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Evaluation of cylinder shape solar dryer on natural convection heat transfer

Sriwichai Susuk[1]*, Rachain Visutthipat[1], Natsacha Inchoorrun[2] and Weerayuth Promjan[2]

[1]Biodiversity Research Center, Research and Development Group for Bio-Industries, Thailand Institute of Scientific and Technological Research (TISTR), Pathum Thani 12120, THAILAND

[2]Expert Center of Innovative Health Food (InnoFood), Research and Development Group for Bio-Industries, Institute of Scientific and Technological Research (TISTR), Pathum Thani 12120, THAILAND

*Corresponding author: sriwichai@tistr.or.th

ABSTRACT

This research supports that renewable energy sources were used to power the drying process for design in a solar dryer, leading to the preservation of agricultural products and suitable preservation systems. The drying system involves complex physical atmospheric mechanisms, with relations between the dry air and the moisture content of each product, which affect the performance of solar drying systems. Steady laminar natural convection heat transfer formulas that are accurate based on a boundary-layer have been used to evaluate the flow caused by nonuniform density in an air flow based on dimensionless equations, and natural flow (buoyancy) inside the indirect solar dryer. Results show the heat transfer coefficient for natural convection 5 – 6 W/m^2°C, heat energy 25 - 65 J/s, collector efficiencies 29 - 40.6 % and drying rate 0.18 - 0.98 kg/hr. The heat and mass increased according to dry-air flow through the dryer under trends of solar radiation 312 - 513 W/m^2 and temperatures inside the indirect solar dryer 39.7 - 53.7°C, respectively, as ambient temperature 30.5 - 42.5°C, relative humidity 36 - 52% schedule 08:00 a.m. - 04:00 p.m. (daylight clear sky recorded). Experimentation, a test with a similar climate condition, with an initial moisture content of 85% to the final moisture content of 15% on a wet basis, showed a drying rate of 0.08 - 0.19 kg/hr.

Keywords: Renewable energy, Solar dryer, Laminar natural convection, Boundary-layer, Buoyancy

INTRODUCTION

The sun is an abundant energy source widely utilized, especially for preserving agricultural products, one of the oldest and traditional techniques. As the global world transitions towards green energy sources, solar drying has become an essential technology for sustainable agricultural production, offering a clean energy, more efficient alternative to conventional drying methods, and advantages over traditional methods, including faster drying rates and reduced energy costs. Solar drying is one of the renewable energy sources, desirable as compared to other fossil fuels that pollute the environment (greenhouse effect), not only contributes to a better environment but also gives a strong and sustainable boost to the economy through work opportunities, as well as encourages the safety of agricultural products through preservation systems. Moreover, it is a or rural societies living far from the electric grid. Traditionally solar drying techniques is one of oldest make use of an open space (open sun drying or direct sunlight) is the simplest and cheapest method of drying, However, open sun drying has a various limitation on the long drying time periods, (un control temperature and time), dependence on weather conditions, requires a large space area and physical changes in product such as shrinkage, deterioration of quality by overheating, hostile ambient may lead the products to burn instead of drying affects the color, texture, flavor, loss of nutrient and volatiles components, Furthermore contamination of products from the foreign materials and infestation by insects, birds, rodents and other animals. To overcome the limitation of open sun drying, the improvement and utilization of solar dryers is essential, which involves moisture content in the product, heat and mass transfer phenomenon that removes moisture from a product by passing hot-air flows around it to carry away the released vapor, continues until the vapor pressure of the product and ambient environment are equalized. The designs of solar drying systems include various solar collector configurations, dryer geometries, and air flow mechanisms, which are crucial for efficient drying. Heat transfer equations and dimensionless quantities are required to obtain the air flow rate, especially the heat transfer coefficient. Nevertheless, one of the issues in solar dryer designs is the lack of modeling and dimensionless heat transfer data for optimal process design [1-5].

