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Thermal evaluation of a mixed tunnel-type solar dehydrator under different operating conditions

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Introduction

The economic and social development of countries depends on energy resources and in this sense, Mexico has a great potential in terms of the use of alternative energies; such is the case of solar energy. Despite some barriers, it has been predicted that renewable energy technologies are a suitable strategy for food drying that brings some benefits such as low cost, high efficiency, increased employment opportunities, etc. (Poggi et al., 2018).

In tropical countries, the drying of agricultural products has conventionally been carried out in the open sun drying. The disadvantage of open sun drying is the uncontrolled heat transfer to the produce and slow drying speed, as well as losses due to fungi, insects, birds, rodents, unexpected rains and other meteorological effects. As a result, the quality of the products is very poor and they cannot compete in the international market (Lakshmi et al., 2019).

Methodology

In this work, the thermal evaluation of a mixed tunnel type solar dryer was carried out under different operating conditions. The tests were carried out in the month of february, 2023 from 10:50 to 14:50 h (it is worth mentioning that there are two hours before and after solar noon, which was at 12:50 h). Measurements of temperature and solar irradiance, humidity and the inlet mass flow were taken every minute, while air velocity measurements at the outlet of the dryer were taken every 15 minutes.

Figure 1 Measuring instruments

Tunnel type solar dehydrator

The tunnel type solar dryer consists of four solar air heaters connected in series (each one with an area of 1.8 m^2, total array area 7.2 m^2), they are connected to a 550 W direct current fan that work with a photovoltaic array of two panels of 315 W, which sends the hot air from the solar collector array to the interior of the dryer (Figure 2).

Figure 2 Tunnel type solar dryer

Tunnel type solar dehydrator

The drying chamber is made of 1" steel profiles and has 6 mm polycarbonate cover on the walls allowing direct solar radiation to enter the chamber, so the heat gains inside the dryer are a combination of the heat gained by the solar collector array plus the solar irradiance entering directly through the polycarbonate. The tunnel type drying chamber length is approximately 5.50 m, and it has a capacity for 40 aluminum trays of 63 cm x 43 cm.

Figure 3 Drying chamber

Instrumentation

Instrumentation used for the measurement of different variables:

Quantity	Measuring instrument	Accuracy
6	Temperature PT1000	±0.5°C
2	Pyranometer kipp & zonen	±2%µ/w/m^2
1	Volumetric flowmeter Sierra Quadra Therm	±1% Nm^3/h
1	Air velocity meter Extech	±5% m/s
4	Omega humidity sensor	±5%RH
1	Digital balance Ohaus	±0.01 g
2	PYREX 500 ml beaker	±5% ml

The location of sensors is shown in the following figure:

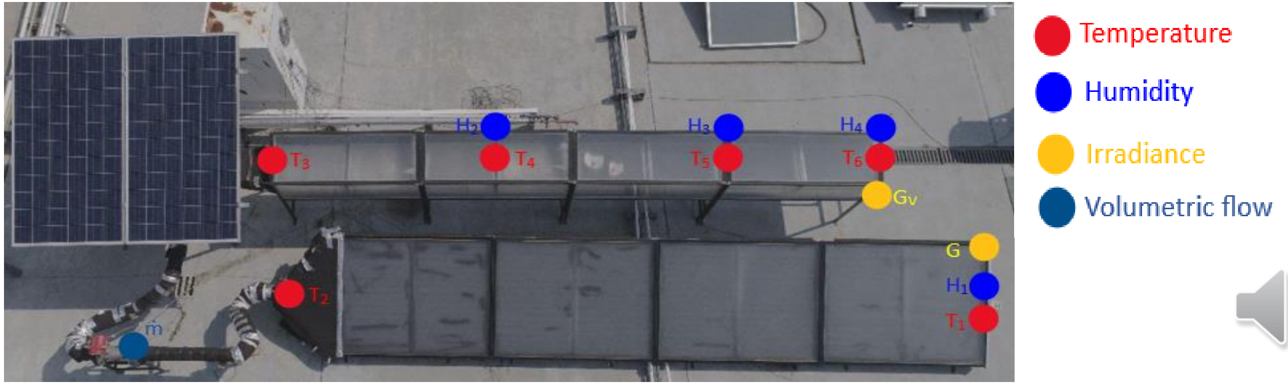

Figure 4: Temperature, humidity and air volumetric flow sensor locations

Experimental tests

Two different tests were carried out in the tunnel type solar dryer in order to evaluated the system thermal performance. The first four ones were from 10:50 h until 14:50 h. Each test was carried out at different fan velocity (different air mass flow rate). Temperatures, solar irradiance, air mass flow rate and humidity were measured. In the tests of water evaporation, the dryer was filled with 20 trays with a volume of 500 ml of water, having an initial volume in the tunnel type solar dryer of 20 liters.

