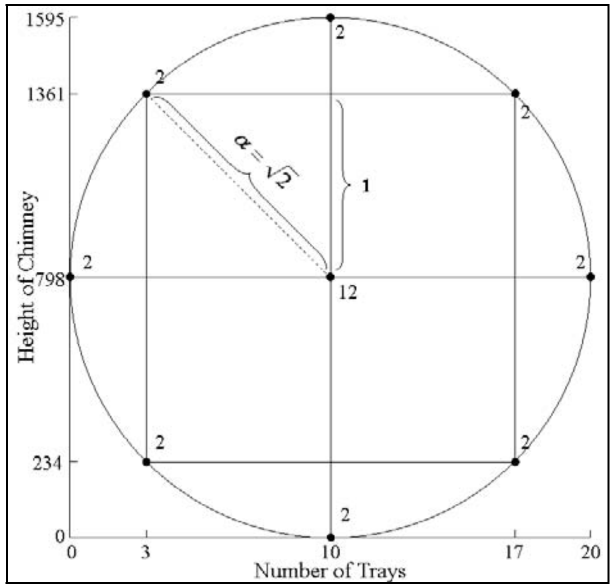

Figure 1. Experimental design, including number of observations taken at each treatment (numbers accompanying each bolded intersection on the graph), α is a scaling value equal to the radius of the parameter circle

Sample preparation

Potatoes were chosen as the test food product as it was both readily available and closely mimicked the characteristics of target root crops (taro and cassava). The potatoes, purchased at a local food market, were sliced using a rotary meat cutter to a thickness of 3mm. The slices of potato were then cut into uniform disks using a 38mm diameter sharpened borer. The potatoes were placed in a 1% (w/w) citric acid bath, to prevent browning, and held overnight at 2°C.

Description of dryer's product load

Amount of product placed in the dryer was varied according to the number of trays placed in the dryer. Each tray had a consistent number of uniformly sliced potatoes randomly spaced across the entire tray. Each tray was 44% covered by potato slices leaving 56% of the tray area open to unobstructed airflow. The trays were placed in the dryer so as to evenly space the potatoes throughout the entire volume of the dryer.

Measurements

Temperature and relative humidity

Temperature (°C) and relative humidity measurements (%RH) were recorded at one minute intervals, by data loggers (Dickson temperature and humidity data logger TP120, Illinois, USA) placed at the bottom of the solar collector. Temperature (°C) only was recorded by the data loggers placed at the top of the solar collector (bottom of the drying chamber), and the top of the drying chamber. The wet bulb temperature (°C) of the air exiting the dryer was also recorded at one minute intervals using an air flow meter with built in temperature and humidity functions (Omega HHF11 deluxe all-in-one air flow meter, Connecticut, USA). A temperature probe located at the top of the drying chamber provided real time temperature monitoring of the effluent air.

Air flow

Air flow (m/s) measurements were taken and recorded by hand every minute by use of the previously mentioned air flow meter. The sensor for this air flow meter was placed at the exit of the chimney.

Sun inclination

The angle (°) between the incident rays of the sun and the solar collector surface was measured using a protractor mounted on the side of the solar collector. These measurements were taken every five minutes.

Solar irradiance and barometric pressure

The absolute barometric pressure (kPa) was recorded every minute using a Texas Electronics TB-2012M solid-state sensor (Texas Electronics, Inc. Texas, USA). Solar irradiance (W/m^2) was measured using a Texas Electronics TS-100 photovoltaic thermopile (Texas Electronics, Inc. Texas, USA). Both instruments were located on the roof of the Eyring Science Center at Brigham Young University in Provo, Utah. The solar drying experimentation was accomplished at the base of this building in a walled area that provided some shelter from ambient breezes.

Procedure for testing a treatment

At the start of any given test run, a chimney of a given height was attached to the dryer, the dryer was placed in the sun, and the glazing over the solar collector was wiped to remove dust. Trays were loaded with potatoes with 60 slices/tray (~377g±3.6g) and pre-heated in an atmosphere of 46°C, 90%RH until the potatoes reached a temperature of 38°C as measured by a hand held infrared thermometer (Oakton® TempTestr® IR, Oakton Instruments, Illinois, USA). This was accomplished to reduce the time required to reach equilibrium once the

DOI: 10.2202/1556-3758.1500

potatoes were placed in the dryer. The trays were then introduced into the dryer and spaced evenly throughout the dryer. The dryer chamber was then closed and the temperature monitored. Once the temperature stabilized and remained constant for one minute, data recording began and continued for ten minutes. The dryer was realigned with the sun every five minutes. Following the ten minute data recording interval, the dryer was emptied of trays and made ready for the next treatment.

