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DESIGN, CHARACTERIZATION AND SIMULATION OF U-SHAPED SOLAR COLLECTOR FOR DRYING OF AGRICULTURAL PRODUCTS IN AREQUIPA REGION

[1]Jorge Gilbert Mamani Calcina, [1]Jesús Ruben Mamani Calcina, [2]Silvia Marisel Espinoza Suarez and [3]Klinge Orlando Villalba-Condori

[1]Professional School of Physics, Universidad Nacional De San Agustín De Arequipa, Perú
[2]TECSUP, Office of Educational Quality, Perú
[3]Universidad Continental, Arequipa, Perú
Emails : jmamanicalcin@unsa.edu.pe , jesus619mc@hotmail.com , sespinoza@tecsup.edu.pe , kvillalba@continental.edu.pe

Abstract

This research belongs to the framework of appropriate technologies for sustainable rural development. This work characterizes process of heating air and drying capacity of an active solar dehydrator of forced convection distributive type to protect maximum of agricultural products from external agents. This system is based on use of solar energy to heat air entering drying chamber using a flat solar collector. To characterize its efficiency, a mathematical model based on an energy balance was developed where variables are climatic conditions of place temperature, humidity of environment, solar irradiation on inclined plane, wind speed in addition to design parameters of collector, flow of air and characteristics of materials used. Using an iterative method, they have been validated with experimental results from literature obtaining small relative errors (less than 6%). Once inlet and outlet temperature were obtained, a mathematical model was developed. Maximum drying efficiency was calculated using collector; based on experimental results with approximate values of (85 ± 10) % for two particular cases, proposing improvements. Finally, a parametric analysis was performed based on an established nominal case, to study how variations in design and operation conditions influence operation of collector by setting one of them. Results show that temperature of the air at outlet of collector is higher depends permanency time or if collector it is wider. It was also verified that temperature increases for low mass flows depending on convection coefficient. The outlet temperature increases proportionally with ambient temperature and solar irradiation; however, temperature decreases with wind speed as this causes more losses. Regarding efficiency of collector, results indicate a significant improvement when working with high mass flow rates, however this does not favor outlet temperature of collector or drying efficiency, since there is a limit value of mass flow from which are no longer getting better results. Solar irradiation coupled with ambient humidity and dimensions of collector, positively influence drying efficiency, while high ambient temperatures or winds peed penalize such efficiency. This study allows adjusting parameters of solar collector to ensure temperatures required in drying of agricultural products thus guaranteeing their quality.

Keywords **:** Design, characterization, simulation of U-shaped solar, agricultural products, electricity for rural areas, solar energy

Introduction

Most of world's energy has been generated from fossil reserves of coal and oil, but since depletion of these is already foreseeable, it is necessary to consider their conservation and use of other sources. Since 1970s, research and development of different systems for collection and use of solar energy has increased, which is abundant. Solar energy can be used in thermal photo conversion: water heating (Montoya & Pacheco, 1998) room heating, water pumping and/or generation of moderate amounts of electricity for rural areas (Duffie and Beckman, 2013). Importance of using solar air heating systems is that they represent one of most common forms of practical use of solar energy, which borders average 1000 W/m^2 per year in City of Arequipa, Peru.

A solar air heater is a simple mechanism that heats air using solar energy (Manrique, 1984), which has many applications in drying agricultural products. Also, solar air heaters could be used in building heating systems as auxiliary air heaters. Different configurations are possible for flow of air inside passage. Corrosion and leakage problems are many minors compared to solar liquid heater systems. Main disadvantage of an air heater is that heat transfer coefficient between absorbent plate and air is low, which results in a low thermal efficiency of heater. Hence here different modifications are suggested and applied.

