Thermal Evaluation of the Indirect Air Heating System in a Solar Thermal Drying Plant for Agricultural Products

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Abstract

This paper presents a system of indirect air heating coupled to a drying chamber (type tunnel) for agricultural product. The energy for the drying process comes from a solar water heating system (92.4 m^2) with thermal storage or working directly. The water heating system has thermal efficiencies between 47-57%, depending on the temperatures reached by the water in the hot water thermal storage tank and the weather conditions. The indirect air heating system is by means of a heat exchanger of finned tubes that has an average heat transfer capacity of 50 kW, delivering temperatures at the entrance of the tunnel between 45-75 °C. The heat transfer efficiency of the water-air exchanger is around 85%.

Keywords: solar energy; solar drying; thermal efficiency; solar collectors

1. Introduction

A method widely practiced by farmers in Mexico and developing countries since ancient times, open-air sun drying for the preservation of food and agricultural crops has inherent limitations: large post-harvest crop losses caused by inadequate drying; fungal attacks; insect, birds and rodents invasion; and, unexpected rain and other meteorological phenomena. Losses using conventional drying methods, such as open sun drying, classical drying and others are estimated to correspond to 30-40% of total production in developing countries [1]. The above-described limitations result in a low-quality product that, in most cases, will not comply with minimum food safety standards.

Among the various types of solar dryers, distributed-type forced solar convection dryers have been reported to be superior in drying speed and quality [1]. Distributed solar dryers are basically composed of a solar energy collection system and a drying chamber. Usually the working fluid of the solar collection system is air. However, solar collectors based on a liquid thermal fluid can also be used indirectly to heat the air using a liquid-gas heat exchanger [2], which also allows to store the energy to be used even after the sun goes down.

Given environmental concerns and finite fossil fuel resources, it is necessary to further reduce energy consumption in the food sector and decouple food prices from unstable and increasing fossil fuel prices. Thus, it is desirable to use renewable energy for drying agricultural products. Given the foregoing, a plant using solar thermal systems (solar air heaters and flat-plate solar water heaters), with conventional LP gas support, was developed and installed for the drying of agricultural products in the state of Zacatecas, México; which operates by forced convection in a tunnel-type drying chamber.

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2. Method and Results

2.1 Description of the drying plant

The plant has a distributed-type forced convection hybrid solar drying system. It has a semi-continuous tunnel type drying chamber with a maximum capacity of 2700 kg of fresh products depending on the type of food. Up to eight drying racks can be accommodated inside the tunnel and each rack can contain a maximum of 120 perforated trays. The interior of the tunnel, drying racks and trays are made of food grade stainless steel.

The thermal energy required for the drying process can be provided by two solar collection systems: a direct air heating system using 48 solar air heaters (111.1 m^2) and an indirect air heating system using water-based solar collectors (92.4 m^2). In addition, there is an LP gas burner to back up thermal energy. The integration of the different technologies offers a versatile system for heat generation. It can easily and quickly adapt to different modes of operation: conventional, solar and hybrid. In the conventional mode, the air is heated by the direct combustion of LP gas and is injected into the drying chamber by the thrust force of the centrifugal fan, while the inlet temperature is controlled automatically by flame regulation undertaken via fuel flow variation. In the solar mode, solar heat generation systems can operate on either an independent or coupled basis. A coupled system harnesses the heat collected by the two solar systems during the day, thus increasing the plant's operating hours even after sunset. In the hybrid mode, when the plant is operating continuously and the solar collection technology is unable to supply the heat required by the dehydration process, the air is passed through the backup air heating system (LP gas burner) to obtain the desired conditions in the drying chamber. Figure 1 shows schematically the distribution of the components that integrates the drying system of the plant, as well as some of the sensors installed for its evaluation. The operating variables of the solar drying system are monitored and recorded simultaneously in one minute periods by a data acquisition unit. In this work, the thermal analysis of the indirect air heating system is presented.