Figure 5 Water trays

Experimental tests

The instantaneous thermal efficiency of the solar collector array was determined by equations (1).

$$\eta_{col} = \frac{\dot{Q}_{air\ cole}}{\dot{Q}_{sun}} \quad (1)$$

$$\dot{Q}_{air\ cole} = \dot{m}Cp(T_6 - T_3) \quad (2)$$

$$\dot{Q}_{\mathrm{sun}} = GA \quad (3)$$

Where: ṁ is the air mass flow rate (kg/s), Cp is the specific heat of air at constant pressure (J/kg K), G is the instantaneous solar irradiance at the solar collector plane (W/m^2) and A is the gross solar collector array area (m^2).

Experimental tests

The drying efficiency was calculated with equations (4), and the total insolation with equation (9).

$$\eta_{sec} = \frac{Q_{water}}{Q_{sun} + Q_{tunnelPo1} + Q_{tunnelPo2} + W_{fan}} \quad (4)$$

$$\dot{Q}_{water} = m_T Cp(T_{eva} - T_{initial}) + m_e L \quad (5)$$

$$\dot{W}_{fan} = IVFt \quad (6)$$

$$\dot{Q}_{tunnelPo1} = G * A_{ss} \quad (7)$$

$$\dot{Q}_{tunnelPo2} = G_v * A_{sv} \quad (8)$$

$$Total\ insolation = [(G * (A_c + A_{ss})) + (G_v * A_{sv})] * t \quad (9)$$

Where: m_T is the total mass of water (kg), T_{eva} is the evaporating temperature (°C), $T_{initial}$ is the initial temperature of the water (°C), m_e is the mass of evaporated water (kg), L is the water latent heat of evaporation (J/kg), I is the electric current (A), V is the voltage (V) of the fan and F is the performance factor of the fan motor, G is the solar irradiance at the collector plane (W/m^2), A_{ss} is the top cover area of the tunnel dryer (m^2), G_v is the vertical solar irradiance (W/m^2), A_{sv} is the vertical cover area of the tunnel dryer (m^2), and t is the time (s).

Experimental results

Experiment results using fan at 4000 rpm (0.069 kg/s).

