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Pineapple drying using a new solar hybrid dryer

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Abstract

This paper presents the results of an experimental pineapple (***Ananas comosus* L.**) drying study in a new solar hybrid dryer. The dryer is a direct and integrated type, with a black mate pan which measures 1.675 x 0.61 x 0.055 m (1.02 m^2). It uses a copper helical tube that conducts hot water, at 80°C, generating extra heat for the drying process; the tube is located at the bottom of the black pan. A caliber 6, transparent vinyl film is used as a cover and the walls and base of the dryer are isolated by 0.0254 m thick fiberglass. It is inclined 23° south and uses pump to recirculate water. The variety of pineapple used was honey, 1/4 of grown age. Each slice was 0.005 m thick, resulting in a mass density of 2.83 kg/m^2 in the drying trays area. To be able to have useful comparisons, drying tests were performed during winter and spring of 2013, using both the hybrid dryer and the traditional solar dryer. Results showed that when initial humidity between pineapples is quite similar (this being one of the most influential factors in changing efficiency, time and other important process variables), evaporation efficiencies are higher in the traditional process; such efficiencies ranging between 22.7% and 24.0%; while the efficiency of the hybrid dryer ranges between 9.3% and 14.0%. This is basically due to the increase of energy loss when using both sunlight and heated water. On the other hand, the time the process took to reach the humidity goal (24.0% humid base or 0.32 dry based) was much faster when using the hybrid dryer. This dryer ended the process in a range of 6.0 to 6.8 hours while the traditional solar process took between 8.0 and 8.8 hours. It is also important to note that the final process was basically homogeneous throughout the dryer, especially when the drying trays on the top end of the dryer were placed 0.03 m further away from the top, and produced a fine quality product with only slight discoloration of the pineapples' side which faced the sun.

Keywords: solar hybrid dryer; direct and integrated dryer; evaporation efficience, LP gas, hot water

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1. Introduction

This paper is a continuation of studies presented at previous Asociación Nacional de Energía Solar de Mexico (ANES) congresses. The first dealt with pineapple drying curves [1], followed by a paper on pineapple drying using a direct solar integrated dryer [2] and a third about pineapple drying this time using an indirect solar integrated dryer [3]. For these papers, a thorough bibliographic research was conducted about the international and national panoramas on pineapple production and the state of the art on solar drying technology.

Studying these dryers, which worked only on solar radiation, it was evident that they had a very good performance; they were also practical, low cost and easy to handle. These are some of the reasons that they are still being studied and improved in order to provide better options to agro-alimentary producers, which require better ways to preserve their products year-round and have some type of added value.

Nomenclature

A_b	Bottom position
A_c	Collector area, m^2
A_{prec}	Pre-warming area, m^2
A_r	Top position
Ap_e	Aperture at dryer's entrance, fraction
Ap_s	Aperture at dryer's exit, fraction
E_{gas}	LP gas' Energy input, kJ
E_{Sol}	Sun's Energy input, kJ
H_i	Hybrid operation mode
H_t	Total sunlight radiation, kJ/m^2
M_o	Initial moisture content wet basis, water kg / sample kg
M_f	Final moisture content wet basis, water kg / sample kg
m_{H_2Oevap}	Evaporated water's mass, kg
m_{gas}	Consumed gas' mass, kg
S_o	Solar operation mode
T_p	Entrance and exit mean pineapple temperature, ºC
t	Total drying time, h
v	Wind speed, m/s
X	Humidity content dry basis, water kg / dry solid kg
η_{evap}	Water vaporization efficiency, %

Among the great diversity of papers and practical-theoretical studies related to solar drying worldwide, some have used dryers which incorporate thermal storage of solar energy using rocks or water. This stored energy is later used when there is no solar radiation available (night or cloudy days). Other studies use a photovoltaic cell to power up a fan which removes moist air inside the dryer. Finally, some have studied the possibility of hybrid dryers; their purpose is to complement solar energy with a conventional energy source (biomass, electricity, LP gas) with the intention of having a better drying process, making it continuous and even useful during nights and cloudy days [4] where an unfinished drying test could be concluded or a new process begin.

Both Benon and Fuller [5] and Madhlopa and Ngwalo [6] studied the operation of an indirect integrated solar dryer which used biomass incineration energy as a backup for a pineapple drying process. These authors report that the system was able to maintain a continuous drying process, including nighttime and days without solar radiation incidence; moisture removal efficiency and general performance proving satisfactory.