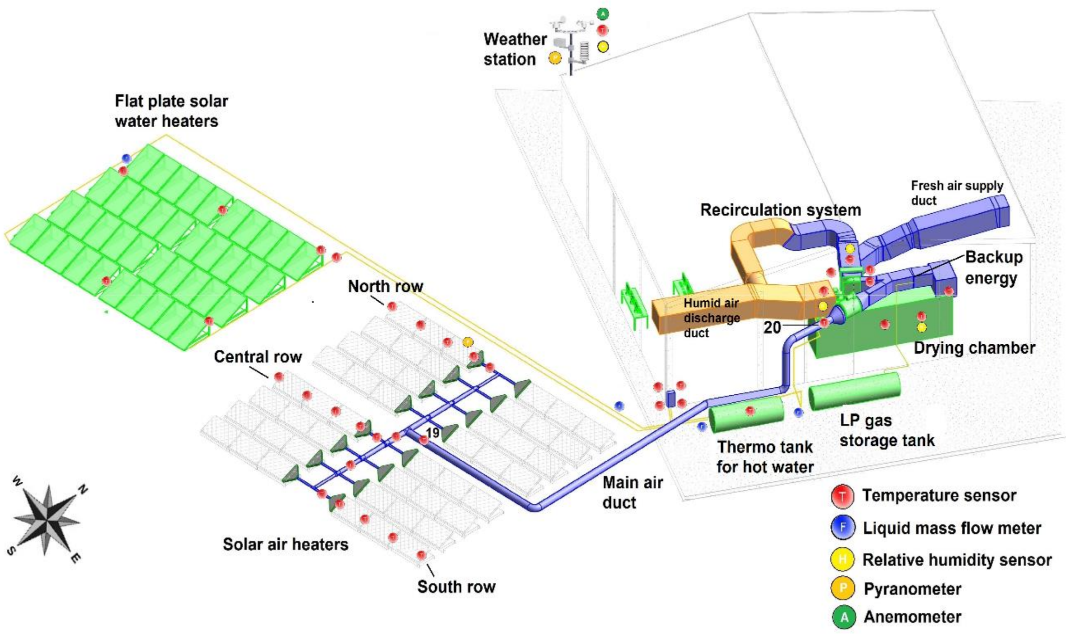

Fig. 1. Schematic representation of the distribution of some of the measurement sensors installed in the plant.

2.2 Description of the indirect air heating system

The solar air heaters are not the only solar thermal systems for drying applications. Also the solar collectors based on a liquid thermal fluid can be used indirectly using a gas-liquid heat exchanger. Nonclercq *et al.* [3] designed a prototype solar drying cabinet type capable of processing more than 40 kg of fresh tomato (S. lycopersicum) in 10 h. The interior temperature of the dryer reached up to 65 °C with the help of radiators, a thermo-tank and solar water collectors. Tiwari *et al.* [4] designed an indirect solar dryer with hot water storage and a solar water heating system. Water has a heat capacity four times more than air and a higher thermal conductivity, these properties allow it to be a heat-carrying fluid more efficient than air. A flat solar collector system for water heating was installed and evaluated at the drying plant. The indirect air heating system is integrated by (see Figure 2):

• Field of flat plate solar collectors.
• Liquid-liquid plate heat exchanger
• Thermal storage tank
• Water-air finned tube heat exchanger
• Centrifugal fan
• Auxiliary equipment: instrumentation, pumps, expansion vessel, valves and air eliminators

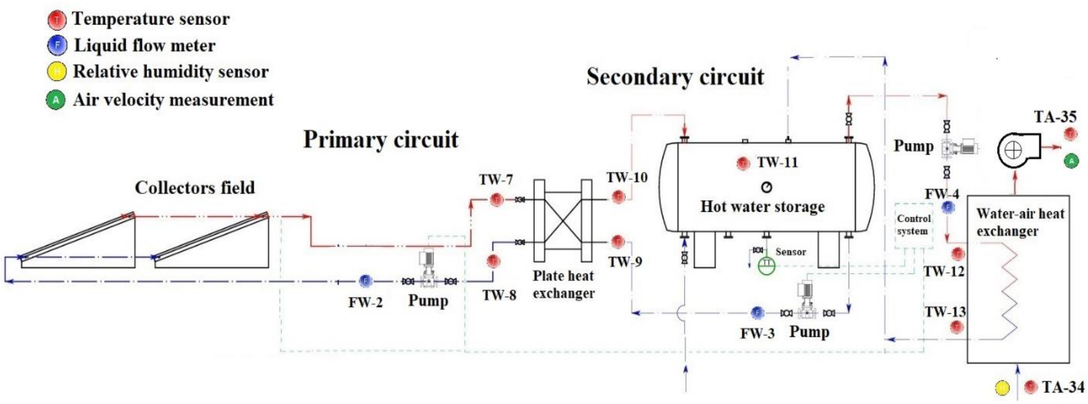

Fig. 2. Indirect air heating system with the instrumentation of its components.