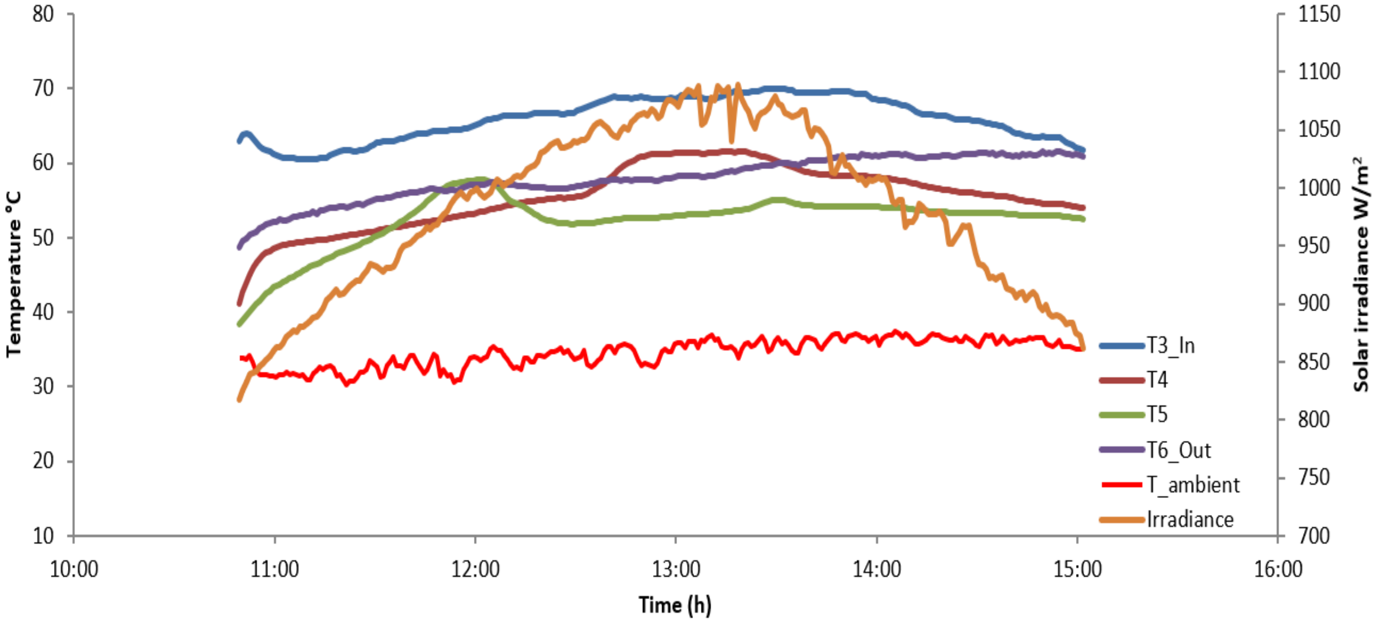

Figure 6 Temperature and solar irradiance measurements

Experimental results

Experiment results using fan at 4000 rpm. The average instantaneous thermal efficiency of the solar collector array was 0.46 (46 %)

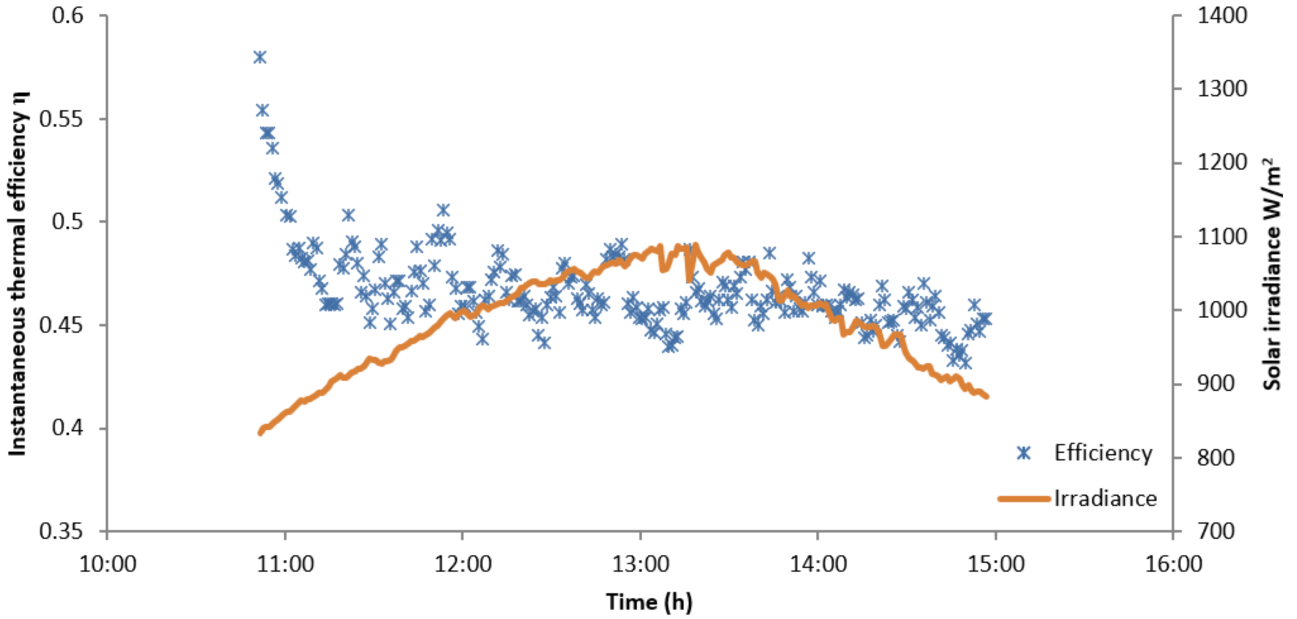

Figure 7 Instantaneous thermal efficiency of solar collector array

Experimental results

To be able to clearly have the distribution of trays in the dryer. The numbers 1 to 8 represent the doors of the drying tunnel, number 8 being the closest to the hot air inlet of the solar collector array and the row with the numbers 1 to 5 represent the vertical position of the trays.

Figure 8 Distribution of trays in the drying tunnel

Experimental results

At the end of the test, the water contained in each tray was measured to see how much water was evaporated. The values obtained in ml can be seen in Table 1. A total of 11.6 l were evaporated (58 % of the total water deposited at the beginning) , and the tunnel type drying efficiency obtained was 16.04 %

Table 1 Evaporated water in ml in each tray. Total insolation: 161.9 MJ. Average relative humidity: 16.4 % Average T_{amb} of 31.4°C.