Boughali and collaborators [7], report the study of an active (forced convection) indirect solar-electric hybrid dryer used for tomato drying. This dryer worked at different temperatures and a high range of mass flows throughout the dryer (0.04 to 0.08 kg/m^2); they found that temperature has a greater influence than wind speed and it is better to use small air flows for the tomato drying process. They also compared different think layer drying models concluding that the Middli model was best used for this process. Additionally, the economic study showed that return of investment period was only 1.7 years with a 15 year lifecycle estimated for the product.

There are two companies that use of LP gas as a second energy source in Mexico: SAECSA, Solar energy [8] and BRECTO, Solar Engineering [9]. The products they distribute use a drying chamber where heat is provided by a thermic radiator through which hot water runs, this water gets its temperature from a solar heater before it runs through a LP gas boiler. This last step is to ensure that water running into the drying chamber is warm enough to carry out the process even if there is not enough solar radiation.

There are also studies focused specifically on the thermic performance of solar air collectors used in drying systems that operate under either forced convection or natural convection. Following this line of study there is a practical-theoretic work related to the hybrid dryer discussed in this paper [10]. Such study used the mathematical model presented by Duffie and Beckman [11] which used individual equations in order to determine heat transfer coefficients by radiation, convection and conduction to have a configuration similar to the mentioned air solar collector. With these coefficients and a complete energy balance it was possible to determine both the total heat loss coefficient and the heat removal factor; these are used to determine the available heat acquired by the collector at some determined instant and then the instant efficiency. The study shows characteristic, theoretic and experimental performance curves from the collector, showing concurrence between these. In this works case, energy for the process was exclusively obtained from the LP gas commercial boiler which heated water circulating through a helical tube, while energy used to obtain different temperatures for entry air was obtained through electrical resistance.

Clearly there is a vast interest in the scientific community to study drying processes and thermic behavior of solar collectors for air heating. There have also been efforts to improve such processes using conventional energy sources. Under this context, and taking into account the positive results of previous work with this type of dryer, the present paper's objective was to study the thermic performance of the new hybrid dryer during a pineapple drying process. In order to do this, the hybrid dryer using LP gas as a secondary energy source is compared to the same dryer operated using only solar energy. The final goal of the study is to improve the direct integrated solar dryer's design which has been presented in diverse forums and used for a variety of food products [2] [12] [13]. Specifically, improving the ability of the dryer to generate a dry product, without depending on the availability of solar radiation is the aim of this work.

2. Experimental

Eight pineapple drying tests were carried out using the new solar hybrid dryer: 2 used only solar radiation while 6 operated in hybrid mode using both solar energy and LP gas. These tests were performed at ITESO University's solar area, located in Tlaquepaque, Jalisco, Mexico. The experiments took places during both winter and spring of 2013, from February 21^{st} to May 31^{st}. Every test started between 9 a.m. and 10 a.m. in order to start out with sufficient solar radiation.

For the dryer to permit a air's natural convection effect within it, it always operated with a 23° inclination facing South; it used entry and exit one half apertures (Ap_e=Ap_s=1/2). Aperture indicates the free height fraction of the dryer's total height (0.07m), meaning the aperture is 0.035 m of free height.

The variety of pineapple used was honey pineapple; it had approximately one fourth of grown age and was obtained at the local market. Each pineapple slice was 0.005 m thick which produced a density of 2.83 pineapple kg/m^2 of tray area.

2.1. Procedure

During each test, the first steps consisted of washing, skinning and slicing the pineapple. Immediately after this, each of the 3 trays used in the dryer were loaded until a total mass of 0.850 kg/tray was achieved. Mass variation through moisture loss was monitored at the entrance and exit of the dryer using small sampling trays where the pilot product sample of 0.151 kg was placed on each tray. As a final moisture goal, 0.24 on wet basis (0.32 dry basis) was set in order to conclude each test. The small trays were identified as "1" for entry and "2" for exit positions on the dryer. It is noteworthy that in previous studies, the moisture goal as 0.18 on wet basis; for this work the goal was changed in order to have both the hybrid and the solar tests finish in only one day, which reduced variations related to environmental and other drying conditions. Initial pineapple moisture was determined according to Mexican norm NMX-F-83-1986.

The previous hybrid dryer study [10] showed that the dryer's performance may be altered if the temperature readings at the exit are taken too far inside or too far outside the dryer; during the current work, the first two tests were done with the trays placed all the way to the top of the dryer. Because of this, one of the small sampling trays was right on the edge of the system. For the last 6 tests, this changed, the trays were moved inwards; this way the top sampling tray was 0.03 m away from the edge.