In order to dry the product more evenly, during the full dehydration process experiment, the product was rotated every 1.5 hours, taking trays from the middle of the dryer and moving them to top and bottom of the dryer. The dryer was realigned with the sun every 20 minutes. Air flow data was collected every minute for three minutes and then extrapolated for the time between readings.

Calculation of efficiency

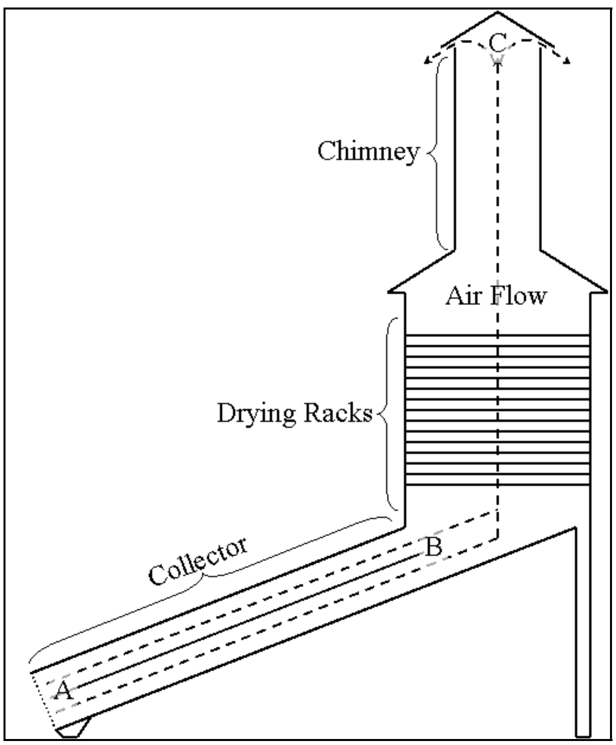

Figure 2. Side cutaway view of dryer with labeled points indicating where measurements were taken

Using functions documented by ASHRAE (1997), calculations were performed on the data to yield the following: the change in enthalpy or heat energy per unit mass, of the air from the bottom of the collector and the top of the collector, and the difference in moisture content between the ambient air and the air leaving the dryer as measured by the humidity ratio (w, $kg_{moisture}/kg_{dry\ air}$). All of these values were calculated in the following manner (refer to Figure 2 for visualization clarity):

The total efficiency (equation 1) was calculated as a product of the individual efficiencies of the collector and dehydrator sections of the dryer.

$$Efficiency_{Total} = Efficiency_{Collector} \cdot Efficiency_{Dehydrator} \tag{1}$$

The efficiency of the collector (equation 2) was evaluated by calculation of the difference in enthalpy (Δh, J/kg$_{\text{dry air}}$) of the air entering the collector (point A) and exiting the collector (point B), the air mass flow rate (m, kg$_{\text{dry air}}$/min), the solar irradiance (I, W/m^2), and the collector aperture (Ap, m^2).

$$Efficiency_{Collector} = \frac{Energy\ gained\ by\ air}{Energy\ incident\ from\ sun} = \frac{m \cdot \Delta h}{I \cdot Ap} \tag{2}$$

The efficiency of the dehydrator was evaluated by calculating the humidity ratio (w, kg$_{\text{moisture}}$/kg$_{\text{dry air}}$) for the ambient air conditions (point A), the air exiting the dryer (point C), and the maximum possible humidity ratio corresponding to 100% relative humidity. This analysis capitalizes on the principle that air will cool and gain moisture, from conditions measured at the top of the collector (point B) to conditions at the exit of the dryer (point C), while enthalpy, wet bulb temperature, and dry bulb temperature remain constant. Furthermore, at 100% relative humidity wet and dry bulb temperatures are equal.

$$Efficiency_{Dehydrator} = \frac{Water\ in\ air\ removed}{Water\ removed\ at\ air\ saturation} = \frac{w_{final} - w_{ambient}}{w_{Max} - w_{ambient}} \tag{3}$$

Data analysis

Statistical analysis was performed by using Microsoft Excel 2003. Excel was used to generate graphs of the data and the data analysis package was used to fit regression equations to the data.