	1	2	3	4	5	6	7	8
1	476	491	500	500	500	500	500	500
2	217	155	173	186	240	262	331	490
3	130	117	163	182	213	224	426	500
4	134	106	149	174	200	203	283	385
5	172	153	175	210	213	237	347	500

Experimental results

Experiment using fan at 3000 rpm (0.054 kg/s).

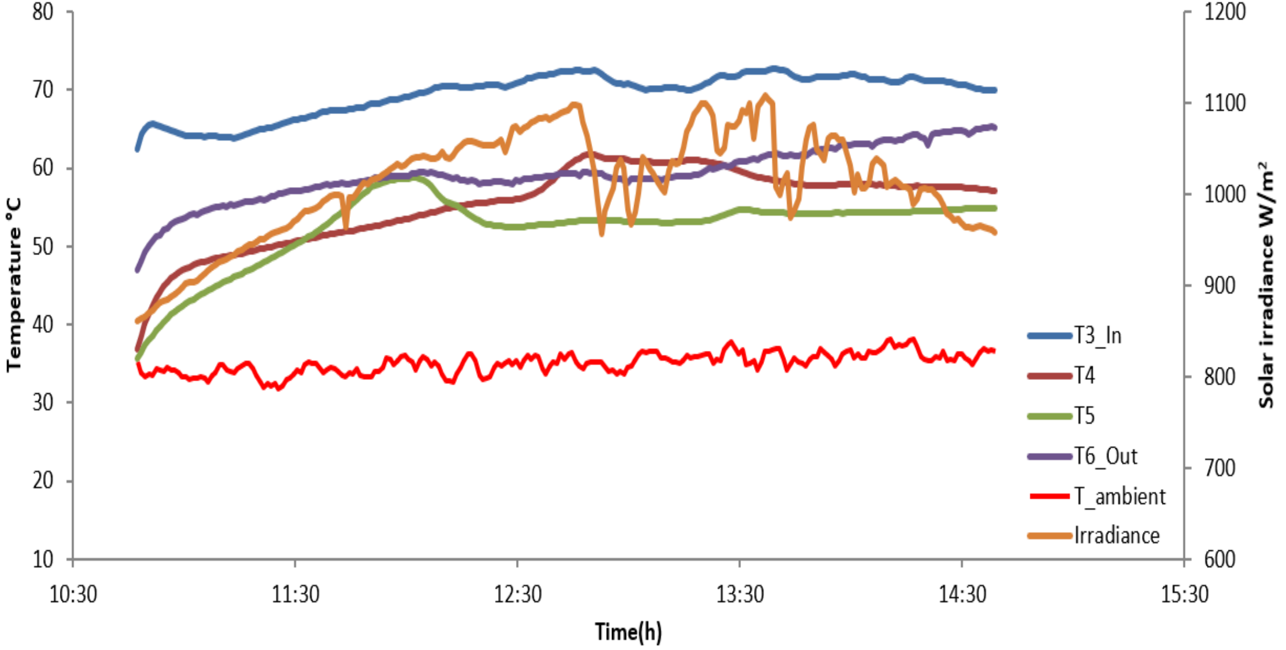

Figure 9 Temperature and solar irradiance measurements

Experimental results

Experiment using fan at 3000 rpm. The average instantaneous thermal efficiency of the solar collector array was 0.42 (42 %)

