American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-13, Issue-10, pp: 25-36
www.ajer.org
Research Paper Open Access

Analysis, Testing of Heat and Mass Transfer in the Solar Dryer Curve Front

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ABSTRACT : *Environmental and energy crises pushing towards using more widespread application of renewable energy systems. One of them is solar dryer. This work is a purpose to utilize the benefits of using sun energy through drying. The solar dryer curve front shape was designed, constructed and tested based on cheaply and sanitarily preserving food agriculture and herb items, in Thailand on latitude of 14°0'48.46" North and longitude of 100°31'49.76" East climate condition. The drying performance of solar dryer was evaluated by heat transfer equations, indirect solar dryer condition. The experimental drying show that temperatures inside the dryer was higher than the ambient temperature during most hours of the day. The efficiency increased as the temperature and heat transfer coefficient increased, lead to more moisture removing rate. The dryer consists of the dryer consists of area's curve front shape as collector energy. The results primary information show average solar radiation range between 354.3 and 561.5 W/m^2, ambient temperature range between 29.8 and 40.5 °C and inside dryer range between 37.8 and 67.7 °C respectively. The heat transfer equations obtained show heat transfer coefficient range between 3.9 and 5.0 W/m^2°C, thermal efficiency range between 16.6 and 39.8 % based on no load condition. Similar condition, test with the agriculture produce, the results shows moisture removing rate range between 0.08 and 0.93 kg/hr. During the period of test, the average air velocity through the solar curve front shape was 2.7 m/s and average daylight efficiency of the drying was 45.2%, energy saving 2610 W and CO_2 emission approximately 1.51 kg/day.*

KEYWORDS *renewable energy technologies, heat transfer natural convection, energy solar radiation, heat transfer coefficients*

Date of Submission: 01-10-2024 Date of acceptance: 11-10-2024

I. INTRODUCTION

Climate change , warming on pollution linked energy cost, and the need to preservation post-harvest losses, the fossil, which take more millions of years to fuels form are being depleted faster than they are produced, leading to climate change like air pollution, and water contamination [Maundu et al., 2016]. The sun is the oldest preservation agricultural product crops and food and it is the most common economical, environment friendly. Because of continuous nuclear fusion taking place in its core. It is an essential process utilized all over the world for preservation of food and agriculture product, Solar drying can simply be analysis as an elaboration of sun drying. As an alternative to open sun drying, with possibility of improved post-harvest that is sustainable for increased drying, free of energy and without any danger to the environment. Solar drying system have added advantages of savings cost, energy, time and space requirement during drying operations. It's also form a sustainable renewable energy resource that has a great potential for applications because it is abundant and accessible. It's overcome the drawbacks of open sun drying such as contamination from foreign material and infestation by insect birds and other animals, lack of control over heat drying condition, bring structural and physical changes in the product. The solar energy drying offers an alternative which can be preserved food and agricultural crops in clean and sanitary condition. Drying is commonly described as the operation of the process of removing excess moisture from products to meet standard specifications, which exerts a vapor pressure less than that of bound moisture, this process requires a certain amount of energy, The solar dryers are classified into two major groups, namely; an active solar-energy drying system and passive solar-energy drying system. Both the heat energy required for removing the moisture as well as the energy source necessary for driving the dry air flow are generated in the most cases by solar energy only.

The heat transfer on dryer depends on the operating parameter of heat transfer coefficient and dry air flow character. Heat transfer take place cover between solid and fluid surrounding it, and fluid move due to action of forces base on buoyancy regime called natural convection else it is forced convection, generally heat transfer coefficient natural convection are much smaller than forced convection. The temperature difference between surface and surrounding are important in the investigation [Cengel et al., 2002][Romeo et al., 1999].

The objective of this paper is to estimate the ability of solar dryer's curve front indirect mode used energy equation and compare the result with the experimental ones. An analysis of solar radiation at several main agriculture form in Thailand shows that solar radiation is possible to use in solar drying, traditional method are under the open sun drying with not so much reduction of moisture content and slowly even under condition high humidity. An alternative to the traditional techniques and contribution towards the solution of these problems could be using solar dryer.