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The objective of this research is carried out calculate under the assumption of steady the boundary and incompressible constant fluid laminar flow conditions to evaluate the performance of the indirect solar dryer, using dimensionless quantities [6] as Nusselt Number, Rayleigh Number, Grashof Number, Graetz Number, Reynolds Number, Prandtl Number, Peclet Number, Pohlhausen and heat transfer equations to analyze heat collector on the vertical and horizontal solar dryer's surface (caused by air buoyancy with different temperatures) and compare the result with the experimental drying with the banana (represent agriculture products).

MATERIALS AND METHODS

Description of solar dryer

The cross-sectional view of the solar dryer uses materials easily obtainable from the local market. Figure 1 shows a diagram of the workflow analysis of the solar dryer vertical cylinder shape, the prototype of the solar dryer cylinder vertical shape, consisting of main parts, material Polycarbonate-bright white color plate 6 mm thick, diameter 0.80 m, and height 0.60 m. Contracture body cover and bottom plate made by SUS304 stainless steel (Food grade material), the cover plate is designed for protecting against overheating, preventing the food from burning instead of drying [5], and it can support the fan, blower, or heater utilized for drying continuously until the finished process. The tray made of SUS304 stainless steel had dimensions of 30 cm width, 30 cm depth, and 32.5 cm height. It has the capacity to accommodate 10 kg of material per batch. The door has been provided at the top, and hot air flows into the dryer through the inlet at the bottom, and leaves through the upper side. The solar radiation is absorbed by the surface and covers approximately 1.25 m^2 of the solar dryer approximately 1.25 m^2.

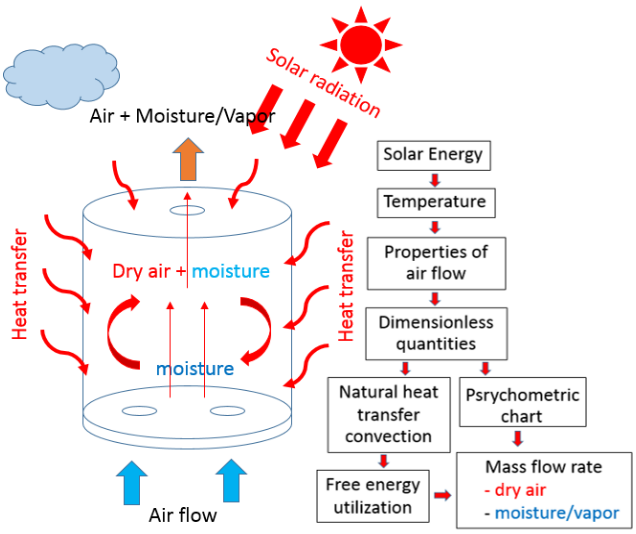

Figure 1 Diagram work flow analysis solar dryer vertical cylinder shape.

Equations and mathematics analysis

Mathematical equations governing natural convection flow and the heat transfer in a solar dryer (cylinder shape) are the dimensionless quantities (boundary conditions) and energy equations. A major problem in heat transfer is the estimation of heat transfer coefficients to be used for design purposes. These hc values must be determined from the fluid's properties and the system's geometry. Equations that describe systems with similar characteristics can be superimposed on each other to form a single expression suitable for all systems. The following dimensionless quantities have been identified and used in correlations involving the heat transfer coefficient equations (1)-(9). The quantity of air needed for drying: Using a psychrometric chart, it is a study of the physical and thermodynamic properties of moist air, i.e., a mixture of dry air and water vapor, and shows the humidity ratio to be kg water/kg dry air, corresponding from the gas laws [7-9].

Experimental set-up

Figure 2 Experimental setup test with a banana fruit.