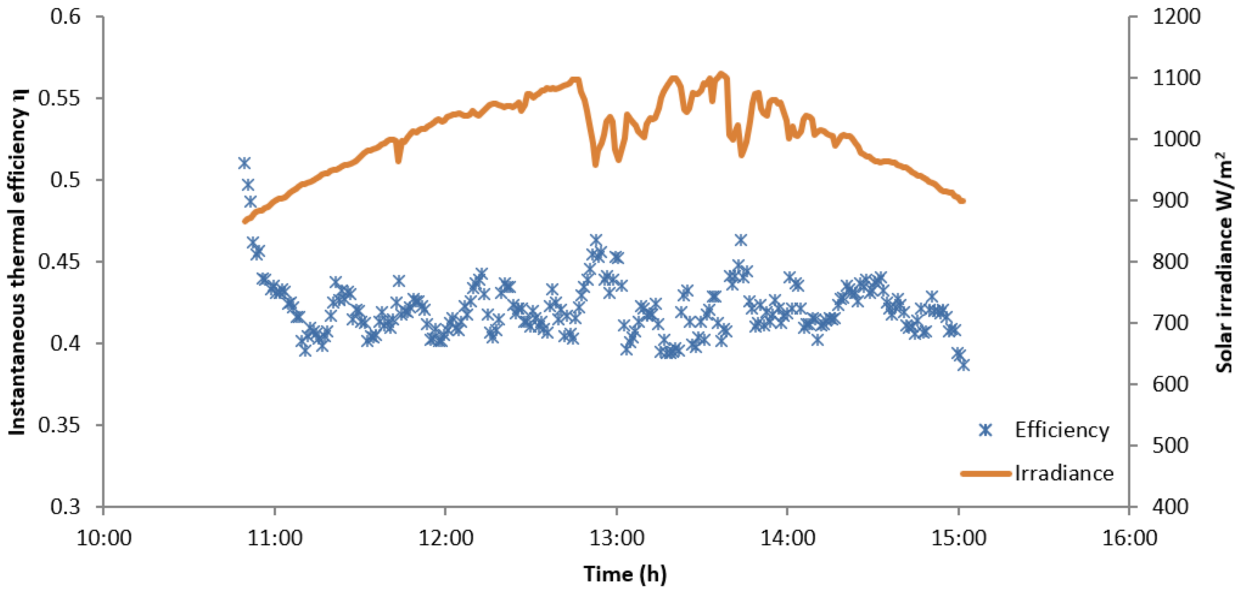

Figure 10 Instantaneous thermal efficiency of solar collector array

Experimental results

At the end of the test, the water contained in each tray was measured to see how much water was evaporated. The values obtained in ml can be seen in Table 2. A total of 11.7 l were evaporated (58.5 % of the total water deposited at the beginning) , and the drying efficiency obtained was 15.78 %

Table 2 Evaporated water in each tray in ml. Total insolation: 166.1 MJ Average relative humidity: 10.9 %, average Tamb of 31.5°C

	1	2	3	4	5	6	7	8
1	495	490	500	500	500	500	500	500
2	217	179	206	218	243	266	356	500
3	110	152	136	178	206	251	411	500
4	129	129	128	164	205	186	295	439
5	125	149	157	200	209	245	353	500

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Experimental results

Experiment using fan at 2000 rpm (0.035 kg/s).

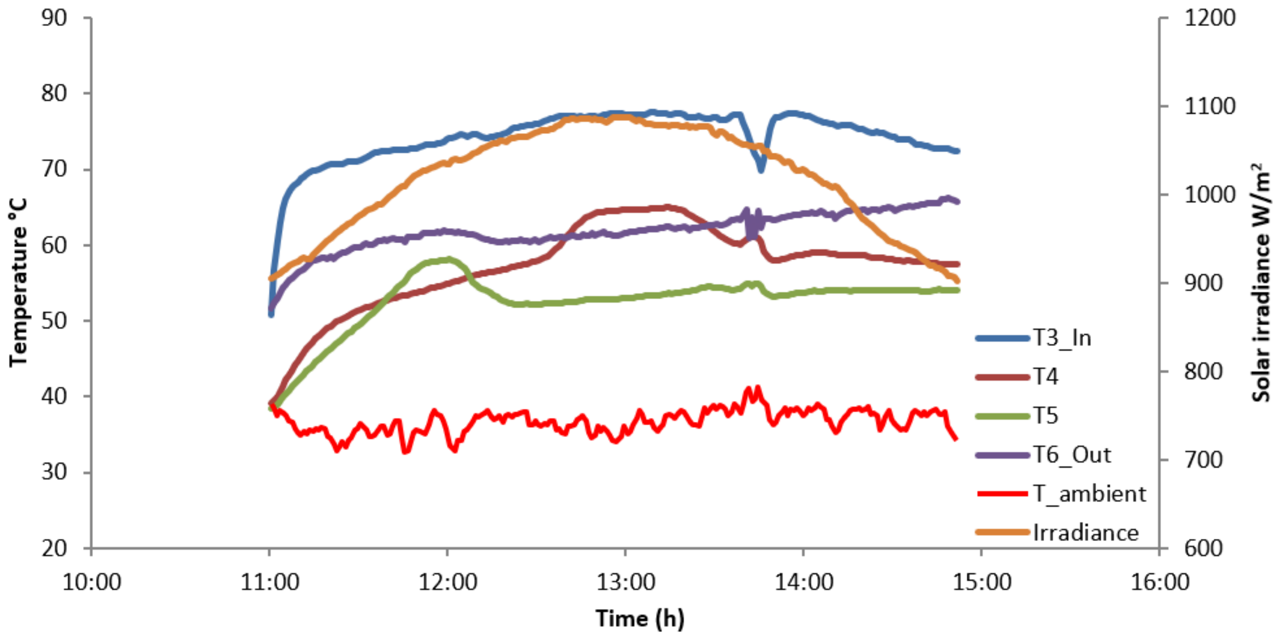

Figure 11 Temperature and solar irradiance measurements

Experimental results

Experiment using fan at 2000 rpm. The average instantaneous thermal efficiency of the solar collector array was 0.33 (33 %)