RESULTS AND DISCUSSION

Dryer's product load

Figure 3 illustrates that increasing product load results in increasing total efficiency to a point. Total efficiency declined as product loads were increased beyond this point. Through regression analysis of the data a formula was derived (equation 4). This regression equation has an R-square value of 0.9558 and has a p-value of <0.001 for the model. This equation leads to a maximum efficiency at 15.65 trays of thinly sliced potatoes. This equation reached a maximum within the range of trays tested, allowing the dryer to be optimized solely by manipulation of the number of trays placed in the drying chamber. While strong in its predictive value this equation is inherently limited to potatoes, as they were

DOI: 10.2202/1556-3758.1500

the only product tested. However, the results suggest that evaluation of the product load is of primary importance in optimization studies.

$$Efficiency_{Total} = 0.1172 + 0.0529Trays - 0.0017Trays^2 \quad (4)$$

The analysis of the data, not shown, indicated that there was little statistical significance in the chimney effect, and thus it was left out of this regression analysis. However, due to the over-riding effect that the product load had on total efficiency, it was thought that the effect of the chimney might be masked. Therefore, as the chimney height appeared to be insignificant in concert with the variation of the product load, subsequent experimentation was conducted to evaluate the effect of the chimney height alone while holding the product load constant.

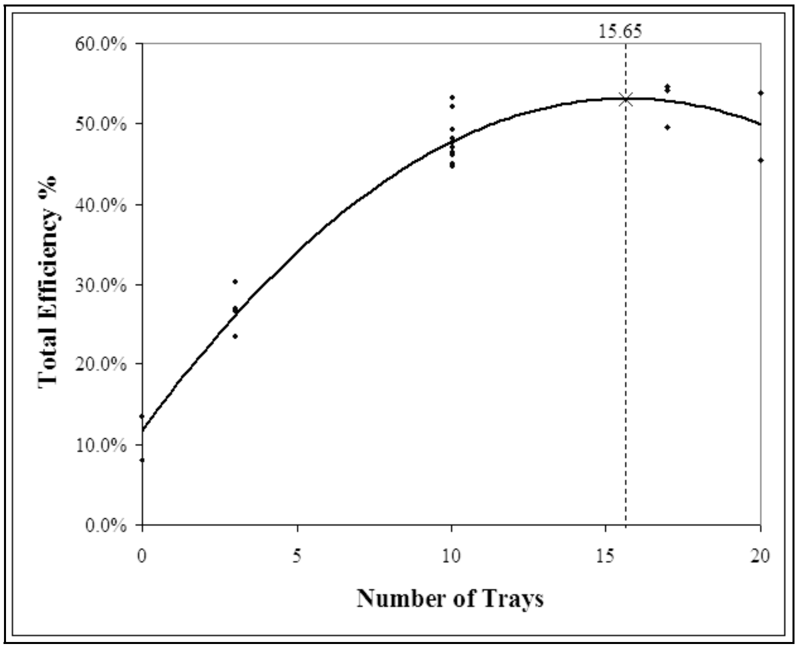

Figure 3. Dryer optimization for potatoes by variation of number of product filled trays.

Chimney height

The results of chimney height on efficiency and on air mass flow rate are found in Figure 4. Analysis of the efficiency data resulted in a regression formula (equation 5) which shows an increase of four percentage points of total efficiency per meter of increased chimney height.

$$Efficiency_{Total} = 0.4395 + 4.01 \times 10^{-5} Chimney\ height_{mm} \tag{5}$$

The model, describing the total efficiency as a function of chimney height, was found to be significant (p-value for model = 0.019, R-square 0.7184). Unlike the effect of the product load, that eventually peaked within the test set parameters, the value of the efficiency as impacted by the chimney height reached a maximum at the tallest chimney height tested. Chimney height had a positive effect on the total efficiency and air mass flow rate of the dryer. This finding is consistent with Madhlopa et al. (2002) who indicated that an added chimney would increase the thermosiphoning abilities of the dryer.