The objective of solar dryer's curve front was design and calculated energy base on the collector tilt for average collection of incident solar radiation for all year round operation of a collector is to be taken as the latitude of the site where it is located in practice (Tambon Khlong Ha, Amphoe Khong Luang, Pathum Tani, Thailand). Solar radiation, temperature inside dryer and ambient are measured to provide a understanding of the flow due to heat transfer by natural convection in the dryer, utilize design process to achieve product quality longer safe storage and reduction in an herb losses, temperature not higher than 55˚C for prevented nutrient and volatiles components of generally fruit vegetables and herbs. Focus on utilize renewable solar radiation on January 2023- July 2024 at 08:00 a.m. to 04:00 p.m. local region. All experiments were conducted under climatic condition (a latitude of 14°0'48.46" North and longitude of 100°31'49.76" East), testing were carried out on solar drying of ginger slices (July 2024) compare with heat transfer equation for ensure design's optimization utility.

II. EXPERIMENTAL DETAIL

Description of solar dryer

Gross dimension of this solar dryer's curve front shape consists of the dimension of curve length approximately 1.885 m width 0.91 m and height 1.2 m. It is covered with a transparent material (Polycarbonate-bright white color plate) 6 mm thick, the materials that are easily obtainable from the local market. Figure 1 shows the schematically of the prototype of solar dryer which consists of main contracture made by steel. The tray made by stainless steel 5 plates dimension was 0.8m x 0.8m x 0.8 m., area collector approximately 1.72 m^2 and volume approximately 1.03 m3. It's capacity to accommodate 10 kg of material per batch. The air flowed enters dryer Experimental set-up ; Temperature profile of the dryer was determined by measuring the hourly of thermometer, testing under no load conditions (Figure 1) were carried out recorded 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 set-up under no-load and then drying test consists of the banana 25 kg 80% to 15% wet basis [Olusegun et al., 2018], average temperature were measured about 9 hours per day, (Figure 2) the small-scale system used in this study for dry-air process, experiment analysis sampling weight of the ginger slices at 08:00 a.m. to 04:00 p.m. local time in Thailand a latitude 14°0'48.46" North and longitude 100°31'49.76" East. Mathematical equations governing natural convection flow base on dimensionless quantities have been identified and utilized in correlations involving the heat transfer in solar dryer's curve-front shape (boundary condition) and energy equations. Major problem in heat transfer is the analysis of heat transfer coefficients to be used for design purposes, values of heat transfer coefficients (h_c) must be determined from the properties of the gas, fluid and the geometry of the system. The equations that describe different systems having 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 equation (3)-(8). The governing mean collector efficiency range of 30-50 % (Sodha et al., 1987) under assumptions as followed according to equations [Adelaja et al.,2013][Mehmet et al., 2021][Houghton et al.,2013].

Equation of dimensionless

Nusselt Number (Nu)

$$N_u = 0.274 R_a^{1/4} \quad (1)$$

Rayleigh Number (Ra)

$$R_a = \mathrm{P_r} \times G_r \quad (2)$$

Grashof Numder (Gr)

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

Reynolds Numder (Re)

$$\mathrm{Re} = \left(\frac{N_u}{0.664\,\mathrm{Pr}^{1/3}}\right)^2 \quad (4a)$$

$$\mathrm{Re} = \frac{L.v.\rho}{\mu} \quad (4b)$$

Prandtl Numder (Pr)

$$\mathrm{P_r} = \frac{C_p \mu}{k} \quad (5)$$

Peclet Number (Pe)

$$\mathrm{P}_e = \mathrm{R_e} \times \mathrm{P_r} \quad (6)$$

Heat transfer coefficient (hc)

$$h_c = \frac{k N_u}{L} \quad (7)$$

Blasius's numerical solution for boundary-layer thickness

$$\delta = \frac{4.64 L}{\mathrm{Re}^{1/2}} \quad (8)$$

Equation quantity of dry-air

A phenomena of removal of liquid by evaporation (moisture) from a solid, it is mechanical methods for separating a liquid from a solid are not generally considered drying.