Measurements were recorded throughout the whole test in 1 hour intervals. These intervals included recordings of mass changes in the small sampling trays and solar radiation. The rest of the recorded variables were recorded continuously, these included: ambient relative humidity and temperature, air temperature and relative humidity at the entrance and exit of the system, pineapple temperature and wind speed. Mass change was recorded as fast as possible, to avoid errors, due to the fact that this was measured outside the system, where the environmental conditions could alter the controlled drying process. To further avoid this situation, during the last three tests, longer intervals were used between measurements.

When the dryer was operated in hybrid mode, the hot water input started at 11:00 a.m. First, the boiler and the water pump were turned on, all traces of air were purged out and a hot water flow was established at 3 l/min. After this temperature was constantly monitored and the right amount of gas was regulated so that water temperature stayed at 80°C. In every hybrid case, water input started at the top of the dryer, going against the air flow which, by natural convection, entered at the bottom part of the dryer and moved upward.

2.2. Dryer characteristics

The hybrid dryer used is of the direct and integrated type and it is constituted by a black mate pan of 1.675 x 0.61 x 0.055 m which represents a collector area (A_c) of 1.02 m^2. It uses a transparent vinyl caliber 6 cover and a copper helical flexible tube (radiator) with a diameter of 0.0127 m placed at the deep bottom of the dryer. It is through this radiator that the heater water (heated by LP gas) flows to transfer heat to the drying air (figure 1(a)). This radiator is the main difference between the new dryer and the previous solar designs. The tube is fixed, using thin welded plates which hold it to the absorbing plate, throughout the base of the dryer. Space between the tubes is 0.08 m. The first 0.175 m, through the long side of the dryer, are used as a pre-warming area (A_{prec}=0.11 m^2) when the trays were placed towards the top of the dryer, when the trays were 0.03 m towards the middle of the system, the pre-warming area was A_{prec}=0.089 m^2 (0.145 m long). The remaining dryer area is used to place 3 trays made from an aluminum frame and a polypropylene net measuring 0.5 x 0.6 m each where a single layer of drying product is placed (figure 1 (b)) to receive direct sunlight. Its lateral walls and its base are insulated with 0.025 m thick fiber glass. The dryer has a 23° slope to permit the air's natural convection.

(a) (b)

Fig. 1. Hybrid dryer: (a) without product; (b) during pineapple drying process

2.3. Measurement instruments and equipment

The following measurement instruments were used: Mettler Toledo analytical scale PG-S model to measure mass changes, Sartorius electric humidity analyzer MA-45 model to determine initial moisture, Tor-Rey vegetable processor for pineapple slicing, Kipp and Zonen pyranometer C3 model and solar radiation system CC20 model for solar measurements.

The rest of the equipment which constitutes the system and enables this study are: Bell and Gossett circulatory hot water pump NRF-22 model, Blue and White polysulfone flow-meter 0.5 to 5 LPM, type T calibrated thermocouples, Measurement Computing USB-TC 8 channel recorders which directly sent the measurements to a PC at a 2 measurement per second rate, digital thermo-hygrometers USB-500 to measure relative humidity and air temperature and finally diverse valves and connections to regulate a water flow of 3 l/min.

2.4. Thermal operation

The dryer's thermal operation was mainly evaluated by its evaporation efficiency's calculation and elaborating drying curves. Evaporation efficiency is defined as the quotient of energy required to evaporate water from the pineapple and the total energy input of the system be it by only solar energy or a combination of LP gas burning.

The enthalpy value of evaporation was calculated from an average pineapple temperature. The drying curves show the change in humidity in dry basis (X) as drying time (t) runs and provide information on how fast and homogenous the drying process is.

3. Results and discussions

The main results obtained from all 8 tests are shown in tables 1 and 2. Table 1 shows initial moisture content wet basis (M_o), average wind speed (v), tray positions: upwards (A_r) and downwards (A_b), average pineapple temperature (T_p) and total drying time (t). Table 2 shows: vaporized water mass ($m_{H2Oevap}$) which is the difference between initial and final pineapple mass, consumed gas mass when operating in hybrid mode (m_{gas}), gas input energy (E_{gas}) which is calculated by multiplying consumed gas by its calorific power (49948.5 kJ/kg), received sunlight (H_t), solar energy input (E_{Sol}) obtained by multiplying sunlight by the collector's area, and vaporization efficiency (η_{evap}). Both tables show test date and operating mode (Op. mode): solar (S_o) or hybrid (H_i).