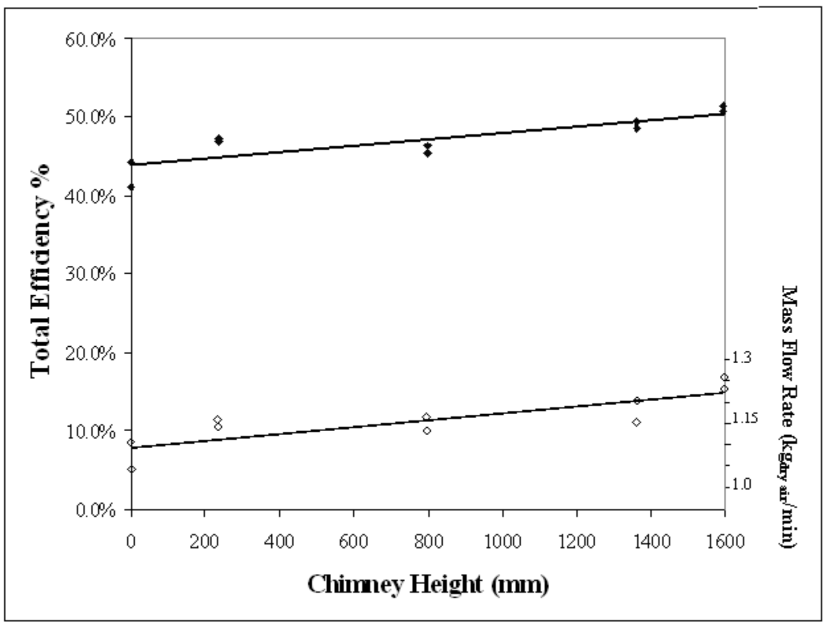

Figure 4. Dryer optimization for potatoes by variation of attached chimney height at a constant fifteen product filled trays (♦ Total Efficiency measurements, ◊ Mass Flow Rate measurements).

It is further noted that the total efficiency at the 234mm chimney height appears to be slightly elevated and may be explained by the nature of the attachment mechanism between the dryer body and the chimney proper. The 234mm chimney had a tighter fit than any of the taller chimneys, accounting for a decrease in air loss through the joint leading to an increase in the siphoning ability of the 234mm chimney. These findings suggest that the chimney's connection mechanism needs to be redesigned in order to reduce losses from the dryer to chimney joint, which would result in overall greater efficiencies.

DOI: 10.2202/1556-3758.1500

Full dehydration process

The results of the full dehydration can be found in Figure 5. It can be seen that as time progresses throughout the drying process the efficiency of the dryer decreases as there was less moisture in the air exiting the dryer per unit (J) of input energy. It was also noted that though the trays were periodically rotated, to reduce differences in drying rate between trays, the batch containing 15 trays had far greater variation in finished dryness as compared to the batch containing 8 trays. This variation was not between trays, but rather was the variation in moisture on a single tray, meaning that 90% of the potatoes on a tray could be completely dry while the remaining 10% would be almost dry. In a few extreme cases the potatoes might even be very moist. This inconsistency may be caused by variations in the air velocity across the cross-section of the dryer. Two actions could be taken to reduce this variation: first, the product could be periodically shifted around on the trays; or second, dry material could be taken out and the non-dry/partially dry product could be run again on the next day at the bottom of the dryer where the temperatures are hottest.

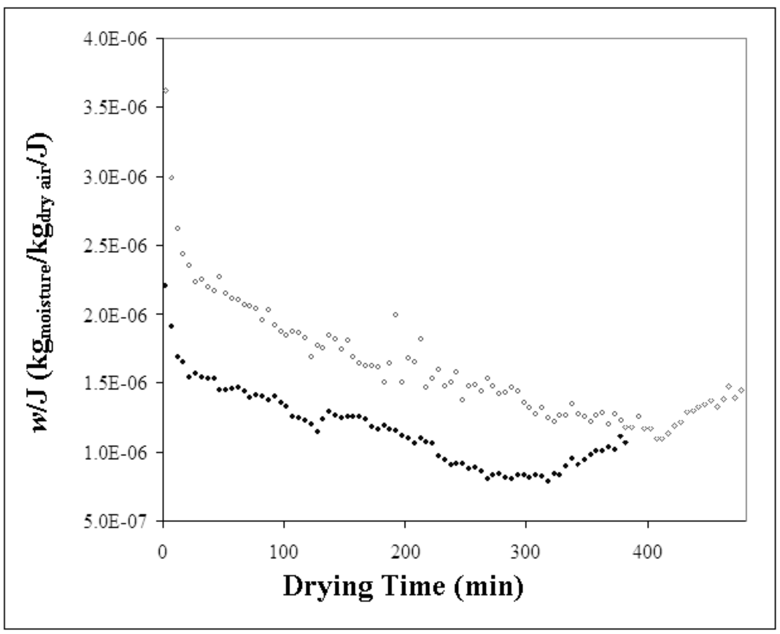

Figure 5. Full dehydration of potatoes on two consecutive days with treatments of eight full trays on day one and fifteen full trays on day two (♦ 8 tray batch, ◊ 15 tray batch).

