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Efficiency of a hybrid solar–gas dryer

Erick Cesar López-Vidaña, Lilia L. Méndez-Lagunas *, Juan Rodríguez-Ramírez

Instituto Politécnico Nacional, CHIDIR Oaxaca, Hornos 1003 Sta. Cruz Xoxocotlán, 71230 Oaxaca, Mexico

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Abstract

The thermal and drying efficiency of three operating configurations for a hybrid solar-gas dryer were calculated in transitory state. The hybrid dryer, comprising a solar collector, auxiliary LPG (liquid propane gas) combustion heater, and a drying chamber, can be operated through an LPG (GHS) heating system, a hybrid solar-gas (HHS) heating system, or a solar (SHS) heating system. Global efficiency was calculated considering the energetic contributions of the solar collector and/or the auxiliary heating system, in accordance with the mode of operation being evaluated. Losses resulting from reflection and absorption were considered in the analysis of the solar collector. The thermal efficiency of the collector was principally affected by air mass flow, collector angle of inclination, and the difference between ambient temperature and the collector’s internal temperature. A simulation varying air velocity parameters inside the solar collector was utilized to estimate the air mass flow needed to produce a thermal efficiency greater than the efficiency calculated under current design and operational conditions (26%). Maximum drying efficiencies were 86%, 71%, and 24% for GHS, HHS, and SHS, respectively. HHS and GHS exhibited similar drying rates in the constant period of the curve (≈0.030 kg H₂O/kg d.s. min). The efficiency of the hybrid drying system was similar to the LPG drying system, with the advantage of consuming 20% less fuel without sacrificing quality in the dried product.

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1. Introduction

More than 80% of the food is being produced by small farmers in countries in development (Murthy, 2009; Jairaj et al., 2009). In these countries, small producers need agriculture equipment with low investment and maintenance and easy to operate, such as small size dryers operated by solar energy (Farkas et al., 1999). On the other hand, the preservation of the quality becomes more and more important in the processing of agricultural products. (Seres and Farkas, 2007). Solar energy has great potential for many low temperature applications, especially the drying of agricultural products (Karim and Hawlader, 2006; Shobhana and Subod, 2012). Air heated with solar energy can be utilized directly in the drying process, reducing consumption of non-renewable sources of energy.

Current foodstuff drying systems have high operating costs. The 7–15% of the quantity of industrial energy in industrialized countries is utilized in foodstuff drying (Keey, 1992).

Brooker et al. (1974) found that high temperature drying processes, both continuous and discontinuous, require up to 6.9 MJ of energy per kg of water extracted, that is why non-renewable fuels such as carbon, petroleum, and wood are widely used to heat air for drying processes (Murthy, 2009).

According to Bennamoun and Belhamri (2003), storage of fresh produce is one of the most important stages of the...
production process, as it is during this stage that significant quantities of the foodstuff may undergo deterioration. As such, preservation is key in reducing food loss; dehydration, one of the major preservation methods, has been used for centuries to minimize these losses (Murthy, 2009). Solar drying in closed structures is a conservation method, employed to minimize post-harvest losses and improve the low quality associated with traditional drying methods that utilize non-renewable fuels (Forson et al., 2007). Closed systems prevent exposure of the food product to solar rays, as well as contamination as a result of dust, insects, rodents, and rain, and deterioration of the nutritional properties of the product (Amer et al., 2010).

Solar drying systems are classified according to mode of heating (direct or indirect) and the manner in which solar energy is used. In general terms, these systems may be placed into one of two main groups: (a) active solar drying systems, and (b) passive solar drying systems (Ekechukwu and Norton, 1999a). There are three distinct subclasses for each major class, defined primarily by the design and arrangement of the components and the mode in which solar energy is utilized: (a) integral-type solar dryers; (b) distributed-type solar dryers; and (c) mixed-mode solar dryers. However, the disadvantage of these dryers is the fact that their energy derives exclusively from solar radiation.

Hybrid solar dryers, in contrast, utilize solar energy in addition to another source of energy, derived from a conventional source (electricity or fossil fuels). These dryers employ an auxiliary heating system, enabling them to operate at night or under other non-ideal irradiance conditions. Both electric systems and biomass burners have been used as auxiliary heating systems in this type of dryer (Boughali et al., 2009; Amer et al., 2010; Prasad et al., 2006).