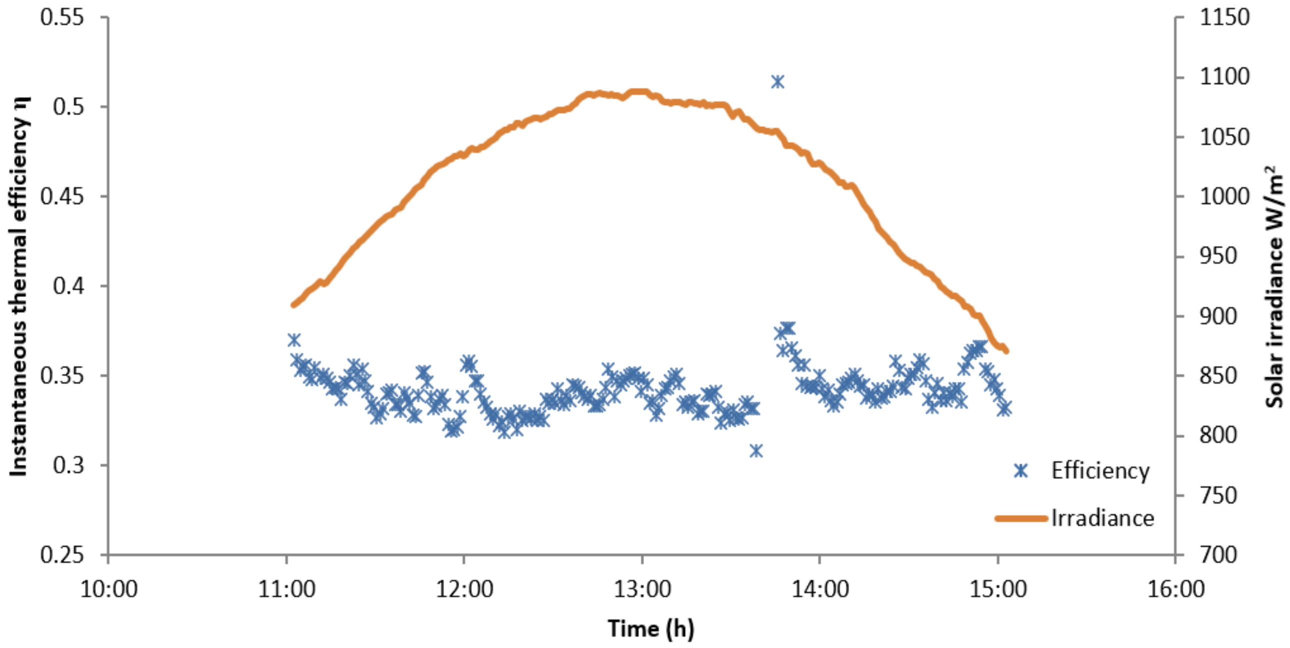

Figure 12 Instantaneous thermal efficiency of solar collector array

Experimental results

At the end of the test, the water contained in each tray was measured to see how much water was evaporated. The values obtained in ml can be seen in Table 3. At total of 10.3 l were evaporated (51.5 % of the total water deposited at the beginning) , and the drying efficiency obtained was 14.64 %

Table 3 Evaporated water in each tray in ml. Total insolation: 159.2 MJ Average relative humidity: 10.4 %, average Tamb of 31.3°C

	1	2	3	4	5	6	7	8
1	471	494	500	500	500	500	500	500
2	164	153	158	176	178	215	276	464
3	73	109	122	154	163	205	335	500
4	80	102	108	145	160	180	200	366
5	100	120	133	159	165	210	297	441

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Experimental results

Experiment with natural convection (without fan and solar collector array).