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

(9)

$$\mu_v = 1.718\times10^{-5} + 4.620\times10^{-8}T_i$$

(10)

$$K_v = 0.0244 + 0.6773\times10^{-4}T_i$$

(11)

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

(12)

Energy of thermal collector

The energy input of the solar thermal collector can be determined equation:

$$E_i = I \times A \quad (13)$$

$$\eta_C = \frac{E_o}{E_i}\times100 \quad (14)$$

$$\dot{q} = \dot{m}\times C_v \times \Delta T \quad (15)$$

$$\dot{q} = h_c \times A \times \Delta T \quad (16)$$

$P_A V_A = m_a R_A (T + 273.15)$ *Gas Laws, temperature in Kelvin* (17)

$P_s V_w = m_w R_w (T + 273.15)$ *Gas Laws, temperature in Kelvin* (18)

$m_w / m_a = 0.622 P_s / (P - P_s)$; *Ps = enthalpy; saturate analysis* (19)

Major part of energy consumption during drying is for the evaporation of liquid water in to its vapors (2.258 MJ/kg at 101325 Pa) and the average specific heat capacities drying processes are given 1.97 kJ/kg˚K. A phenomena of removal of liquid by evaporation from a solid, it is 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 mechanical conventional drying and here concerned mainly with solar drying. However in general, it must be noted that conventional drying principles and phenomena are independent of the type of energy used. [Oko et al., 2010][Ji et al., 2017][Ekechukwu et al., 1999][Mujumdar et al., 2007].