The temperature profile of the dryer was determined by measuring the hourly temperature. Testing under no load conditions was carried out, measuring the hourly temperature, humidity, solar radiation, and air velocity by Solar power meter model SM206-SOLA, Anemometer model CBzSGHJ001, Temperature & Humidity model L563A, Temperature model TM 1803, Weighting scale model VIGO, and Moisture meter model OHAUS MB23. Experimental studies under no load conditions were conducted in Tambon Khlong Ha, Amphoe Khong Luang, Pathum Tani, Thailand, at a latitude of 14°0'48.46" North and a longitude of 100°31'49.76" East. The temperature profile of the dryer was determined by measuring the hourly temperatures collected between 08:00 a.m. and 04:00 p.m. Experimental studies set-up test with

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banana fruit 5 kg (average diameter 3 cm. and length 8 cm.) was reduced from an average 85% to 15% wet basis (Figure 2), specific heat ranged from 1574.0-2506.8 J/kg°C. [10].

Equation of dimensionless

Nusselt Number (Nu) vertical analysis [5,11].

$$\overline{N_u} = 0.68 + \frac{\left(0.67 R_a^{1/4}\right)}{\left(1+\left(0.492/\Pr\right)^{9/16}\right)^{4/9}} \quad (1)$$

Nusselt Number (Nu) horizontal analysis [12].

$$\overline{N_u} = \frac{0.544 Ra^{1/5}}{\left(1+\left(0.477/\Pr\right)^{3/5}\right)^{1/3}} \quad (2)$$

The Pohlhausen Equation [13].

$$N_{ulam} = 0.664 \mathrm{Re}^{1/2} \Pr^{1/3} \quad (3)$$

Rayleigh Number (Ra).

$$R_a = \mathrm{P_r} \times G_r \quad (4)$$

Grashof Number (Gr).

$$G_r = \frac{L^3 g \beta \rho^2 \Delta T}{\mu^2}, \frac{d^3 g \beta \rho^2 \Delta T}{\mu^2} \quad (5)$$

Graetz Number (Gz).

$$G_z = \frac{\pi}{4}\left[\mathrm{Re}\times \Pr \times \left(\frac{d}{L}\right)\right] = \frac{\dot{m}}{k_v \times L} \times C_p \quad (6)$$

Reynolds Number (Re).

$$\mathrm{Re} = \frac{L \times v \times \rho}{\mu} \quad (7)$$

Prandtl Number (Pr).

$$\mathrm{P_r} = \frac{C_p \times \mu}{k} \quad (8)$$

Peclet Number (Pe).

$$\mathrm{P}_e = \mathrm{R_e} \times \mathrm{P_r} \quad (9)$$

Heat transfer coefficient (h_c).

$$h_c = \frac{\overline{N_u}}{L} \times k_v \quad (10)$$

The quantity of air needed for drying: Using a psychrometric chart and taking input air temperature and relative humidity, it describes the physical and thermodynamic properties of moist air and the hot air drying process, i.e., Parameters for dry-air analysis Table 2. Most common dehydration processes use hot air as the drying medium, as the air delivers heat to the product to evaporate moisture. The property data are usually provided in charts and tables. The assumption is that there is no heat loss between the collector and the drying. The physical properties of humid air can be determined using the following equation (11-14) [13-15].

$$C_v = 999.2 + 0.1434 T_i + 1.101\times10^{-4} T_i^2 - 6.7581\times10^{-8} T_i^3 \quad (11)$$

$$\mu_v = 1.718\times10^{-5} + 4.620\times10^{-8} T_i \quad (12)$$

$$K_v = 0.0244 + 0.6773\times10^{-4} T_i \quad (13)$$

$$\rho_v = \frac{353.44}{(T_i + 273.15)} \quad (14)$$

The total collected solar energy, efficiency, and mass flow; the energy input of the solar thermal collector area can be determined from equations (15-17) [16]. Solar collector received maximum solar radiation during test, equation (15), energy output of the solar thermal collector can be determined by equation (16), and efficiency of the solar thermal collector can be defined as the ratio between the useful outputs of energy to the input energy using equation (17). The evaluation of water to be removed from the product using equations (18-20).