Evaluation of a drying system provides relevant information on thermal and drying efficiencies, facilitating improvements in its design. The principle components of solar dryers are the solar collector and the drying chamber. The most determining parameters in thermal efficiency include design, collector manufacturing materials, absorbing plate geometry and coat paint, angle of inclination, and air flow velocity inside the collector.

Previous studies have evaluated the thermal efficiency of solar collectors in a stationary state under controlled laboratory conditions, with lamps employed to simulate solar radiation and constant air flow. This method does not take into account the transitory nature of solar radiation, and as such does not accurately represent the real conditions of
energetic contributions to the system. Furthermore, past studies have determined the optical efficiency of the glazing system based on ideal data obtained from optimum value graphs for the product \(\text{Koyuncu, 2005; Karim and Hawlader, 2004, 2006}\). The calculated thermal efficiency given in the reports available in the literature fails to take into account the environmental conditions under which experiments are performed.

Establishing drying efficiency makes it possible to evaluate the effects of other parameters that intervene in the process, such as drying rate, air flow distribution, and temperature inside the drying chamber, among others. The uniformity and energetic contribution of the auxiliary heating system affect the dryer’s efficiency. Boughali et al. \(\text{2009}\) reported a drying efficiency of 20–30% for forced convection dryers; however, the efficiency of hybrid dryers has not yet been reported.

The present work evaluates a hybrid drying system that employs solar energy, complemented with LPG combustion energy, in field conditions, or transitory state. The optical efficiency of the glazing system of 2 covers is calculated analytically. Both components (the solar collector and the LPG burner) are considered individually in analysis of energetic contributions to the system.

\[ \text{2. Theoretical analysis} \]

The global efficiency of a hybrid drying system was evaluated considering the energetic contribution of each component (the solar collector and the auxiliary LPG combustion heating system), depending on the selected mode of operation: solar, LPG, or hybrid.

Efficiency of the solar collector (Eq. (1)) is a function of various external factors that cannot be controlled, due to their transitory nature.

\[ \eta_{dc} = f(T_a, \dot{Q}_a, U_L, I, F_R, \beta, \varepsilon) \]  

(1)

In order to take the variability of environmental parameters into consideration, real data obtained during operation of the collector was used. Experimentation took place in Oaxaca, Mexico \(\left(+17°02'00"N, -96°44'00"W\right)\) in December of 2010, on clear days, in order to guarantee maximum incidence of solar radiation on the solar collector.

\[ \text{2.1. Thermal efficiency of the solar collector} \]

The solar collector was analyzed in a transitory state to obtain its efficiency throughout the day. The uncontrollable and unpredictable nature of the parameters involved in solar drying systems is an obstacle to exact theoretical study \(\text{Karim and Hawlader, 2006}\). In transitory-state operating conditions (Fig. 1), the thermal efficiency of a solar collector is described by an energy balance that indicates the distribution of incident solar energy among useful energy gain, thermal losses, and optical losses over time \(\text{Koyuncu, 2005}\).

The thermal efficiency of the solar collector was calculated using the equation proposed by Hottel-Whillier and Bliss \(\text{Karim and Hawlader, 2004}\):

\[ \eta_{dc} = \frac{\dot{Q}_a}{A_p I} = F_R(\varepsilon t) - F_R U_L \frac{(\theta_i - \theta_a)}{I} \]  

(2)

where \(F_R\)

\[ F_R = \frac{\dot{m}C_{air}}{U_L A_p} \]

\[ F_R = \left[ 1 - \exp \left( \frac{F^* U_L A_p}{\dot{m}C_{air}} \right) \right] \]  

(3)

In Eq. (2), \(F_R(\varepsilon t)\) and \(F_R U_L\) are the principle parameters that comprise the equation that describes the efficiency of the collector. \(F_R(\varepsilon t)\) related to thermal gain and \(F_R U_L\) related to thermal losses; \(U_L\) is equal to the sum of the energy lost through the top \(U_t\), bottom \(U_b\), and sides \(U_e\) of the collector.

\[ U_L = U_t + U_b + U_e \]  

(4)

Optical efficiency is defined as the quotient of energy absorbed by the receptor and incident energy in the collector.
aperture. Optical efficiency depends on the optical properties of the materials involved, the geometry of the collector, and any and all imperfections derived from the construction of the collector (Kalogirou, 2009).