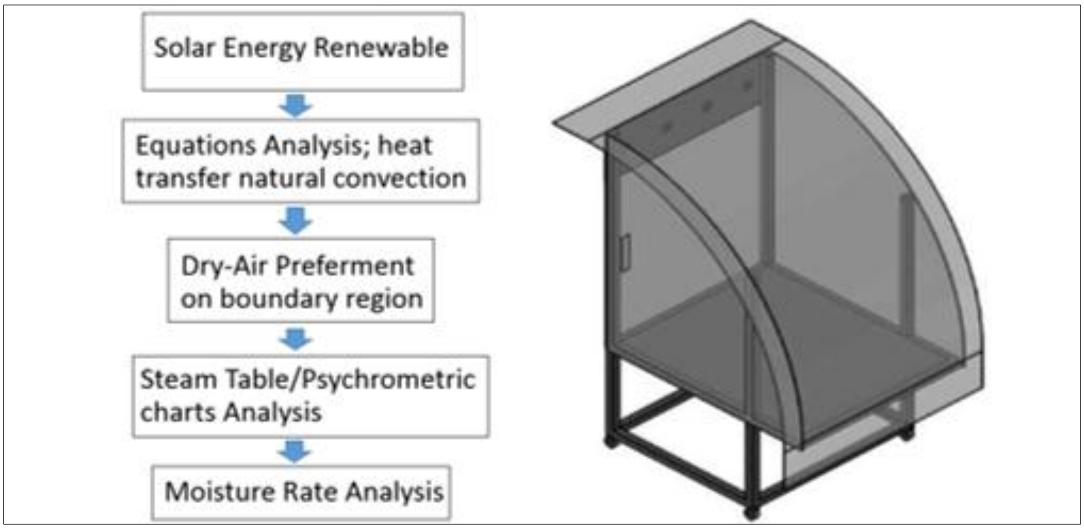

Fig. 1. Solar dryer's curve front and flow chart design analysis

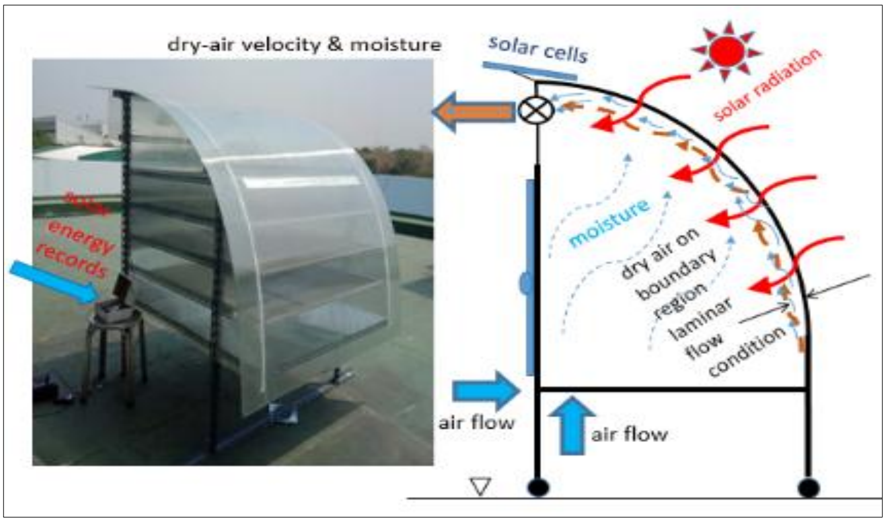

Fig. 2A. Experimental setup solar radiation record

Fig. 2B Experimental setup test with load

Local time	08:00 a.m.	09:00 a.m.	10:00 a.m.	11:00 a.m.	12:00 a.m.	01:00 p.m.	02:00 p.m.	03:00 p.m.	04:00 p.m.
Solar radiation (W/m2)	354.8	421.70	478.5	528.2	559.7	561.5	560.8	531.6	487.50
Average ambient temperature. Tam (°C)	29.8	32.8	35.9	37.3	39.2	40.5	39.4	37.7	36.3
Average temperature. (°C) inside dryer	37.8	44.7	51.7	56.6	60.7	67.7	60.8	54.8	48.7
%R.H. ambient outside dryer	53.3	48.4	45.3	40.6	37.7	35.9	39.8	46.6	55.5
%R.H. in dryer no load test	31.3	27.2	25.4	22.3	20.5	18.7	21.4	22.8	25.5

Table 1 Variation of solar radiation and temperature: average 6 months

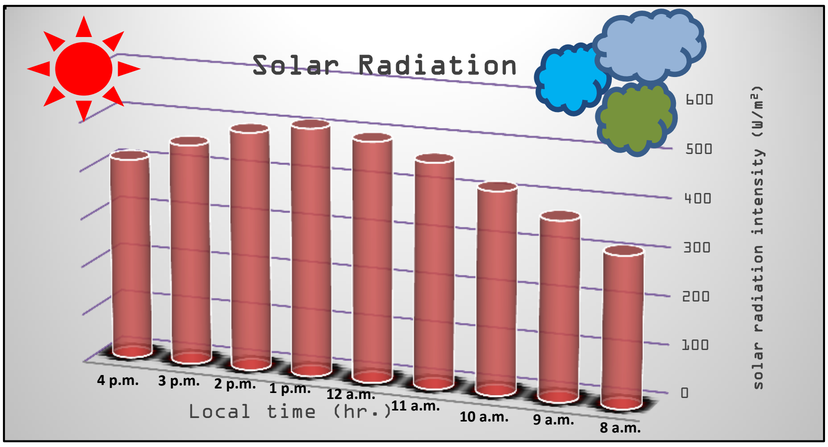

Fig. 3. Variation of solar radiation and local time

Table 2 Parameters condition for dry-air analysis

Item	Average	Units	Equation
C_v	1007.2	J / kg ˚C	9
μ_v	0.0000195	kg/m.s	10
K_v	0.028	W/m˚C	11
ρ_v	1.085	kg/m^3	12
β	0.00306	1/°K	-
I	498.3	W/m^2	measurement
P	101325	Pa	standard
T_i	53.7	°C	measurement
T_{am}	36.5	°C	measurement
E_i	604	W	12
g	9.81	m/s^2	standard
R_A	287.1	J/kg°K	standard
Nu	279	dimensionless	1
Ra	$9.8x10^9$	dimensionless	2
Gr	$1.4x10^{10}$	dimensionless	3
Re	$2.8x10^5$	dimensionless	4
Pr	0.706	dimensionless	5
Pe	199199.5	dimensionless	6
v	2.7	m/s	1,4
h_c	4.7	W/m^2°C	7
δ	0.0165	m	8