$$E_i = I \times A \quad (15)$$

$$\dot{q} = h_c \times A \times \Delta T \text{ ; The rate of energy collection} \quad (16)$$

$$\eta_C = \frac{\dot{q}}{E_i} \times 100 \quad (17)$$

$$P_A V_A = m_a R_A (T + 273.15) \text{ ; Gas Laws of air} \quad (18)$$

$$P_w V_w = m_w R_w (T + 273.15) \text{ ; Gas Laws of vapors} \quad (19)$$

$$\frac{m_w}{m_a} = \frac{0.622 P_w}{P_A} = \frac{0.622 P_w}{P - P_w} \text{ ; Specific humidity} \quad (20)$$

A major part of energy utilization during drying is for liquid water's evaporation into its vapors (2258 kJ/kg at 101325 Pa), and the average specific heat capacities of drying processes are given as 1970 J/kg°K. A phenomenon of removing liquid by evaporation from a solid, mechanical methods for separating a liquid from a solid are not generally considered drying. The water may be contained in the solid in various forms, like free moisture or bound form, which directly affects the drying rate. These principles are applied, in general, to conventional mechanical drying and are concerned mainly with solar drying. However, it must be noted that conventional drying principles and phenomena are generally independent of the type of energy used [17, 18].

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Table 1 Solar radiation, temperature and %RH.

Time	8 am	9 am	10 am	11 am	12 am	1 pm	2 pm	3 pm	4 pm
Solar radiation (W/m^2)	312	371	419	465	497	513	494	456	416
Average ambient temp. (°C)	28.5	32.0	34.7	36.6	39.2	40.3	39.6	38.0	35.7
Average temp. (°C) inside dryer	36.7	42.2	46.8	50.3	54.7	56.8	54.5	49.6	43.8
%R.H. ambient outside dryer	52.2	46.7	44.1	40.0	39.9	36.2	38.0	39.5	42.6
%R.H. in dryer no load test	32.6	28.7	26.8	24.3	23.5	20.5	21.9	23.1	25.4

Table 2 Parameters for dry-air analysis.

Item	Average	Units	Equation
C_v	1006.4	J / kg °C	11
μ_v	0.0000194	kg/m.s	12
K_v	0.0277	W/m°C	13
ρ_v	1.103	kg/m^3	14
β	0.00311	1/°K	-
P	101325	Pa	standard
P_A	89365	Pa	20
g	9.81	m/s^2	standard
R_A	287.1	J/kg°K	standard
A	1.25	m^2	-
Nu (vertical)	95.7	dimensionless	1
Nu (horizontal)	212.6	dimensionless	2
Ra (vertical)	0.18x10^{12}	dimensionless	4
Ra (horizontal)	24x10^{12}	dimensionless	4
Gr (vertical)	0.26x10^9	dimensionless	5
Gr (horizontal)	0.61x10^9	dimensionless	5
Gz	65	dimensionless	6
Re	0.26x10^5	dimensionless	7
Pr	0.706	dimensionless	8
Pe	18539	dimensionless	9
m_w/m_a	0.084	kg/kg	20
$\dot{q}$	87.6	J/s	16

RESULTS AND DISCUSSION

No load test (dry air analysis)

The first results described previously of the prototype solar dryer cylinder vertical shape utilized a natural, renewable energy source of heat energy that continuously changed from hour to hour, depending upon the time and sky cover of the day, making it difficult to control. Preliminary evaluation, the air is a gas, as if a medium that can absorb moisture from food products during the drying process by using a solar dryer (heats the air within the collector, raising its temperature and increasing vapor pressure, thus reducing its relative humidity). The information used to evaluate the system is presented in Table 1. The general trend in the profiles of solar radiation and temperatures obtained shows increases from 09:00 a.m. to between 01:00 p.m. and 03:00 p.m. followed by a decrease. On the other hand, relative humidity decreases from 09:00 a.m. to between 01:00 p.m. and 03:00 p.m., then increases, tested without trays and with no load. The hourly variation of the incident solar radiation is shown in Figure 3. During the test period, the test ranged from 312 to 513 W/m^2. It is clearly seen that the dryer is hottest around midday when the sun is usually overhead. The maximum solar radiation is observed at around 01:00 p.m., 497 to 513 W/m^2, and the average is 438 W/m^2, respectively (the dryer is hottest about midday when the sun is overhead). While ambient and inside dryer temperatures varied from 30.5 to 42.5°C and 39.7 to 56.6°C, respectively. Figure