Product absorptance–transmittance \((\alpha T)\) was determined through optical analysis of the system of glass covers, using Eq. (5) (Kalogirou, 2009): \[
(\alpha T) \approx 0.96(\alpha T)_b
\]
where \((\alpha T)_b\) is effective radiation.

The solar collector’s angle of inclination is one of the parameters that determine the quantity of solar energy absorbed, and should ideally be oriented towards the north or south, depending on the geographic location and season chosen for experimentation.

The ideal slope (with respect to horizontal) of the collector can be calculated through the following equation (Ekechukwu and Norton, 1999b):

\[
\beta = |\phi - \delta|
\]

The angle of declination \(\delta\) can be obtained through Eq. (7) from Cooper (1969) (Duffie and Beckman, 1980):

\[
\delta = 23.45 \sin \left( \frac{284 + n}{365} \right)
\]

2.2. Calculating drying efficiency

The variables considered in calculating drying efficiency were as follows: amount of moisture to be extracted from the material, energetic contribution of LPG, and energetic contribution of solar energy. LPG consumption was obtained by tracking differences in weight in the LP gas storage tank at each measurement interval.

According to Prasad et al. (2006), drying efficiency relates the amount of energy needed to evaporate a certain quantity of water from a foodstuff \((M_\lambda)\) to the amount of energy that is supplied to the system \((IA_p + C_m)\), provided by the energetic contributions of LP gas combustion and solar radiation. This relationship can be expressed as follows:

\[
\eta_{SHS} = \frac{M_\lambda}{A_p \int_{t_1}^{t_2} I dt + C_{m} \int_{t_1}^{t_2} m dt}
\]

where \(\eta_{SHS}\), \(\eta_{GAS}\) and \(\eta_{HHS}\) represent drying efficiency in solar operation mode, LPG operation mode, and hybrid operation mode, respectively.

3. Experiments

The hybrid solar-gas dryer consists of two parts: the solar collector, where the air used in the drying process is heated, and the drying chamber, where the material to be dehydrated is placed in trays. Air is heated throughout the day in the solar collector; however, in conditions of low radiation intensity, i.e. a cloudy sky or nighttime operation, the dryer activates the auxiliary LPG combustion heating system.

3.1. Solar collector

The solar collector has a V-corrugated aluminum-coated black absorbing plate. The absorbing plate has a 60° angle aperture-channel, which allows it to have a 3.2 m² effective area of incidence at midday. The double glass cover system is 0.006 m thick with a separation of 0.05 m between the glass covers. The width of the absorbing plate is 1.095 m. The collector is stationary, with a 40° angle of inclination with respect to horizontal. The bottom and sides are isolated with expanded polystyrene, 0.019 m thick (Fig. 2).

3.2. Drying chamber

The drying chamber was built with a steel structure. The walls were made from zinc-coated steel sheet metal and were isolated with a one inch layer of fiber glass. The total capacity of the drying chamber (Fig. 3) is 10 trays and each galvanized steel mesh tray has a drying area of 0.42 m².

A 246 W motor powers 2 radial fans, located in the lower part of the chamber, generating an air velocity of 0.2 m/s. The auxiliary LPG combustion heating system raises the air temperature when it falls below 50 °C. This is controlled by a temperature regulator that activates and deactivates the flame, maintaining an internal temperature between 55 °C and 65 °C. Air mass flow rate within the drying chamber is maintained at 150 kg/h in continuous circulation.

Fig. 2. Frontal section of the solar collector.
3.3. Operating systems

Three distinct conditions were evaluated in terms of energetic contributions to the drying system: LP gas operation (GHS), hybrid operation (HHS), and solar operation (SHS).

Fresh air is introduced to the system by way of the solar thermal collector entrance. Secondary fresh air enters the combustion system when the system is in LPG burning or hybrid mode. 15% of the air recirculated in the drying chamber is removed as saturated air.