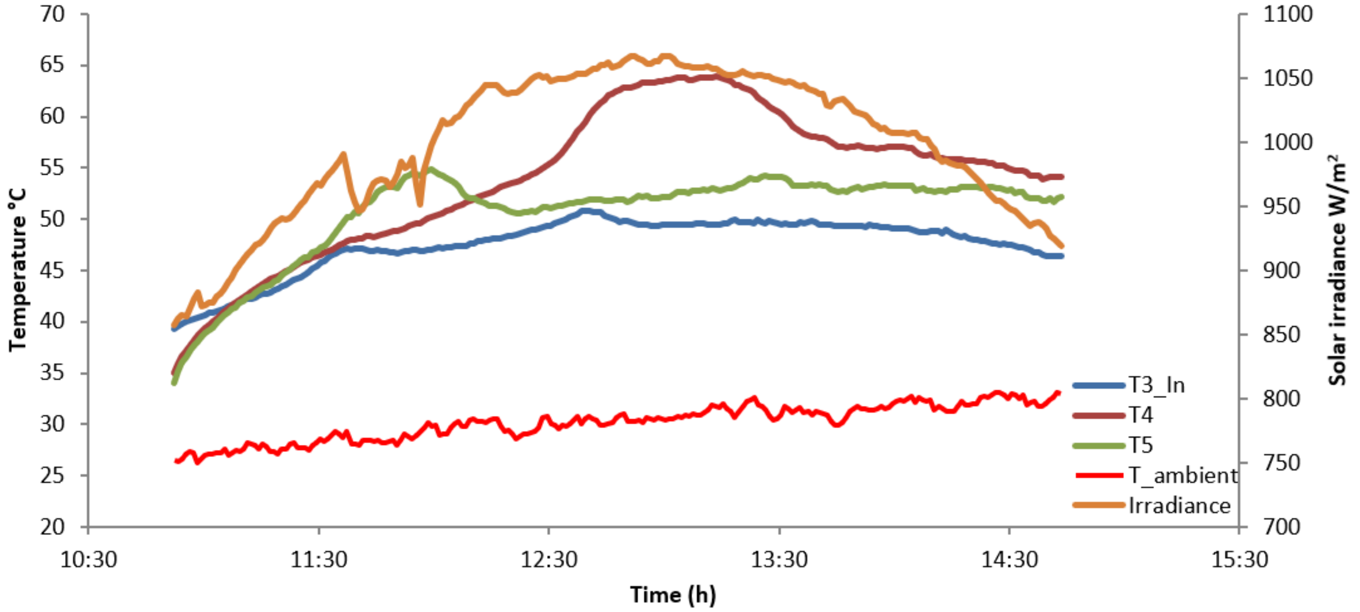

Figure 13 Temperature and solar irradiance measurements

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Experimental results

At the end of the test, the water contained in each tray was measured to see how much water was evaporated. The values obtained in ml can be seen in Table 4. A total of 6.3 l were evaporated (31.5 % of the total water deposited at the beginning) , and the drying efficiency obtained was 9.64 %

Table 4 Evaporated water in each tray in ml. Total insolation: 160.4 MJ Average relative humidity: 13.3 %, average Tamb of 30.4°C

	1	2	3	4	5	6	7	8
1	445	466	469	461	456	476	476	489
2	118	75	102	109	93	86	90	108
3	67	63	73	86	79	52	69	77
4	48	65	62	90	70	56	82	69
5	74	71	88	93	82	100	81	110

Chilacayote drying test

The chilacayote is a type of pumpkin, from the cucurbitaceae family. The word chilacayote comes from the Nahuatl word tzilacayotli: "tzilac", which means smooth, and "ayotli", which means pumpkin. In other words: smooth pumpkin. It is a source of vitamin A, vitamin C and iron. Moreover, from a medicinal point of view, this fruit has been related to hypoglycaemic properties (lowering of blood glucose) (Bautista R.,2020).

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Figure 14 Tunnel drying kinetics

Chilacayote drying test

Chilacayote drying test was carried out by filling the dryer with 300 grams (±20 grams) of chilacayote in 5 mm slices in each tray, giving a total of 12 kg of chilacayote to be dried. The test was obtained for fan speeds of 4000 rpm and 2000 rpm. Three drying kinetics of Chilacayote were obtained for each different speed (one drying kinetic at the beginning (C_{start}), in the middle (C_{half}) and at the end (C_{end}) of the tunnel as shown in Figure 15).