III. RESULTS AND DISCUSSION

No load test (dry air analysis)

The first results described previously of prototype solar dryer cylinder vertical shape utilized natural renewable energy source of heat energy continuously changed from hour to hour depending upon the time and sky cover of the day consequently so difficult to control. Preliminary evaluation, the air is a gas as if medium that can absorbed moisture facilitate from food products during the drying process by using solar dryer (heats up the air within the collector, rising its temperature and increasing vapors pressure thus reducing its relative humidity)[Maundu et al., 2016]. The information used for evaluation of the system are presented in Table 1. The general trend in the profiles of solar radiation and temperatures obtained shown increases from 09:00 a.m. to between 01:00 p.m. and 03:00 p.m. than decrease, on the other hand relative humidity decrease from 03:00 a.m. to between 01:00 p.m. and 03:00 p.m. than increase, tested without trays and with no load. The hourly variation of the incident solar radiation is shown Figure 3. During the period of test from 354.3 to 561.5 W/m^2. It is clearly seen that the dryer is hottest around mid-day when the sun is usually overhead. The maximum solar radiation is observed at around 01:00 p.m. 528 to 561.5 W/m^2 (the dryer is hottest about mid-day when the sun is overhead). While, ambient and inside dryer temperatures varied from 29.8 to 40.5˚C and 37.8 to 67.7˚C respectively average utilized inside dryer 53.7˚C, which is in the range proposed fruits and vegetables [Eshetu et al., 2021]. It is also seen the inside dryer higher than ambient temperature during most hours of the day-light, this indicates prospect for better performance than open air drying was shown Figure 4, Importance of drying system are heat transfer coefficient was shown Figure 5 range between 3.9 and 5.0 W/m^2°C maximum showed at 01:00 pm. 5.0 W/m^2 °C and Figure 6 shown mass of dry air flow rate 47.3 g/s required for get rid of maximum moisture 0.41 g/s and volume flow rate and other information according to Table 3. Figure 7 shown thermal efficiency (collector) of drying system range between 16.6 and 39.8 % [Hussein et al., 2017].