Table 1. Total amount of time required to reach the goal moisture content M_f=0.24

Date	Op. mode	M_o	v (m/s)	Tray position	T_p (°C)	t (h)
21-feb-13	H_i	0.8627	2.70	A_r	40.3	7.3
06-mar-13	H_i	0.8568	0.44	A_r	45.5	6.3
10-abr-13	H_i	0.8483	1.47	A_b	40.0	8.5
12-abr-13	H_i	0.8670	1.97	A_b	42.6	8.0
17-abr-13	S_o	0.8418	----	A_b	45.8	8.0
22-may-13	H_i	0.8748	1.10	A_b	48.3	6.8
30-may-00	H_i	0.8483	1.96	A_b	47. 5	6.0
31-may-13	S_o	0.8733	0.20	A_b	50.8	8.8

Table 1 shows how drying times are shorter when the dryer was used in hybrid mode (between 6 and 8.5 hours) compared to using the solar mode (8 to 8.8 hours). Tests that ran the longest (8 and 8.5 hours) in hybrid mode are understandable; the first of these (12-abr-13) initial moisture content was very high (0.8670) and wind speed was significant (1.97 m/s), the April 10th test happened on a cloudy day where solar radiation was low (table 2) and wind speed was also significant.

Because initial moisture content is one of the main variables which have an influence on the dryer's performance, the best results are obtained by comparing tests with similar M_o. Comparing the last 4 tests, where M_o is quite similar: solar from April 17th (M_o=0.8418) and hybrid from May 30th (M_o=0.8483); and solar May 31st (M_o=0.8733) with hybrid May 22nd (M_o=0.8748) shows that average time is 31.2% faster (equivalent to 2 hours) on hybrid mode than on solar mode. When M_o is not alike, results show much more variability but still the hybrid mode's process is faster.

It is also important to consider that when initial moisture content is higher, a longer time is needed to eliminate water present in the pineapple thus making the drying process longer. This stands out when observing that the May 22nd and 31st tests which high M_o's (0.8748 and 0.8733 respectively) took 11.8% longer, to get to the moisture content goal, than the April 17 and May 30 with lower M_o's (0.8418 and 0.8483 respectively) in either operation mode.

Table 2 shows vaporization efficiencies obtained throughout every test. These efficiencies are lower when the dryer worked in hybrid mode (9.3 to 14%) compared to the solar mode (22.7 to 24.0%). This may be due to the fact that the energy input from the LP gas started at 11 a.m. when solar energy is found in abundance and there was some sort of accumulated energy input in the dryer, causing an important heat loss and thus an efficiency decrease. From previous non-reported tests using only LP gas as an energy source, it is evident that vaporization efficiencies are low (around 10% in those tests). Further testing is required to pinpoint the cause of this situation. With the current information, better understanding and further studying of the system's thermal insulation and the hot water circuit is suggested. The input of LP gas should also start later in the afternoon when solar radiation decreases; this is actually how it is intended to be applied.

In hybrid mode, the lowest efficiency data obtained during this study are from February 21st (9.3%) and April 10th (10.3%). The first of these examples also shower the greatest wind speed among all the tests (2.7 m/s, table 1) and a low ambient temperature. Another possible cause of this low efficiency is that the trays were placed all the way to the top edge of the dryer, where cold air from outside the dryer is combined with the air inside the dryer, decreasing the latter's temperature and its efficiency. The second of this tests corresponds to the lowest solar energy received throughout the study.

Table 2. Dryer vaporization efficiencies

Date	Op. mode	m_{H_2Oevap} (kg)	m_{gas} (kg)	E_{gas} (kJ)	H_t (kJ/m^2)	E_{Sol} (kJ)	η_{evap} (%)
21-feb-13	H	2.1416	0.656	32766.2	22125.6	22606.8	9.3%
06-mar-13	H	2.1149	0.514	25673.5	20095.2	20532.3	11.0%
10-abr-13	H	2.1212	0.627	31317.7	17895.6	18284.8	10.3%
12-abr-13	H	2.1258	0.393	19629.8	23914.8	24434.9	11.6%
17-abr-13	S	2.1231	NA	---	21913.2	22389.8	22.7%
22-may-13	H	2.1147	0.411	20528.8	18684.0	19090.4	12.7%
30-may-00	H	2.1145	0.354	17681.8	18057.6	18450.4	14.0%
31-may-13	S	2.1169	NA	---	20545.2	20992.1	24.0%

3.1. Drying curves

Figures 2 and 3 show the drying curves for March 6th and April 17th when the dryer operated in hybrid mode and solar mode respectively. Both figures show the moisture content on dry basis (X), in water kg/ dry solid kg vs. drying time measured in hours. On the graph's legends final moisture content wet basis (M_f) for each small sample tray is shown for the total process time (t) from table 1; at the entrance (1) and exit (2) of the dryer. The X value of moisture wet basis content of 24% corresponds to a 0.32 water kg / dry solid kg.