One of the best known and experienced solar thermal applications is water heating with flat plate solar collectors. These solar collectors are manufactured in Mexico, with high efficiency at medium temperatures and with long life materials. For this project the high efficiency flat plate solar collector model MAXOL MS2.5® was selected. The collector has an aluminium absorber plate and 11 copper pipes (risers). The absorber surface has a selective coating of titanium oxide to increase the ability to absorb solar radiation. It has a low-iron tempered glass cover. The side walls and the bottom of the collector have a polyurethane and mineral wool insulation. The frame that supports the collector components is made of rolled steel. Table 1 shows the technical characteristics of the solar collector used in the indirect air heating system.

The field of flat-plate solar collectors used in the present study for indirect air heating is composed of 40 collectors equivalent to an aperture area of 92.4 m^2, distributed in four parallel rows, each consisting of two arrays of five parallel collectors connected in series (10 collectors per row). These collectors are oriented towards the Equator with an inclination of 22.72 ± 0.94° in relation to a horizontal plane and a separation between rows of 0.92 m.

Figure 3 shows the distribution of the collectors, as well as their instrumentation.

Table. 1. Technical characteristics of flat plate solar collectors

Characteristics	Flat Solar Collector
Thermal fluid	Water
Dimensions	
Length	2099 mm
Width	1196 mm
High	95 mm
Empty weight	46.5 kg
Gross area	2.326 m^2
Aperture area	2.311 m^2
Cover	
Material	Tempered glass
Transmittance	0.91
Thickness	4 mm
Absorber surface	
Material	Copper
Absorptivity	0.95
Emissivity	0.05
Insulating	
Material	Polyurethane + mineral wool.
Bottom insulation thickness	44 mm
Side insulation thickness	25 mm