Modifications of present work include making air have a U-shaped path, using two glass covers. A first glass located at top and another second located at half height of system forming first air passage inside collector. Between second glass and absorbent plate second air passage is formed, placing a black mesh for a better heat transfer. Most of heat lost by collector is in part of glass cover that is exposed to solar radiation and environment, because sides and back of collector can be adequately insulated. In design of proposed collector, the loss of heat to environment is reduced, forcing flow of air over second glass cover (pre air heater) before passing over absorbent plate causing energy extracted from glass cover be used to preheat air. Design of U-shaped solar collector greatly improves heat transfer to air, because air entered between two glass covers is being preheated and subsequently when air passes over absorbent plate, presence black mesh helps in transfer of heat to air inside collector and thus improves the efficiency of collector machine.

Fundamentals

In work entitled "Simulation and validation of prototype of a solar thermal collector made with recycled tires" where mitigation of environmental impact generated by large number of recycled tires is sought (Mora *et al.*, 2019), technical feasibility of a solar thermal collector is determined, built by reusing used and discarded tires. In this work characterization of dynamic and thermal behavior of collector was developed in computational form, through the academic simulation software ANSYS; concluding that used tires can be reused as solar collectors and that energy use of transformation from solar to thermal energy has an efficiency of 43%.

In research conducted on "Development of an experimental test bench to determine useful heat and efficiency of a flat plate solar collector", work carried out by Metropolitan Technological Institute of Medellin in Colombia, it was evidenced that useful heat of system increasing area in contact, in addition periodicity of use of the pump regularly increases heat transfer therefore a better efficiency is achieved. For Study of technologies applied to collection of solar energy" (Noboa and Vizcaíno, 2019). Larco Noboa in this same article declares how light is generated through solar energy, which can be used in two ways, thermal systems and photovoltaic systems.

In work Modeling a solar collector for air heating, Koulibaly & González (Koulibaly and González, 2015). performed modeling of a solar collector operated with natural convection, analysis of collector is presented by means of non-stationary mass and energy balances applied to each of component elements of collector which allowed to develop a program in Fortran 77 that simulates dynamic behavior of collector before variations of operating conditions and variations of design parameters (dimensions of collector, type of cover material and dimensions, material of absorber plate and its dimensions, optical efficiency and type and thickness of insulation). Results show that software can be used for design of air heating manifolds, besides being able to be used to obtain temperatures of each component of collector and instantaneous thermal efficiency (Koulibaly and González, 2015). Software also offers elements to determine time constant that characterizes the dynamics of collector.

Thermal application from solar energy, using air as a fluid, shows benefits due to simplicity of installation and structure independence in buildings, also due to low risk of overheating and leaks. Thanks to these characteristics, solar thermal air collectors are a good solution to cover ventilation loads in cold seasons (Holguino *et al.*, 2018), (Montes and Cortez, 2016) and (Flores Martell, 2018). However, many energy efficiency solutions in buildings lose their purpose, not taking into account energy and economic costs of installation (Pérez *et al.*, 2016). In order to solve this, a solar air collector has been designed, built and analyzed, reusing and recycling used and discarded materials on a daily basis. For project, results obtained from experimentation of the prototype in different external situations are collected, measuring or calculating: irradiation, temperature and wind speed of environment, temperature and humidity at exit and entrance of collector, as well as air flow and capacity of heating generated (Lammardo and Baritto, 2010). Use of solar dryers for dehydration of agricultural products is one of appropriate technologies for sustainable rural development in growth in developing countries (Ocampo, 2019).

Energy Balance

For this type of solar collector, it indicates that only a fraction of total radiation incident on collector (HTAC) can be used for heating air, since one part is lost to the surroundings by conduction, convection and radiation, others are it loses due to its own reflection characteristics of cover and absorbent plate and latter can be stored in same collector (usually negligible).

This energy balance, can be expressed by:

$$H_T A_C = Q_{abs} = Q_{Useful} + Q_{lost} + \frac{dU}{dt} \quad ...(1)$$

Donde:

H_T : is the intensity of solar radiation (W/m^2)

A_C : is effective area of collector

Q_{Useful} : is useful heat transported to working fluid (air)

Q_{lost} : corresponds to the different heat losses experienced by the collector

With $\frac{dU}{dt}$ which represents change in internal energy stored in collector, this term can be neglected because there is no energy stored in collector, there is a transfer of heat to air to raise its temperature (Chasseriaux, 1990).