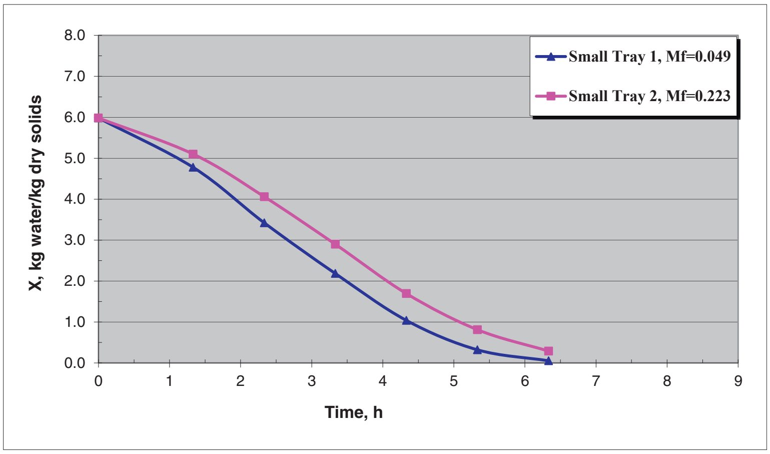

Fig. 2. Drying curves for the March 6th hybrid mode test

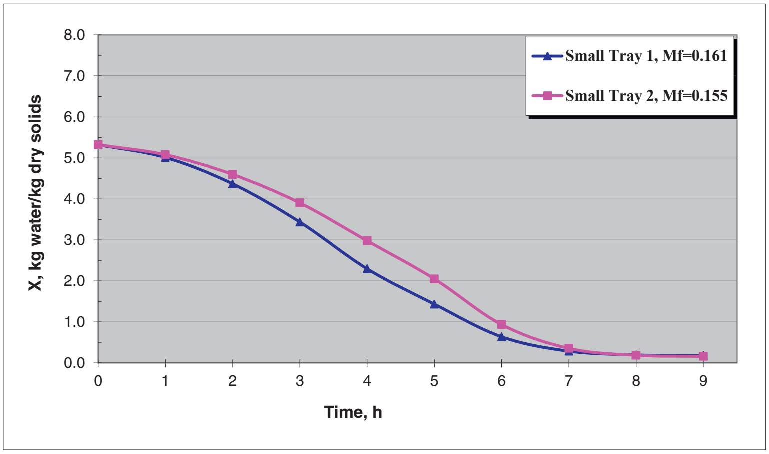

Fig. 3. Drying curves for the April 17th solar mode test

The graphs show that initial moisture content is different between both tests (M_o=0.8568 for March 6^{th} and M_o=0.8418 for April 17^{th}); because of this, it could be expected to find the April 17^{th} test to take less time. This is not the case because, as it was mentioned before, processes which rely solely on the sun's energy take longer than hybrid mode processes.

It is also evident that the change in moisture content through time is quite faster in the small tray 1, located at the entrance of the dryer, than for small tray 2, placed at the end of the dryer. This fact remains until the end of the process for the hybrid test shown on figure 2 showing that this process was not homogenous (M_f values in the figure). This is due to the previously mentioned situation in which the trays were located towards the end of the dryer, making the sample have contact with the external colder air, thus slowing down the process. On the other hand, figure 3 shows a final homogeneous process, this time the trays were placed 0.03 m towards the middle of the dryer, causing both trays to end their process at the same time. This was also observed throughout the rest of the tests which drying curves are not shown.

4. Conclusions

The total drying time when operating in solar mode is in average 31.2% longer (2 hours) than when the dryer operated in hybrid mode, taking into account similar conditions, especially when related to pineapple moisture content.

Initial moisture content is a determining factor in the pineapple drying velocity. The higher the moisture content, the longer it will take to complete the drying process.

Under similar operating conditions (last 4 from table 2) the solar mode process is almost twice as efficient as the hybrid mode; η_{evap}=23.4 and η_{evap}=13.4% respectively. Apparently a great amount of heat from the hot water is lost to the environment; though this requires further study.

The process in both of its modes (solar or hybrid) is basically homogeneous when the trays containing the product are placed towards the middle of the dryer (0.03 m). In addition to this, the dry product obtained at the end of the process shows good quality, has a good flavor but shows slight bleach on the pineapple's face exposed directly to the sun.

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