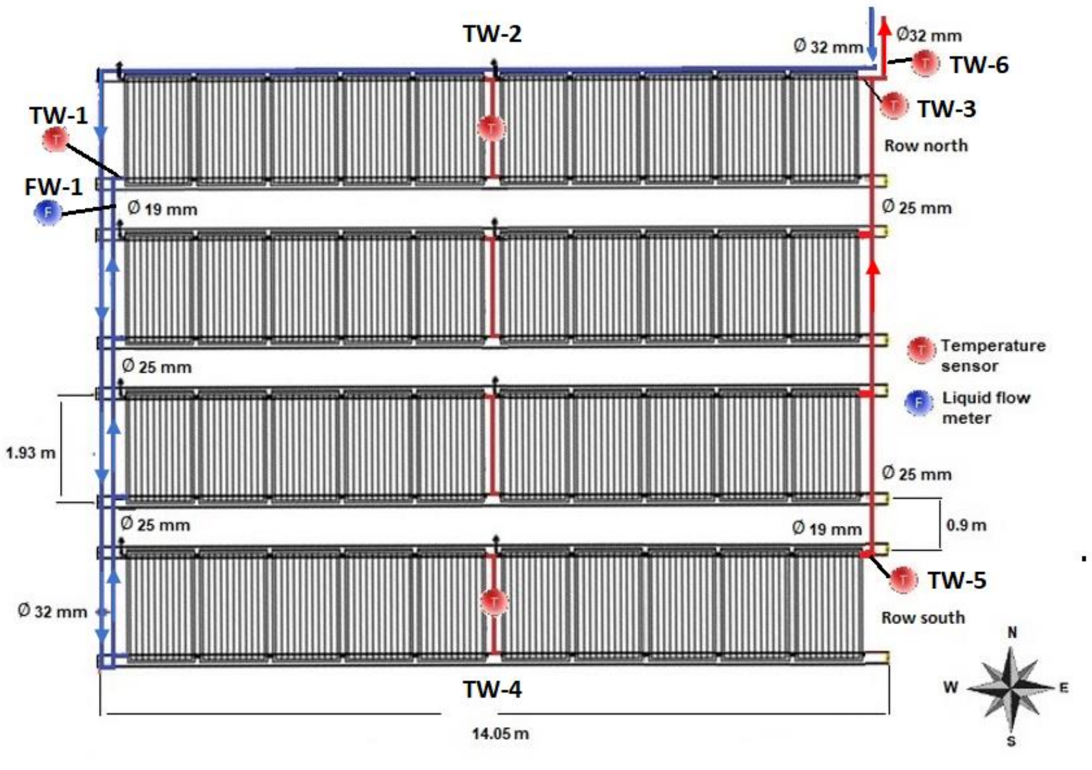

Fig. 3. Field of flat plate solar collectors for water heating, as well as its instrumentation.

The field of solar collectors operates by a forced circulation system composed of a closed primary circuit and an open secondary circuit. Each circuit operates with a 1.5 HP pump with a nominal flow rate up to 160 l/min. The primary circuit has a reverse-return configuration and an expansion vessel of 325.5 l that allows the collector field to remain in stagnation conditions without the need to drain liquid to reduce the pressure in the circuit.

The heat transfer between both circuits occurs via a plate heat exchanger with a capacity of 40 kW. The indirect system is able to operate in two ways: a) the hot water obtained from the solar collector systems is used directly in the water-air heat exchanger; or, b) said hot water is stored in a thermal storage tank for later use. The air is indirectly heated in a water-air finned-tube heat exchanger with a nominal heat transfer capacity of 60 kW. The air that passes through the water-air exchanger is sucked by a centrifugal fan (10 HP motor). A horizontal atmospheric thermal tank with a nominal capacity of 6000 liters is used for hot water storage and a ¾ HP water pump (559.275W) with a nominal capacity of up to 60 l/min is used to supply hot water to a water-air heat exchanger. Both the fan and the pump are connected to a frequency converter that allows them to regulate their flow.

The water heating system has a differential temperature control that activates the primary and secondary circuit pumps when the difference between the temperature of the working fluid at the outlet of the collector field and the temperature of the water in the lower part of the thermotank exceeds 8 °C. When the temperature difference falls below 4 °C the pumps switched off. In addition, the control is programmed to stop the pumps when the thermotank reaches a temperature of 90°C.

The primary circuit has eight temperature sensors, two pressure transducers to measure the pressure drop in the plate heat exchanger and two flowmeters: one to measure the overall flow to the collector field and another to measure only a row flow of collectors (north row). The secondary circuit has two temperature sensors in the plate heat exchanger and a flow meter. A pyranometer was installed in the solar collectors to measure the solar irradiance on the collector plane. The distribution of the sensors allows determining the overall efficiency of the collector field, as well as the efficiency of the heat exchange between both circuits. In the water-air heat exchanger four temperature sensors and two waterside pressure sensors were installed. The thermal storage tank has a temperature sensor; additionally it has a bimetallic thermometer dial in the middle part. There is a weather station composed of: a pyranometer to measure horizontal solar irradiance, an anemometer to measure the horizontal component of wind speed and its direction, a rain gauge to measure the Rainfall and a sensor for the measurement of relative humidity and ambient temperature. Figure 2 and Figure 3 shows the distribution of some of the sensors and Table 2 shows the characteristics of the sensors installed.

Table. 2. Instruments used to measure the variables of the solar drying system

Variable	Instrument / sensor	Range	Accuracy
Air velocity	Hot wire anemometer: TSI model 8345	0 m/s to 30 m/s	± 3 %
Liquid volumetric flow meter	Impeller flowmeters: Seametrics, model SPT-100 and SPX-100.	2 l/min to 150 l/min	± 1 % FSO
Temperature	RTD, class PT-1000	-50 °C to 750 °C	± 0.5 °C
Irradiance	Pyranometer: Kipp & Zonen, model CMP3	0 W/m² to 2 000 W/m²	± 2 %
Temperature and relative humidity	Ibérica, model PCE-P18	-20 °C to 60 °C and 0 % to 100%	± 2 % ± 0.5 % and ± 2 %
Wind speed	Cup anemometer: Davis, model 6410	0.5 m/s to 89 m/s	± 1 m/s
Rainfall	Pluviometer: Davis, model 7852	0 mm/m² to 999.8 mm/m²	± 4 %

Full Scale Output (FSO) is the resulting output signal or displayed reading produced when the maximum measurement for a given device is applied.