The value for Q_{Useful} (Meinel and Meinel, 1982) is obtained from:

$$Q_{Useful} = mc\,(T_{exit} - T_{entry}) \quad ...(2)$$

Donde m : is mass of the air

c : is specific heat of the air

T_{sal} y T_{en} : it is the temperature of exit and entrance of the air respectively.

To calculate efficiency of collector for air heating we use expression (Pitts and Sisom, 1977) :

$$\eta = \frac{Q_{Useful}}{H_T A_C} \quad ...(3)$$

Materials and Methods

For evaluation of heating system, it has been located on the roof of one of hexagons of Basic Physics laboratories of the National University of San Agustín de Arequipa in Peru (UNSA). Process of heating air inside collector has been carried out under normal ambient conditions, because temperatures in system are the most important physical variables to make evaluation of air heating process, it was necessary to use sensors temperature, which were calibrated in the Solar Energy laboratory of the same University. Collector temperatures were measured using the LM35 temperature sensors for their best response in mV/oC and using a DAS 08 / jr data acquisition card, voltage readings were recorded for each sensor where the (average) temperatures were obtained each 10 minutes throughout the day. To measure the solar radiation intensity data, the Kipp-Zonen type CM11 (Data Logger Modas 84) solarimeter was used to record readings for every certain time interval (average values every 10 minutes) (Guía, 1988).

Results

Collector Features

When a solar energy to heat energy transformation system is used, it is necessary to take into account characteristics of heating system, in this case they were:

Length=1.98m, width=0.78m, height=0.44 m, glass gap 0.10m, angle of inclination is between 15 to 30 degrees and flow rate inside 0.3 ± 0.1 m/s

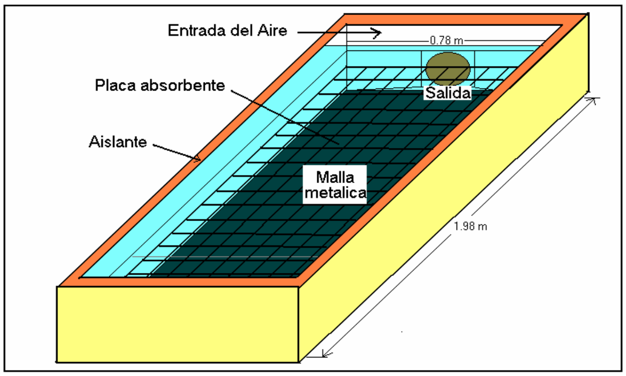

Fig. 1 : Solar collector with U-shaped air passage using a metal mesh.

Material used as thermal insulation was sponge, whose thickness is 5 cm, and placed on sides of collector at bottom (under absorbent plate), cost of materials for construction of heating system is approximately 150 dollars. In order to measure temperature in collector, temperature sensors LM 35 have been placed under the glass1, above glass 2, above the absorbent plate, at the air inlet, at the end of the first air passage (flow between glasses 1 and 2) and at the beginning of second air passage (flow between absorbent plate and glass 2, in presence of the mesh), at the air inlet and outlet.

Temperature and radiation in collector

Temperature data has been permanently recorded using 12-bit DAS 08 / jr data acquisition card with 8 differential channels, incorporated into an 80286-microprocessor computer controlled by Labtech Software Note Book. To measure intensity of solar radiation, a Kipp-Zonen type CM11 (Data Loger Modas 84) solarimeter has been used. To determine speed of air flow inside collector, air speed inside collector was measured with Arnold (Wind Speed Meter). It is necessary to take into account that flow inside collector is forced by an electric fan that sucks air towards exit of system. Flow is laminar, that is to say that air flow is such that it does not become turbulent, so that mathematical model and equations that have to be solved when making energy balance for collector is as simple as possible.