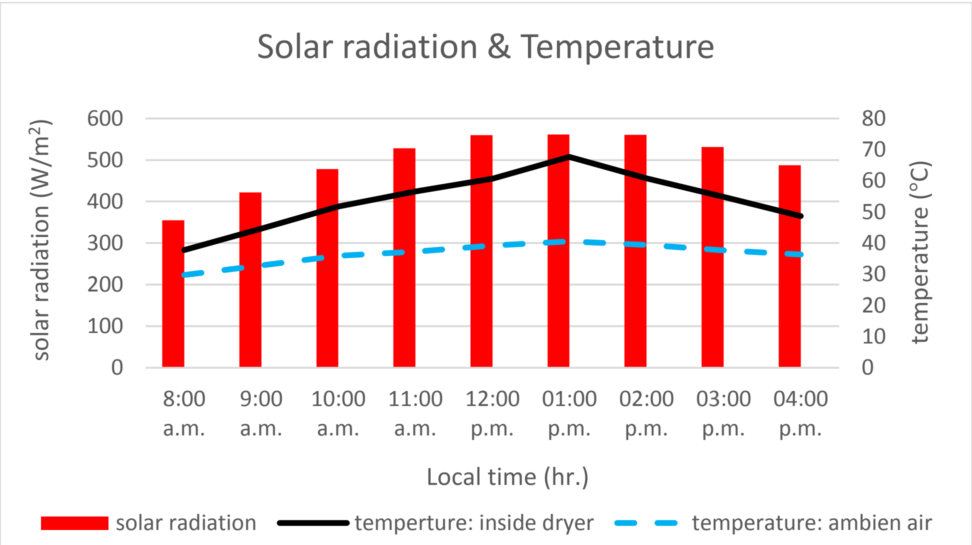

Fig. 4 Variation of solar radiation and temperature

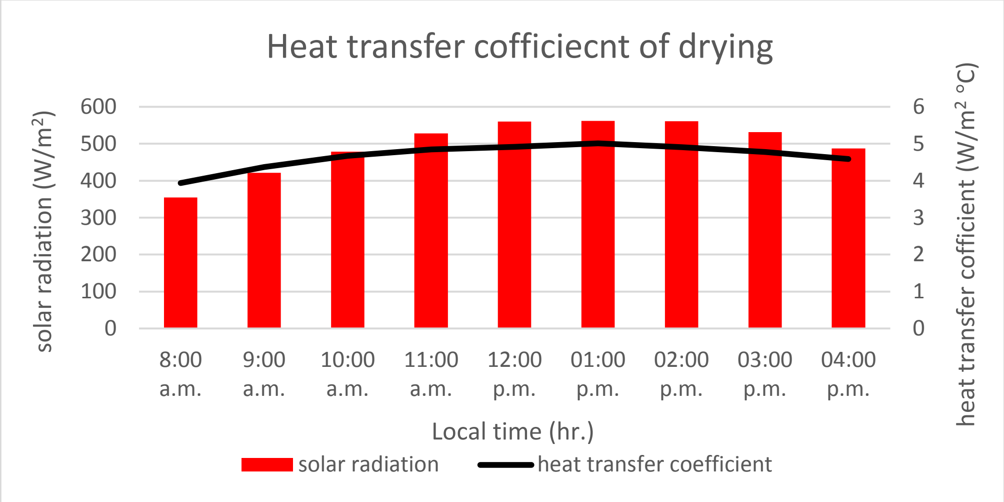

Fig. 5 Variation of natural convective heat transfer

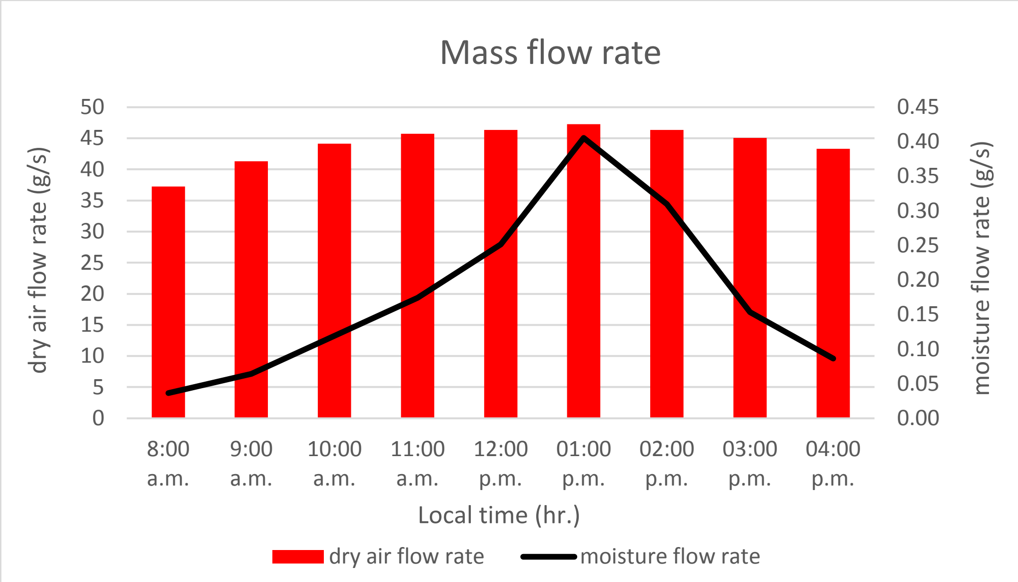

Fig. 6 Variation of mass flow rate (dry-air and moisture)