2.3 Thermal evaluation of the indirect air heating system

The present work reports the results of the operation of the indirect air heating system in storage mode by means of two forms of energy extraction from the hot water tank (test 1 and test 2). Water heating and energy storage was carried out in two days in order to achieve maximum stored energy capacity (water≈90 °C). For both tests, the volume of water contained in the tank was 6150 l. The evaluation of the system can be carried out in two parts: solar water heating system and extraction of the energy stored in the thermo tank

2.3.1 Solar water heating system

The operation of the test 1 system was carried out on September 25 and 26. During the first day of operation, the pumps of the water heating system started at 7:24 h intermittently until 7:53 h; from that time, they were kept on permanently until 15:26 h. The first day of operation, the tank reached a temperature of 71.9 °C. On the second day of operation, the pumps initially started at 8:25 h and operate intermittently according to the differential temperature control parameters and the incident solar irradiance. At 14:04 h the tank temperature reached 89.6 °C and the pumps automatically switched off; however, later the pumps switched on intermittently until they finally went off at 15:43 h. During the operation of the pumps, the pressure of the primary circuit reached up to 4 kg/cm^2. Figure 4 shows the temperature profile: at the inlet (TW-1), at the serial connection of the north row (TW-2) and at the outlet (TW-6) section of the field of flat plate solar collectors. The progression of the temperature in the hot water tank (TW-11) and the solar irradiance on the solar collectors plane (I) for the two days of operation of the system are also included.

The temperature of the tank increases 42.9 °C in the first day. During the waiting period for starting the pumps in the next day (mainly at night), the tank has a thermal loss of 2.49 °C. The temperature increase on the second day of operation is 20.19 °C reaching 89.6 °C. Figure 4 shows how the speed of the increase in water temperature in the tank is significantly lower on the second day, this is mainly because higher temperatures produce greater heat losses and, therefore, the efficiency of the solar collector decreases and the increase in temperature in the tank is slower.

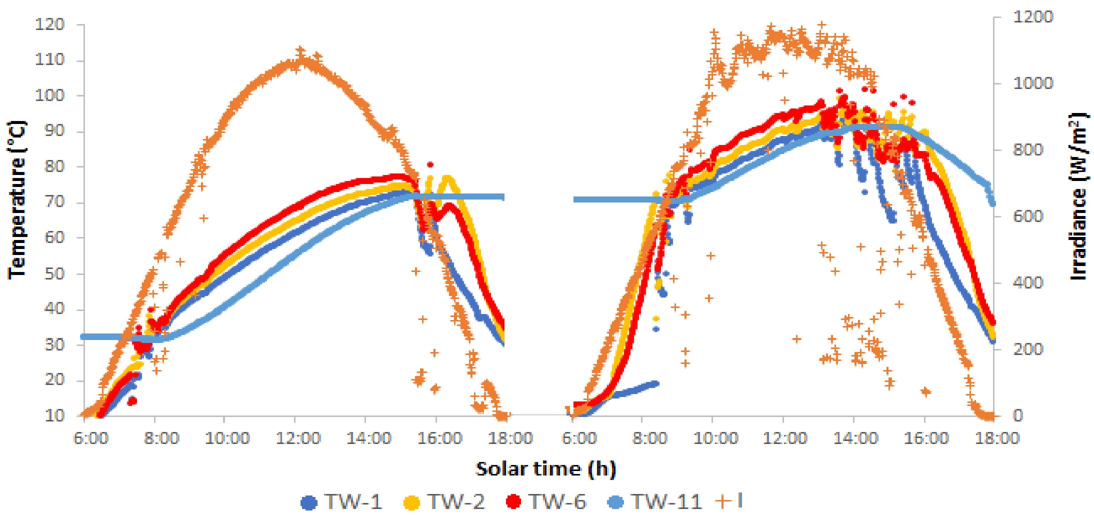

Fig. 4. Temperature profiles in the field of flat plate solar collectors, temperature of water in the tank and solar irradiance on the collector plane for September 25-26.