The entry of fresh air and the expulsion of saturated, exhausted air is controlled by a ventilation valve and saturated air is removed from the system by a divider in the fan outlet duct.

3.3.1. LPG operation

Energetic contributions during LP Gas operation were provided by combustion of LPG; this was carried out in a burner controlled by a temperature regulator set to maintain temperatures between 55 and 65 °C.

3.3.2. Hybrid operation

Energetic contributions during hybrid operation were provided by two sources: combustion of LPG, and the solar collector. When air temperature falls below 50 °C, the auxiliary LPG combustion heating system turn on. This function is controlled by a temperature regulator that activates and deactivates the flame, maintaining an internal temperature between 55 °C and 65 °C. This configuration allows the system to be operated at night and/or in conditions of low solar radiation.

3.3.3. Solar operation

Energetic contributions during solar operation were exclusively provided by energy collection via the solar collector. The yield of the solar system is limited by local climatological conditions.

3.4. Drying product

Temperature and solar radiation were recorded every 15 min using a computer connected to a Mac-14 data acquisition system. Type J thermocouples (Cole–Parmer) with an accuracy of ±0.5 °C were placed in the collector and the drying chamber. Six thermocouples were fixed to the solar collector, distributed in the inlet, middle, and air outlet; these thermocouples were utilized to determine variations in air temperature as the air passed along the plate. In order to evaluate radiative and convective losses, 3, 2, and 1 thermocouples were fixed in the system of covers, bottom plate, and edges of the solar collector, respectively. 5 thermocouples were fixed inside the drying chamber, distributed in the drying chamber air inlet, upper, middle, and lower parts of the chamber, and the saturated air outlet. Incident global solar radiation was recorded on a local level using a Keep and Zonnen pyranometer with a sensitivity of 14.69 E10⁻³ mV. Air velocity in the collector channel and drying chamber, as well as wind speed on the surface of the collector, were measured using a Hot-Wire Thermo-Anemometer (Cole–Parmer) with an accuracy of ±0.03 m/s.

Drying efficiency was evaluated using Saladette tomatoes (Lycopersicum esculentum) with an initial moisture content of 94% (d.b.). Blemish-free, mature tomatoes of a homogenous size were selected, washed, and uniformly quartered. To reduce enzymatic darkening during processing, the tomatoes were blanched in hot water (90–95 °C) without chemical additives for 1 min. They were then placed in a single uniform layer on the trays. Load density in the chamber was 4.75 kg per m² of tray. Weight loss was registered every 30 min for trays 1, 3, 5, 7, and 9 to follow drying kinetics in different points inside the drying chamber. The AOAC (13.002) standard was used to determine moisture content. In order to determine the properties, two samples were taken hourly from each tray over the course of the drying process. The reported data is the average of at least two repetitions of each drying kinetic.

Moisture content (MR) was calculated using the following equation:

\[
MR = \frac{MC_i - MC_e}{MC_i - MC_e}\]

4. Results and discussion

4.1. Thermal efficiency of solar collector

Air temperature inside the solar collector throughout the day is presented in Fig. 4. The highest temperature (60 °C) was recorded between 13:00 and 14:00, with an irradiance of 980 W m⁻². Temperature inside the drying chamber remained between 50 °C and 60 °C for an interval.
of 5 h; this period of time is suitable for drying a wide variety of vegetal products with high humidity contents, without incurring thermal damage.

Fig. 5 shows variations in the thermal efficiency of the V-corrugated-plate solar collector over a 24 h period. In order to obtain the product absorptance–transmittance (ατ) of Eq. (5), the optical properties (absorptance, transmittance, and reflectance) of system of covers for the solar collector were calculated analytically. Air flow recorded in the interior of the collector during experimentation was 0.038 ± 0.01 kg s\(^{-1}\). The maximum efficiency obtained under normal operating conditions was 11.43%.

The effects of the mass flow rate of the air circulating inside the solar collector on thermal efficiency (Fig. 5) were calculated by applying Eq. (2). When mass flow rate was maintained at 0.434 kg s\(^{-1}\), collector yield increased, reaching a maximum efficiency of 38.22%. Greater air mass flow rates did not significantly improve efficiency.