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4, the temperature information inside the dryer is within the safe range limit of the drying agricultural processes. (Prakash and Kumer, 2014) [4].

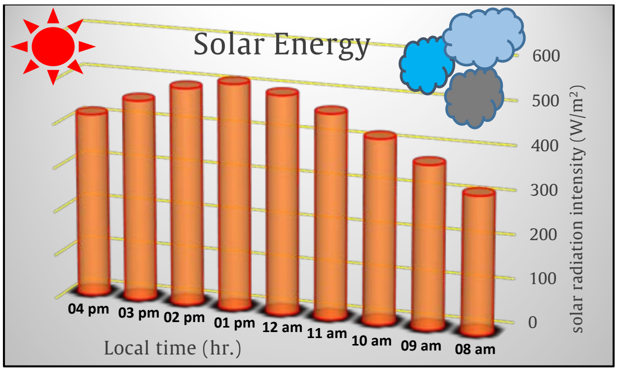

Figure 3 Solar energy radiation.

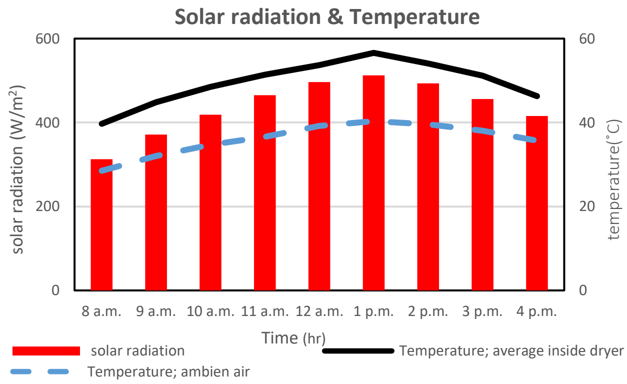

Figure 4 Solar radiation and temperature.

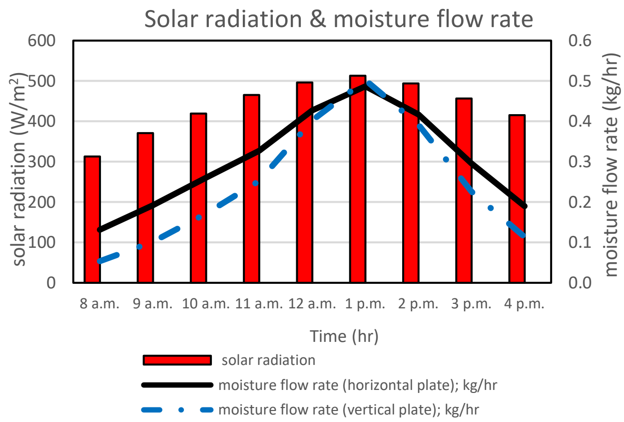

Figure 5 Variation of moisture flow rate.

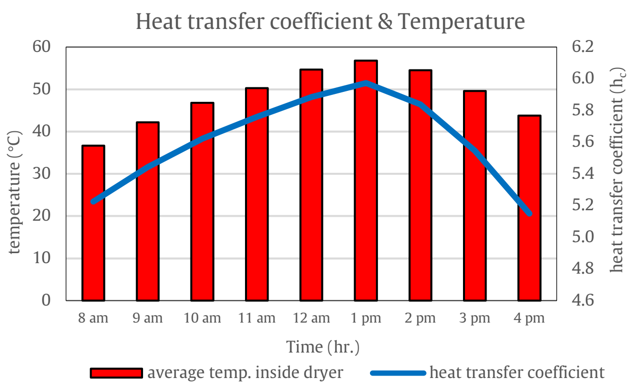

Figure 6 Heat transfer coefficient and temperature.