The useful heat gain supplied by solar collectors was determined via the following expression:

$$\dot{Q}_u = \dot{m}\, Cp_{m_f} \left(T_{f,out} - T_{f,in}\right) \qquad (1)$$

where Cp_{m_f} is the mean heat capacity at constant pressure of the fluid, $T_{f,in}$ and $T_{f,out}$ are the inlet and outlet temperature, respectively.

The instantaneous thermal efficiency of the field of solar collectors is defined as the ratio between the useful heat gain and the incident solar power, and was calculated via the following equation.

$$\eta = \frac{\dot{m}\, Cp_{mf} \left(T_{f,out} - T_{f,in}\right)}{I\, A_C} \qquad (2)$$

where A_C is the aperture area of solar collectors [m^2] and I is the solar irradiance on the collector plane [W/m^2].

Figure 5 shows the instantaneous efficiencies of the north row and global of the field of solar collectors for water heating respectively; as well as the energy accumulated in the thermal storage tank during the two days of operation. Instantaneous efficiency was determined by eq. () using the individual mass flow rates registered. The area used for the efficiency of the north row was 23.11 m^2, while for the global was 92.44 m^2. The average heat capacity of water was considered constant as 4185 J/kg K. The instantaneous efficiencies of the north row are relatively lower than the global one; this is because the water mass flow rate is lower through the north row compared to the other rows of the collector field. The efficiencies gradually decrease during the water heating because the heat losses increase with the increase of the water temperature in the storage tank. During the first day of operation, the water heating system stores 1043.39 MJ of thermal energy, 65.7 MJ is lost during the waiting period for starting the pumps the next day. The second day stores 525.76 MJ to give a total of 1503.5 MJ during the two days of operation. Therefore, the water heating system during the second day contributed only 35% of the total energy stored in the storage tank.

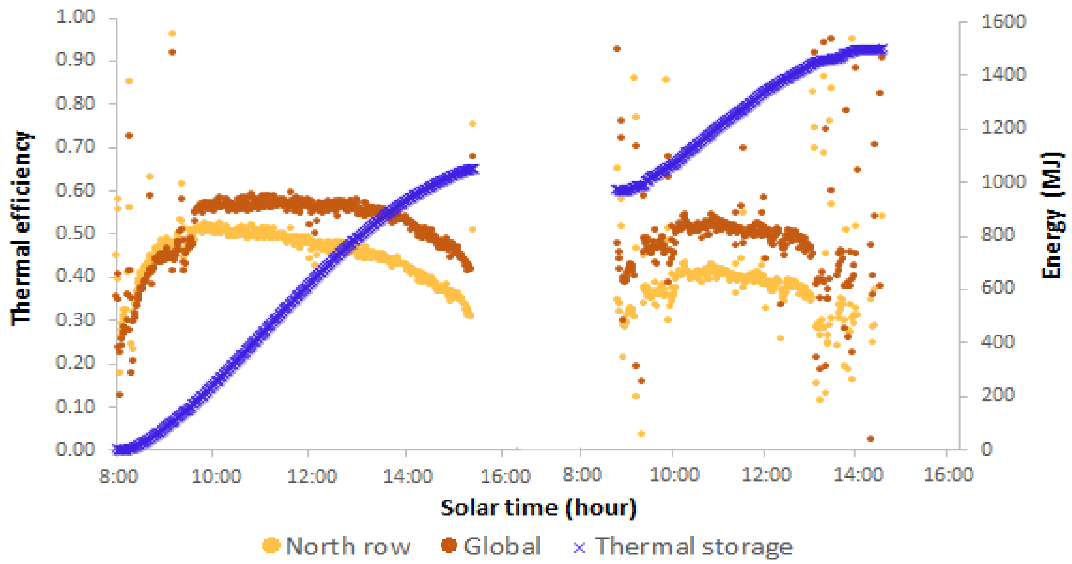

Fig. 5. Instantaneous efficiencies and accumulated energy in thermal storage tank (September 25-26).