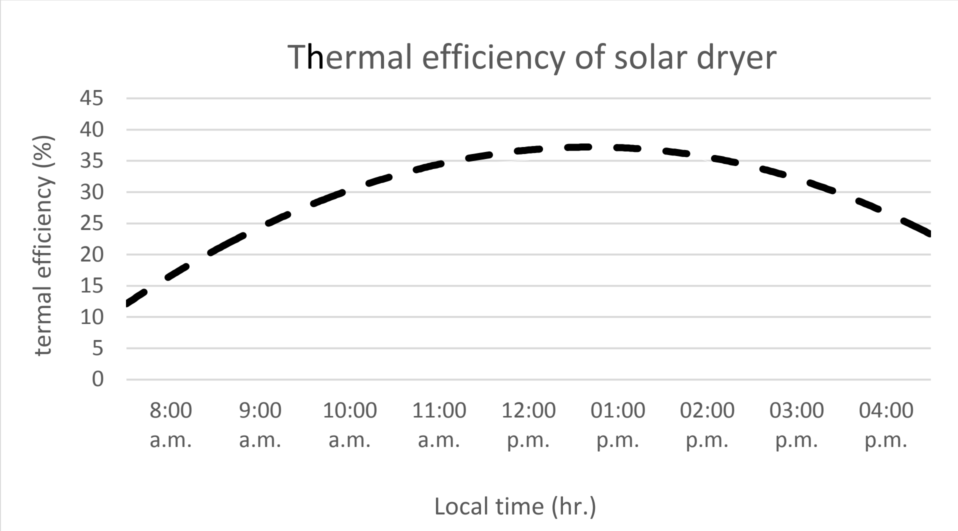

Fig. 7 Variation of thermal efficiencies (collector)

Local time	08:00 a.m.	09:00 a.m.	10:00 a.m.	11:00 a.m.	12:00 a.m.	01:00 p.m.	02:00 p.m.	03:00 p.m.	04:00 p.m.
Solar radiation (W/m2)	354.8	421.70	478.5	528.2	559.7	561.5	560.8	531.6	487.50
Average ambient temperature. T_{am} (°C)	29.8	32.8	35.9	37.3	39.2	40.5	39.4	37.7	36.3
Average temperature. (°C) inside dryer	37.8	44.7	51.7	56.6	60.7	67.7	60.8	54.8	48.7
%R.H. ambient outside dryer	53.3	48.4	45.3	40.6	37.7	35.9	39.8	46.6	55.5
%R.H. in dryer no load test	31.3	27.2	25.4	22.3	20.5	18.7	21.4	22.8	25.5
Average temperature. (°C) inside dryer test with load	27.2	28.1	29.4	30.3	32.4	36.2	32.6	30.2	28.3
Average moisture removed (test with load) ; kg/hr.	0.083	0.147	0.272	0.399	0.577	0.933	0.711	0.351	0.198
energy of dry air ; J/s	71.62	124.53	178.77	218.60	238.58	270.88	237.50	201.45	160.44
Volume of dry air in dryer ; m^3/s	0.03267	0.03705	0.04044	0.04254	0.04366	0.04544	0.04363	0.04169	0.03932

Table 3 Evaluation performance of solar dryer according to standard steam table/psychometric chart and test with product

Test with load (banana fruit)

Compering the evaluation of mass flow rate between no load (maximum absorb moisture) and with load in order to verify performance all information, Experiments ginger slices were dried and the results obtained in drying a ginger slices sample, are shown in Figure 8, It was observed that banana fruit products in dryer can be dried faster at around 01:00 p.m., testing were carried out drying of banana fruit 25 kg similar condition no load items. The drying spent drying time about 41 hours, beginning 80% was reduced to 15 % wet basis[15] conditions. Weight loss or moisture rate between 0.083 and 0.933 kg/hr. according to Table 3.