The hourly variation of the mass flow rate (dry-air and water) is shown in Figure 5. It was observed that products in the dryer can be dried faster at around 01:00 p.m. because the moisture flow rate strongly depends on the solar radiation effect and the temperature. The effect of the moisture rate increases as solar radiation and temperature increase, and the moisture flow rate is between 0.1 and 0.5 kg/hr, with an average of approximately 0.55 kg/hr, respectively.

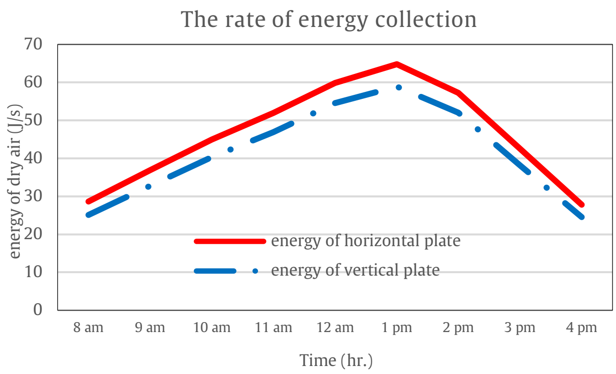

Figure 7 Rate of energy collection (horizontal and vertical plate).

The hourly variation of the heat transfer coefficient of drying is shown in Figure 6. The very heat transfer coefficient values for natural convection are 5.2 and 5.9, with an average of approximately 5.6 W/m² °C, respectively. It can be indicated that the high or low drying system depends on the solar radiation and the temperature effect. The high heat transfer coefficient can achieve high energy, as shown in Figure 7. The rate of energy collection is approximately 25 and 65 J/s, respectively, which can achieve more dry-air volume, leading to dehumidification (moisture removed from the dryer), as shown in Figure 5. This is clearly seen that the maximum heat transfer coefficient similar solar radiation and temperature at around 01:00 p.m.

The hourly variation of thermal (collector) efficiencies on the drying system. It increases as the solar radiation increases Figure 8. This clearly reveals the dependence of the dryer's performance on solar radiation and temperature throughout the system. The efficiency through the solar dryer during the test period was between 29 and 40.6 %. Similar to the previously shown figure at 01:00 p.m., the highest efficiency.

Test with load (banana fruit)

Compering the evaluation of mass flow rate between no load and with load in order to verify performance all information, Experiments banana fruits were dried and the results obtained in drying a banana sample, are shown in Figure 9, It was observed that products in dryer can be dried faster at around 01:00 p.m., testing were carried out drying of banana fruits 5 kg, similar condition no load items. The test banana slices spent drying time about 27 hours, with an average testing four times per week based on the solar radiation effect on the dryer (08:00 a.m.-04:00 p.m.), beginning 85% was reduced to 15% the basis conditions.

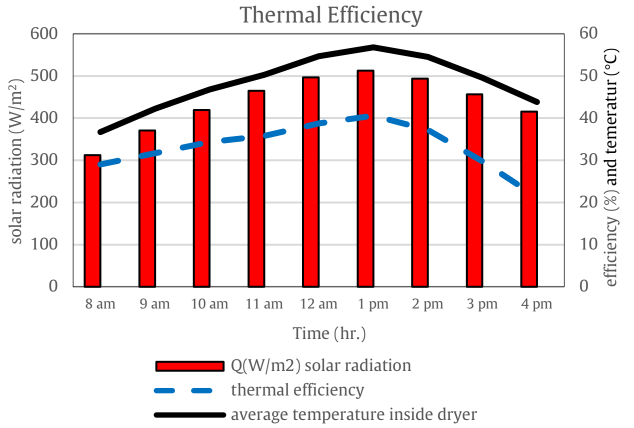

Figure 8 Thermal efficiency.