Table 3 shows the results of solar water heating and energy storage tank of the two tests performed when operating the indirect system in storage mode. The system storage power was similar in both tests: 33.04 kW (test 1) and 33.4 kW (test 2).

Table. 3. Parameters of the water heating system

Parameters	Test 1		Test 2	
	23-may	24-may	25-sep	26-sep
Effective operating time (h)	8.52	5.7	7.68	5.37
Average primary circuit water flow (kg/min)	99.96 ± 1.71	99.92 ± 1.33	112.4 ± 1.81	115.46 ± 1.78
Average secondary circuit water flow (kg/min)	64.95 ± 0.84	57 ± 2.03	73.87 ± 0.62	67.76 ± 6.06
Total incident energy useful in the plane of the collector (MJ)	2196.86	1652.71	2228.21	1830.00
Total useful heat (MJ)	1231.02	787.97	1175.70	878.59
Thermal efficiency of the collector field (%)	56.04%	47.68%	52.76%	48.01%
Water temperature stored at the beginning of the day (° C)	27.76	68.48	31.39	69.38
Water temperature stored at the end of the day (° C)	70.48	91.43	71.94	89.76
Energy stored in the hot water tank (MJ)	1098.69	592.24	1043.40	525.77
Energy lost at night (MJ)	51.49	---	65.70	---
Global efficiency of the water heating system (%)	50.01%	35.83%	46.83%	28.73%

2.3.2 Extraction of the energy stored in the storage tank

Two ways of extracting the energy stored in the termotank were tested. For test 1, the water flow through the heat exchanger was varied stepwise from 18 kg/min to 45 kg/min during the first 40 minutes of operation, and then the water flow remained constant around 55.3 kg/min (maximum pump flow). The energy extraction stopped when the air temperature at the outlet of the exchanger was ≈ 45 °C. For test 2, the flow rate of the water flow through the finned tube exchanger was regulated so that the temperature of the air at the outlet of the heat exchanger was maintained around 55 °C, but not less than 50 °C. For both tests, the volumetric air flow through the exchanger was 6367.8 m^3/ h.

In a heat exchange of two fluids, the fluid of higher temperature (subscript h) gives part of its heat to the fluid with lower temperature (subscript c) and another part is lost to the environment. The thermal efficiency of a heat exchanger is determined by the following expression:

$$\eta_{exchanger} = \frac{\dot{Q}_c}{\dot{Q}_h} = \frac{\dot{m}_c \, Cp_{mfc} \left(T_{fc,out} - T_{fc,in}\right)}{\dot{m}_h \, Cp_{mfh} \left(T_{fh,out} - T_{fh,in}\right)} \tag{3}$$

Figure 6 shows the thermal efficiencies of the water-air heat exchanger (η), the temperature profile of the air at the outlet of the exchanger (TA-35), the increase in air temperature (ΔT_A) and the profile of water temperature inside of the thermotank (TW-11). The variation of the water flow through the exchanger (FW-4) is also presented during the two drying tests. An abrupt decrease in the temperature inside the tank can be observed when the flow of hot water extraction is greater than 30 kg/min. This is due to a greater mixing of the water that breaks with the stratification of the temperature inside the thermotank. It can be seen that during test 2 the stepwise increase in the flow of water through the heat exchanger allowed to maintain the temperature of the air at the outlet around 55 °C.