Figure 15 Position of the Chilacayote samples in the tunnel

Drying kinetics results of Chilacayote

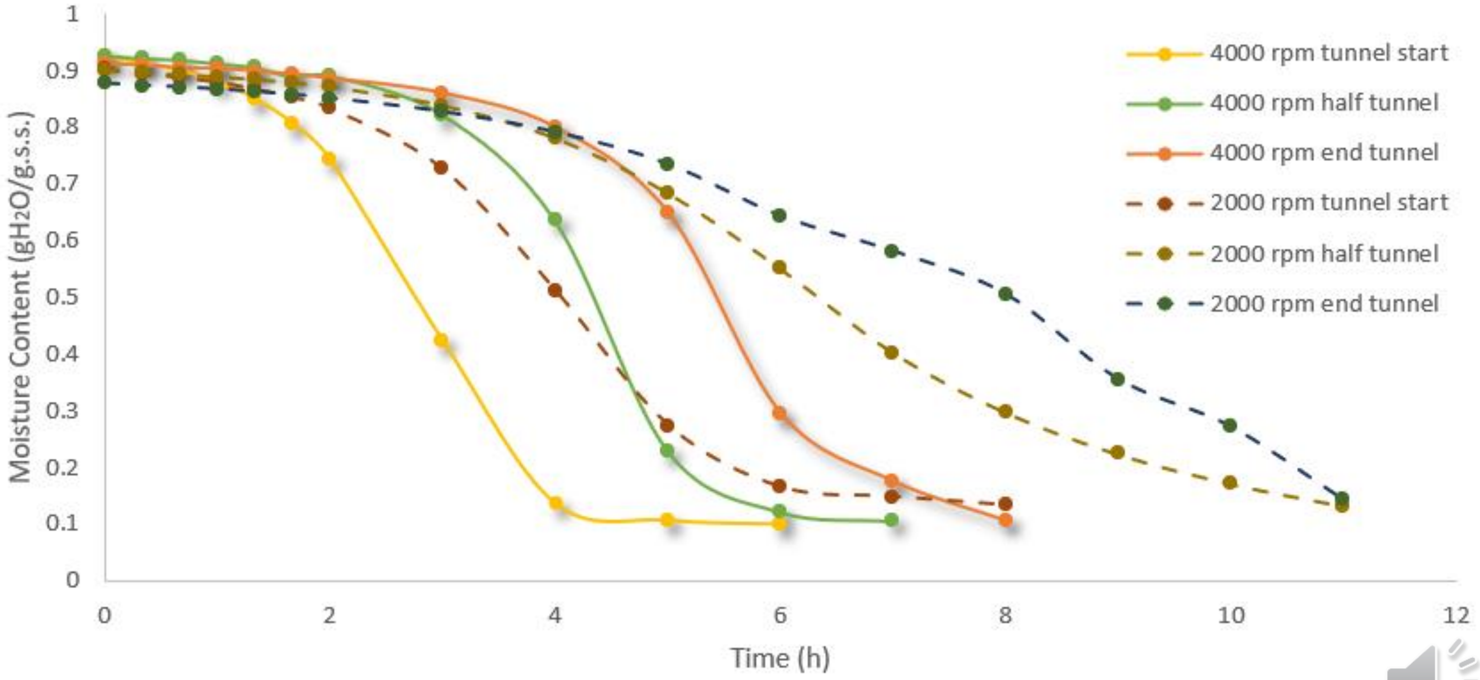

Figure 16 Chilacayote drying kinetics with the fan at 4000 rpm and 2000 rpm.

Chilacayote drying test

At the end, the dried product was made into flour. The drying efficiency obtained for the drying of Chilacayote at 4000 rpm was 9.56 % and for the tests at 2000 rpm it was 5.04 %. Efficiency at 2000 rpm dropped by almost 50 % due to less airflow within the system and the lower mass and heat transfer coefficients that result from this.

Figure 17 Dried chilacayote and flour produced

Conclusions

- In the tests with water, the amount of water removed in 4 hours with the fan at 4000 rpm was 11.6 liters (58.1 % of the total water deposited at the beginning). An average instantaneous solar collector array efficiency was 46 % and the drying efficiency obtained for the tunnel type solar dehydrator was 16.04 %.

- By counterparty, in test with water in natural convection (without fan and solar collector array), the amount of water removed was 6.3 liters (31.5 % of the total water deposited at the beginning). The drying efficiency obtained was 9.64 %.

- The drying kinetics of the Chilacayote coincides with the behavior of the dryer in the test with water. The final moisture content of the Chilacayote was 10.8 % with the fan at 4000 rpm and 8 hours of drying obtained a drying efficiency of 9.56 %. For 2000 rpm final moisture content of 13.53 % was obtained with 11 hours of drying and drying efficiency of 5.04 %.

- A tunnel type solar dehydrator was designed, built and evaluated in Temixco, Morelos for dehydration of agricultural products. According to the results obtained, different kind of products can be dried resulting in substantial fuel savings and environmental benefits.

References

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