Solar collector efficiency was greatest at the beginning of the day, when in ambient air temperature and outlet air temperature was smallest (Fig. 5). The efficiency equation for this particular system is given by the slope-interception form of the equation of straight line, in which the slope value represents global heat lost (\(F_R U_L\)), and its intersection with the y-axis represents heat gained \(F_R(\alpha \tau)\). As can be seen in Fig. 5, efficiency has a negative slope; in the first hours of measurement, thermal efficiency was greater due to the fact that there was a smaller difference between ambient temperature and the air temperature in the interior of the solar collector (\(θ_i - θ_a\)); consequently, radiative and convective losses are also smaller. Thermal efficiency is affected by the difference in these temperatures (\(θ_i - θ_a\)); this difference is greatest at solar noon (Fig. 4), at which point a greater air mass flow rate is required to remove heat and increase efficiency, and to avoid radiative and convective losses.

Air mass flow rate inside the collector has a significant effect on heat transference (Table 1). An increase in air mass flow rate produces an increase in heat removal on the part of the absorbing plate in the direction of the flow. Increased heat removal from the absorbing plate results in an increase in useful heat \(Q_u\) in the air, thus increasing efficiency.

Efficiency is also affected by the inclination of the solar collector. The actual angle used (40°) was greater than the ideal angle (23%) according to Eq. (6), considering the latitude of the site and the season in which experimentation took place.

Koyuncu (2005) and Karim and Hawlader (2004) reported greater efficiencies for a V-corrugated-plate solar collector, with values of 39.05% and 68%, respectively. These efficiencies are attributable to the controlled temperature and inlet air mass flow rate conditions under which the above-mentioned experiments were performed. In addition, neither optical analysis of the solar collector nor the transitory natures of environmental factors were not considered in either analysis. A solar tracking system and/or an automatic inclination control are needed to take full advantage of all available solar radiation. However, these systems are not economically convenient for agricultural product drying applications.

### 4.2. Drying efficiency

#### 4.2.1. LPG operation

As was mentioned in the Introduction, three different operating conditions for this system were analyzed. Fig. 6 displays drying efficiency when energetic contributions...
used to remove moisture from foodstuffs were obtained exclusively by burning LPG. Initial drying efficiency is high (86%), as the moisture that evaporates from the foodstuff is free water and is more easily removed as a result of being closer to the surface. As free water levels drop, linked water migrates from the interior of the foodstuff to its surface. This causes the drying process to proceed more slowly, as mechanisms more complex than simple evaporation intervene. This results in a progressive decrease in efficiency, ultimately reaching a minimum level (7%). It can be observed that drying efficiency has a sustained rate of change resulting from the continuous and sufficient energetic contribution provided by burning LPG. Drying time in this mode of operation was 15 h, with an energetic contribution of 11.24 kW h.

4.2.2. Solar operation

This mode of operation is completely dependent on local climatological conditions, and as such, drying efficiency fluctuates constantly. The efficiency observed in solar mode (Fig. 7) was found to be in the range of 4–24%; this mode was less efficient than hybrid mode and LPG combustion mode, as the energetic contributions provided by the solar collector were less than what was needed to remove water from the foodstuff at an acceptable speed (0.032 kg water/kg d.s. min; average temperature 60 °C). The tem-
perature inside the drying chamber during the first 2 days of experimentation remained between 30–40 °C; in the following 2 days, it remained in the 40–50 °C range, resulting in a prolonged drying time (28 h, or 3.5 solar days). This prolonged drying time led to poor quality in the final product, associated with bacterial growth.

At the end of each drying day, an increase in efficiency was observed; this behavior is attributable to the fact that moisture loss continued at the same rate of change, with a smaller amount of supplied energy. Around 17:30 h, solar radiation dropped sharply to 70 W m$^{-2}$; weight loss during this period remained constant, due to the thermal inertia present within the drying chamber.