Experimental data on temperature and solar radiation during the months of November, December and January (2001-2002) have been considered. The days when there was high solar radiation were chosen to show better results in our temperature curves. To calculate experimental data errors, partial derivative method has been used (Squires, 1988). Figure 2 shows collector temperature graph for day 1 of the start of measurements. Variation of temperatures is observed in different points of collector where LM 35 temperature sensors have been located. Maximum temperature value reached is at noon.

To measure intensity of solar radiation, a Kipp-Zonen type CM11 (Data Logger Modas 84) solarimeter has been used, which is located on the roof of the Basic Physics (National University San Agustín of Arequipa, Peru) laboratories, to detect direct radiation and diffuse radiation instrument measurement error is: ± 5 W/m^2 Figure 3 shows the plot of solar radiation intensity for day 1. Maximum value for radiation intensity occurs at noon, which is consistent with Figure 2. Maximum temperature reached occurs at approximately 12:00 hours temperature of collector for day 2. with respect to intensity of solar radiation, maximum value coincides with same time.

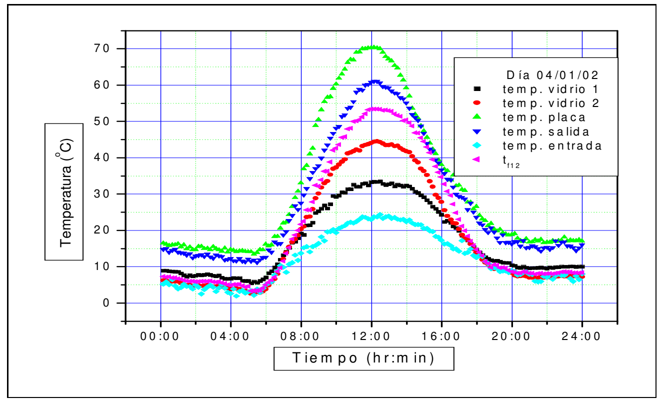

Fig. 2 : Day 1. Temperature as a function of time for collector

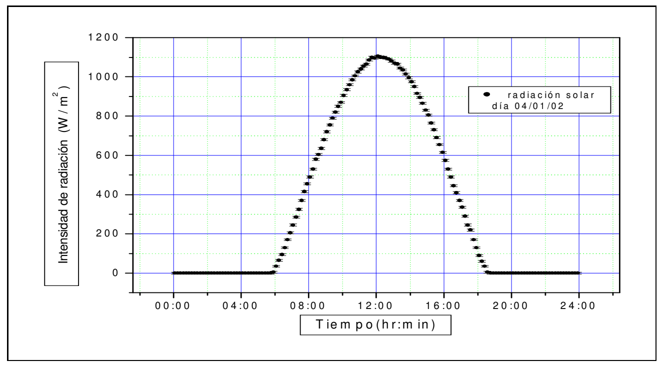

Fig. 3 : Intensity of solar radiation as a function of time for day 1.

For day 4, maximum temperature and radiation value reached occurs at 12:30 pm which differs from previous days. Maximum temperature and solar radiation reached 15 days after start of data collection occurs at 12:00 hours, which differs from previous days.

Useful energy, received energy and collector efficiency

Once the temperature and solar radiation curves are obtained for different days, equation (2) is used to calculate amount of useful or gained energy by the collector, and for the energy received (and absorbed) by collector. Using equation (1), graph (Figure 4) showing us curves of useful energy or energy gained by collector and energy received to heat air in collector for day 3, verifying that much of energy received is used to heat air inside