This within tray variation was not observed to such an extent in the 8 tray batch. It is seen in Figure 5 that nearing the end of the dehydration run there was a general rise of the exit moisture to input energy ratio. This is due to a decrease in the input energy as the sun was past its zenith, combined with a change in dehydration dynamics as seen by a change from a decreasing humidity ratio to a constant humidity ratio. The time to dehydration and weights of final product were 481min for 1055g of potatoes distributed on 15 trays, and 385min for 603g of potatoes distributed on 8 trays. This amounts to a 75% increase in finished product for a 25% increase in drying time or an increase of 38g of final dry product per hour of dehydration time or a 40% increase in dry product per hour of dehydration.

CONCLUSION

It is concluded that the dryer described by Rowe and Steele (2004) can be optimized, as to its energy conversion and use, most easily by increasing the number of full trays within the drying chamber. We chose a whole number value of 15 for the trays within our dryer. Smaller numbers of trays would decrease the drying time and the total product output while higher tray numbers would decrease the throughput while increasing the drying time. This is a useful conclusion since it does not add significant cost to the dryer's manufacture or operation. Also, as the effect of the chimney, on total efficiency, is positive, the user should attach a chimney of maximum height to the dryer; recognizing that there is a reasonable and physical limit to the height of a chimney. It is further concluded that if the chimney is to be detachable, for purposes of storage and transport, special attention should be given to ensuring a good seal at the connecting joint.

NOMENCLATURE

Ap	Solar collector aperture	m^2
I	Solar irradiance	W/m^2
m	Mass flow rate	$kg_{dry\ air}/min$
w	Humidity ratio	$kg_{moisture}/kg_{dry\ air}$
Δh	Change in enthalpy $\Delta h = h_{air\ at\ top\ of\ collector} - h_{ambient\ air}$	$J/kg_{dry\ air}$

REFERENCES

ASHRAE, 1997 ASHRAE handbook fundamentals Inch-Pound Edition, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Chapter 6.

ASHRAE Standard 93-2003. Methods of testing to determine the thermal performance of solar collectors. Atlanta GA.

DOI: 10.2202/1556-3758.1500

Ekechukwu, O. V. and Norton, B. (1997). Design and measured performance of a solar chimney for natural-circulation solar energy dryers. Renewable Energy. 10, 81–90.

El-Sebaii, A. A., Aboul-Enein, S., Ramadan, M. R. I. and El-Gohary, H. G. (2002). Experimental investigation of an indirect type natural convection solar dryer. Energy Conversion and Management. 43, 2251-2266.

Jain, D. and Jain, R. K. (2004). Performance evaluation of an inclined multi–pass solar air heater with in–built thermal storage on deep–bed drying application. Journal of Food Engineering . 65, 497–509.

Karim, M. A. and Hawlader, M. N. A. (2006). Performance evaluation of a v-groove solar air collector for drying applications. Applied Thermal Engineering. 26, 121–130.

Karim, M. A. and Hawlader, M. N. A. (2004). Development of solar air collectors for drying applications. Energy Conversion and Management. 45, 329–344.

Kurtbas, İ. and Durmuş, A. (2004). Efficiency and exergy analysis of a new solar air heater. Renewable Energy. 29, 1489–1501.

Leon, M. A., Kumar, S. and Bhattacharya, S. C. (2002). A comprehensive procedure for performance evaluation of solar food dryers. Renewable Sustainable Energy Reviews. 6, 367–393.

Madhlopa, A., Jones, S. A. and Saka, J. D. K. (2002). A solar air heater with composite-absorber systems for food dehydration. Renewable Energy. 27, 27–37.

Rowe, JP, Steele, FM. 2004. Solar dryer construction and use manual. LDS Welfare Dept.