4.2.3. Hybrid (solar-gas) operation

Operating the drying system in hybrid mode (Fig. 8) leads to intermittent behavior, due to the fact that neither solar nor LP combustion energetic contributions are constant, as a result of the transitory nature of solar radiation and the intermittent operation of the LP gas burner. Temperature in the interior of the drying chamber remained between 50 and 60 °C, and efficiency varied within the range of 8–71% throughout experimentation.

Boughali et al. (2009) reported on the drying kinetics of tomatoes dehydrated in a solar-electric dryer with a 6-tray drying chamber loaded with 12 kg. The solar collector in their study, with an area of 2.45 m$^2$, had a maximum drying efficiency of 31%, lower than that found for the dryer evaluated in the present study (60%), despite the fact that the load in the drying chamber was greater (20 kg) and the area of the solar collector was smaller (1.86 m$^2$).

4.3. Drying rate

Drying rates were calculated for each of the three modes of operation. All three modes exhibited a constant drying rate period and a decreasing drying rate period. A significant difference was observed between the hybrid mode and the solar and LPG modes; the slowest drying rate (0.022 kg water/kg d.s. min) occurred in solar mode, due to the low temperature reached during the process. In contrast, drying rates for GHS and HHS exhibited similar constant drying rate periods, at 0.032 and 0.030 kg water/kg d.s. min, respectively. These rates remained constant until 50% (w.b.) of the moisture in the foodstuff had been dried. After 50% had been reached, drying rates decreased for both modes at the same rate of change, until reaching a final moisture level in the foodstuff of 10 ± 0.02%.

The energetic contributions of the solar collector and LP gas burner in all 3 modes of operation are shown in Table 2. The energy supplied to the system in SHS was greater than that administered in LPG mode or hybrid mode; however, given the low efficiency of the solar collector, only 16% of that energy was utilized. One of the principle objectives of
this work was to evaluate the amount of energy saved in terms of LPG combustion; the results demonstrate a 20% reduction in LPG consumption for hybrid operation (19.74 kWh/h), by comparison with LPG operation (24.59 kWh/h), a quality which makes this option economically attractive.

5. Conclusions

This study evaluated a hybrid dryer with a V-corrugated absorbing plate. The thermal efficiency of the solar collector was found to be lower than that reported in previous studies that evaluated solar collectors in ideal conditions and did not consider the transitory nature of the factors involved in the drying process.

Detailed study of each part of the hybrid dryer (solar-gas) demonstrated that thermal efficiency is affected by the air mass flow rate inside the solar collector. The air mass flow rate recorded in the solar collector (0.038 kg s^{-1}) was insufficient to remove the amount of heat which accumulated in the absorbing plate. This resulted in temperature stagnation in a single area, hindering the removal and transport of energy towards the drying chamber. In addition, the solar collector evaluated in this study had a fixed angle of 40°, greater than the angle that was required (23°) during experimentation. This difference led to reduced optical efficiency, as sunlight reflected off the two glass covers, preventing the plate from absorbing a greater quantity of energy.

Modification of the solar collector inlet air mass flow rate leads to a 36% increase in efficiency, suggesting a direct relationship between air velocity inside the solar collector and heat transfer from the plate to the air flow.

The drying efficiency graphs demonstrate that HHS behaves similarly to GHS. In addition, in terms of drying rates, these graphs reveal a great similarity in the rate periods for these two modes of operation. This confirms that the hybrid drying system has a drying efficiency similar to that of a system that uses conventional sources of energy, with the additional advantage of consuming a lower volume of LPG.

The temperature reached in SHS was not sufficient to dry the tomatoes at an acceptable rate. The prolonged drying time of this mode leads to poor quality in the final product, associated with bacterial growth. Use of the auxiliary LPG burning air heating system maintains internal temperature between 50 °C and 60 °C, even in non-optimal climatological conditions.

Even though the air mass flow rate of 0.035 kg m^{-2} s^{-1} reached in the drying chamber is similar to that recommended by Karim and Hawlader (2004) for drying agricultural products, it was not sufficient to reach an acceptable efficiency. As such, the system should be modified to include a fan at the solar collector air inlet in order to increase airflow speed. Mechanically promoting heat removal from the absorbing plate will decrease energy loss resulting from convection and conduction, and reduce the need for use of the auxiliary LPG air heating system.

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