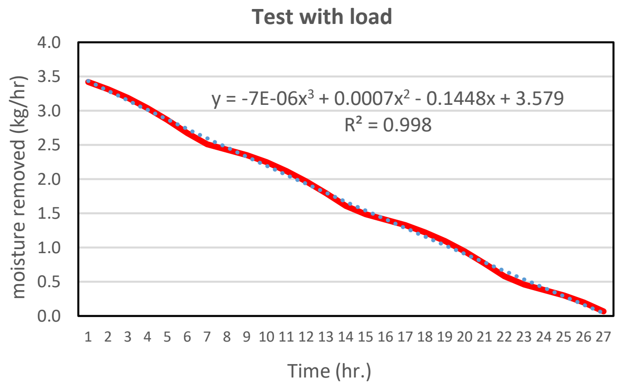

Figure 9 Experiment test with load (banana fruit).

CONCLUSIONS

This research demonstrates a practical way of cheaply and sanitarily preserving agricultural products by utilizing a solar dryer. The solar dryer does not require high technology, and the maintenance cost is minimal once installed. The evaluation of the solar dryer on natural convection heat transfer based on boundary-layer laminar air-flow has been to evaluate the flow caused by the dimensionless heat transfer correlating equation, which was applied to evaluate the heat transfer along with the cylindrical shape of the indirect solar dryer. Heat transfer equations were also used in this study to evaluate heat and mass transfer across the dryer. All equations and experiments show higher solar dryer and air-flow values were obtained with higher solar radiation values. However, solar dryers have a natural disadvantage; they require too long to dry agricultural products due to the buoyancy and insufficient dehumidification to dehumidify the dryer rapidly. An alternate energy source was used to power the drying process during cloudy days and at night. Improvement in efficiency more than this design can add a solar collector or other renewable heat source utilized for drying continuously during off-sunshine and at night or on rainy.

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Nomenclature

Nu	dimensionless	Nusselt Number (mean value)
Nu_{lam}	dimensionless	Nusselt Number (laminar flow)
Ra	dimensionless	Rayleigh Number
Pr	dimensionless	Prandtl Numder
Gr	dimensionless	Grashof Numder
Re	dimensionless	Reynolds Number
Pe	dimensionless	Peclet Number
g	m/s^2	Acceleration due to gravity
β	1/°K	Coefficient of thermal expansion
ρ_v	kg/m^3	Density
ΔT	°C	Temperature difference ; (T_i - T_{am})
T_{am}	°C	Ambient temperature
T_i	°C	Temperature inside dryer
T	°C	Film temperature
v	m/s	Velocity of air
μ_v	kg/m.s	Dynamic viscosity
L	m	Length
C_v	kJ/kg˚C	Specific heat of dry air, at constant pressure

K_v	W/m˚C	Thermal conductivity
E_i	W	Solar energy
t	s	Time
I	W/m^2	Incident insolation
A	m^2	Total collector area
η_c	%	Thermal efficiency
m_w	g	mass of water to be dried
h_{fg}	kJ/kg	Latent heat of water vaporization
V_A	m^3	Volume of dry air
V_w	m^3	Volume of vapors
m_a	kg	Mass of air
m_w	kg	Mass of vapour
P	Pa	Atmospheric Pressure (101.325 kPa)
P_s	Pa	Pressure of steam
R_A	J/kg°K	Gas constant t = 287.1
R_w	J/kg°K	Moisture constant = 461.5
$\dot{q}$	J/s	Energy, rate of heat flow
$\dot{m}$	kg/s	air flow rate
h_c	W/m²°C	Convective heat transfer coefficient

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