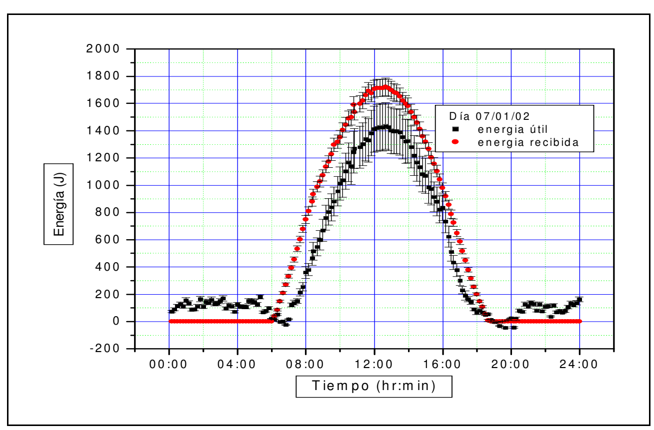

Fig. 4 : Energy received and useful energy per unit time in collector.

To determine efficiency or efficiency of collector, equation (3) was used, where for a given day, this can be seen in Figure (5). Maximum efficiency or efficiency of collector obtained from experimental results is approximately one (85±10) %.

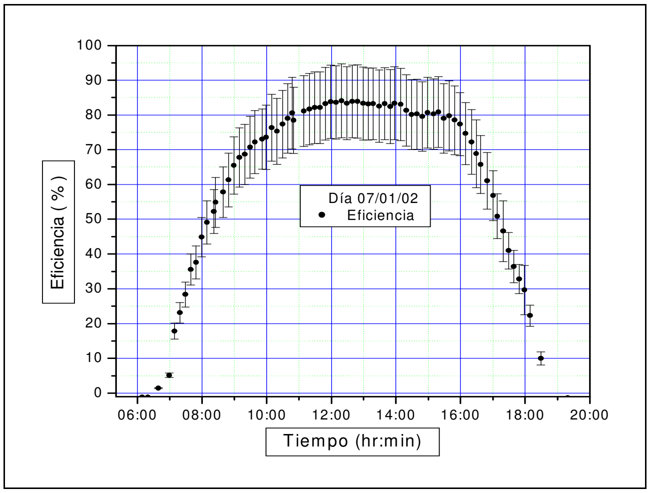

Fig. 5 : Efficiency of collector to heat air during the day

Heating system simulation

Simulation of heating system was carried out in Linux operating system, where Fortran programming language has been worked on. For simulation a program has been developed that uses two subroutines where calculations of temperature matrices are carried out which considers the values of temperature input and output as well as the solar radiation absorbed by glasses and absorbent plate in addition to efficient of heat transfer by convection between upper glass and wind that circulates. Considerations to take into account for the operation of the program is that the calculations are made by taking short sections of collector (lengths of 1 to 3 cm)

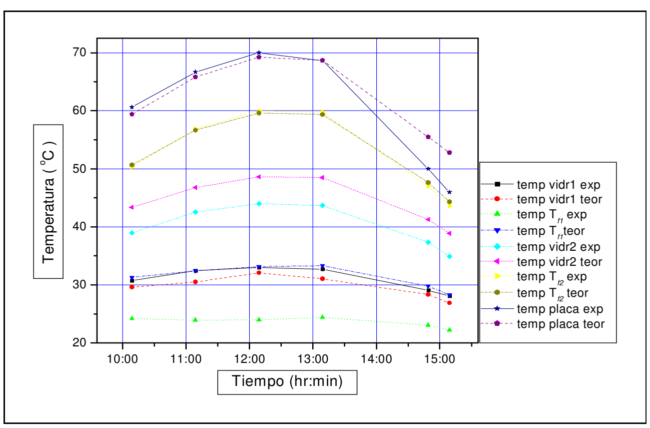

Fig. 6 : Comparison of temperatures, obtained experimentally as well as simulation of heating system for collector

Discussion

Comparison of experimental data with simulation

According to Figure (6) it can be seen that the temperature values obtained from the simulation have an approximation of 0.1 to 1oC for temperatures T_{f2}, T_{plate}, which is good, since temperature error is ± 0.2 °C, while for temperatures T_{f1} and T_{glass2} there is a temperature difference of 5 to 7°C. The fact that values of temperatures obtained from simulation are close to experimental ones, is justified because in model a small displacement of order 10-2m in the flow direction confirmed with postulated has been considered see Figures (7) and (8), where: to $T_{inicial}$ experimental values have been assigned for a given moment and T_{final} is result after simulating with mathematical model (Ong, 1995) and (Ong, 1995).