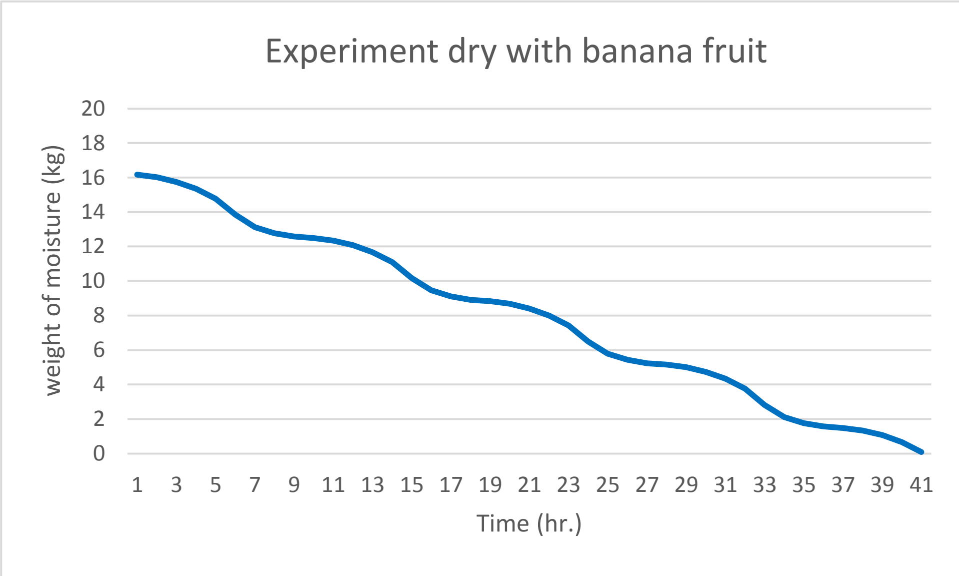

Fig. 8 Variation of moisture removed out of solar dryer curve front shape

IV. Conclusions

The solar dryer's curve front process saves energy, time, occupies less drying area, improves product quality, it is very environment friendly and will enhance energy conversion. Both equation and experiment, simultaneously to ensure the utilization Fig.8 variation of experiments banana fruit drying. Table 3 Evaluation performance of solar dryer according to standard steam table/psychometric chart and test with product of drying system. A simple mathematical formulation was applied to evaluate the indirect passive solar dryer. In this design and experiment

Practical way of comfortable movement, cheaply and sanitarily preserving fruit and vegetables, design and test system use drying and had been demonstrated. It of the dryer does not require high technology and the maintenance cost is minimal. During the test, solar dryer had operated satisfactorily five hours between 10:00 a.m. and 01:00 p.m. local time, because of generated higher energy and performance effective transmittance of dryer (polycarbonate) lead to higher efficiency. The experiment has provided useful information in drying process design for food, fruits, herbs, vegetables and more agriculture which can assist in preservations. The dryer was tested and the following conclusions results obtained:

Maximum temperature of solar dryer's curve front shape was Table1, 3 (inside dryer) which interest is the temperature obtained in the prototype solar dryer, it optimum for drying fruits and vegetables. Heat transfer coefficient natural convections are found to be average approximately 4.7 $W/m^{2}{}^{\circ}C$ obtained for buoyancy condition. Similar condition no load items. The experiment also revealed the weight of banana fruit decrease dependence on solar radiation and temperature through the system, the testing spent drying time about 41 hours (08:00 a.m. - 04:00 p.m.), removed moisture of dryer. (weight banana fruit loss) energy saving 2610 W and carbon dioxide CO_2 emission approximately 1.51 kg/day compere with electric oven.

Improvement in efficiency more than this design can add up solar collector or other renewable heat source utilized drying continuous during off-sunshine and the night time or rainy.

Acknowledgements

The research team would like to thank the Expert Center of Innovative Health Food, [innoFood] Thailand Institute of Scientific and Technological Research (TISTR) for supporting the budget, place, tools, and equipments for this research.

Nomenclature

Nu	dimensionless	Nusselt Number
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
v	m/s	Velocity of air
δ	m	Boundary-layer thickness
μ_v	kg/m.s	Dynamic viscosity
L	m	Length
C_v	kJ/kg˚C	Specific heat of dry air, at constant pressure
C_{pw}	kJ/kg˚C	Specific heat of moisture 1.97 , at constant pressure [8]
K_v	W/m˚C	Thermal conductivity
T_i	°C	Temperature inside dryer
E_i	W	Solar energy
E_o	J/s	The rate of energy collection
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
T_{am}	°C	Ambient temperature
V_a	m^3	Volume of dry air
V_w	m^3	Volume of vapors
m_a	g	Mass of air
P	Pa	Pressure
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
h_c	$W/m^2 °C$	Convective heat transfer coefficient

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