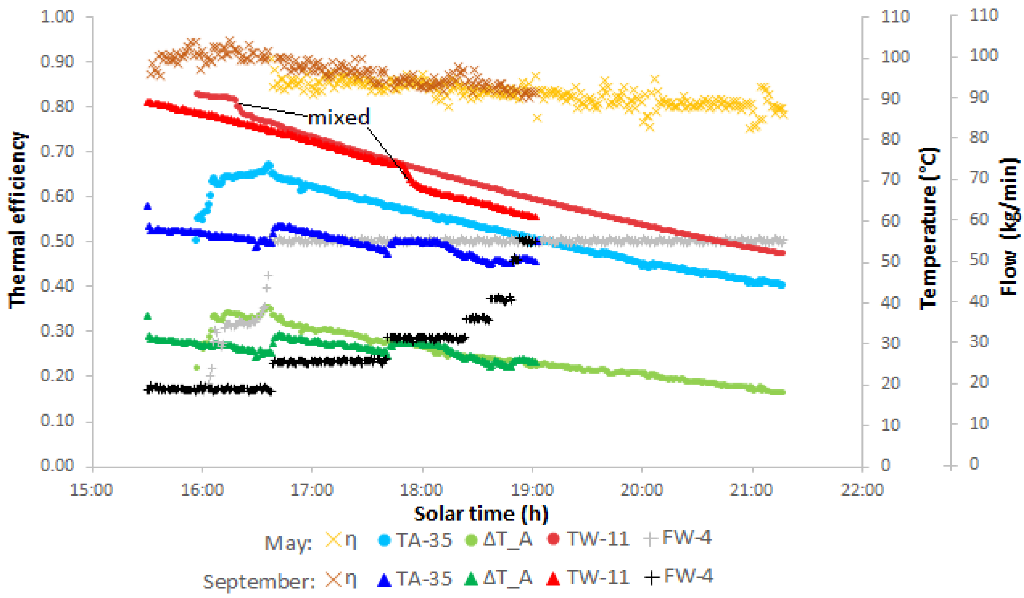

Fig. 6. Thermal efficiencies and air temperature in the heat exchanger; as well as the temperature in the thermotank.

Table 4 shows the operating parameters of the indirect air heating system by extracting the energy stored in the hot water thermotank. In test 2, the indirect system operated 1.82 hours less than in test 1 and with a stepped extraction flow. Therefore, in test 1, more energy was extracted from the thermotank and, therefore, there is a lower temperature inside the thermotank at the end of the operation. The greatest use of energy wss made at the expense of the decrease in temperature at the tunnel entrance at the end of the operation. The water temperature in the hot water thermotank drops, providing a total of 1006.44 MJ (test 1) and 726.78 MJ (test 2) of thermal energy for indirect air heating, this is equivalent to 61% and 48% of the energy stored during the two days of operation of the water heating system, respectively. The thermal efficiency in the water-air heat exchanger was higher when it regulated the flow of water through the exchanger because temperatures were maintained lower than those obtained by the maximum water flow. The unused stored energy allows the indirect air heating system to operate continuously in a hybrid way with the conventional system preheating the air. Alternatively, it allows to decrease the heating time of the water stored in the subsequent days of drying, being a good solar day enough to be able to reach the desired temperatures for the drying process.

Table. 4. Parameters of operation of the air heating system

Parameters	Test 1 24-May	Test 2 26-Sep
Effective operating time (h)	5.35	3.53
Initial temperature of the hot water thermotank (°C)	90.97	89.20
Final temperature of the hot water thermotank (°C)	51.94	61.02
Total energy received by the air in the heat exchanger (MJ)	794.25	571.39
Thermal efficiency of the water-air heat exchanger (%)	83.44	88.07
Average temperature at the tunnel entrance (°C)	56.74	53.72

3. Concluding remarks

The results of the thermal analysis have shown the technical feasibility of the use of solar thermal technologies for indirect air heating for drying products at an industrial plant. Some highlights of the work are:

- The system of indirect air heating provides operating in storage mode allows uniform temperatures at the entrance of the drying chamber, as well as having thermal energy during the night and periods with adverse weather conditions (very cloudy and rainy days). It also allows the system to be operated in a hybrid way with gas backup or with direct air heating systems.
- Indirect air heating systems are able to deliver the temperatures required in the food drying process, that are, temperatures between 50 °C and 70°C.
- Different kind of food products can be dried on the thermosolar plant designed, resulting in substantial fuel savings and environmental benefits.
- The development of robust solar drying technologies that adapt to the needs of the agroindustrial sector and other industrial sectors is relevant. Given environmental concerns and finite fossil fuel resources, it is necessary to further reduce energy consumption in the food sector and decouple food prices from unstable and increasing fossil fuel prices.

The development and implementation of solar drying systems technology, initially at demonstration scale, in the Mexican industrial sector could allow a technical and economic maturation of the technology, and the benefits could be presented in the short term.

4. Acknowledgment

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5. References

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