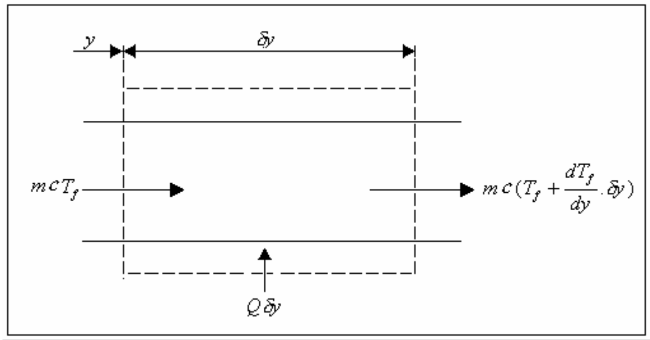

Fig. 7 : Energy balance in a travel element along the flow direction

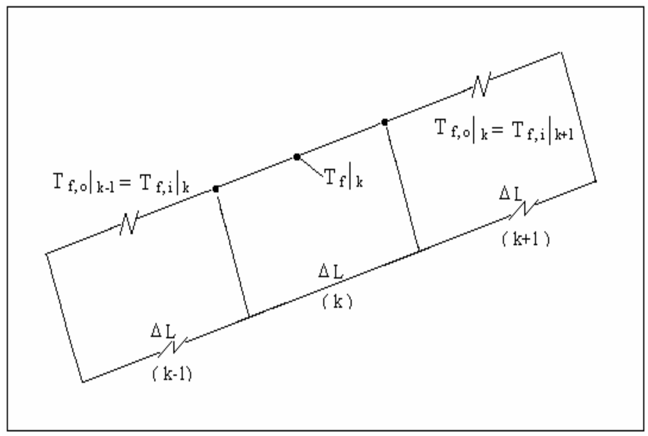

Fig. 8 : Temperature variation along collector.

In Figure (4) if two energy curves are compared, it can be seen that most of (solar) energy received by collector is used (useful energy) in collector to heat air, however considering errors value of these energies are not equal, because if not all the solar energy would be used to heat air and system would reach an efficiency of 100%, which is not possible. In the efficiency curve for collector shown in Figure (5), maximum value reached occurs between 12:00 and 13:00 hours, this is higher the heat collector receives, greater air heating will be. Comparing value of efficiency that has been achieved, with that of other solar heating systems [6], this efficiency has been improved for several reasons:

- Design of collector helps transfer more heat to the air, reducing losses to environment.
- Value of solar radiation intensity is greater in our environment (Cotrina *et al.*, 2004).
- Amount of air mass contained in our collector is greater compared to the other collectors (Mohamad, 1995).

Importance and possible applications of research

The importance of this project is that from design of the collector, use of solar energy has been improved, and so simulation carried out will serve to better study process of heating air inside collector. Fact of considering a displacement of relatively small length (1 to 3 cm) will allow to establish conditions for comparison of experimental temperatures and obtained from simulation through mathematical model. Program that has been developed to determine calculation of temperature matrices (for a very small length of collector); program can be improved in such a way that more information on air heating process can be obtained. Due to temperatures reached by the design of proposed collector, it could be used as an auxiliary heating system in some environments where solar radiation does not reach, it could also be used in agricultural product drying systems (Reyes, 2018) and (Lopardo and Torres, 2018).

Conclusion

Using U-shaped manifold design and placing a metal mesh on absorbent plate improves heat transfer to air inside manifold, heat losses have been reduced, since much of Energy received by collector is used to heat the air. The thermal efficiency of the solar collector varies with intensity of solar radiation, that is, at noon it is when heat energy of collector is most used. Design of collector reaches a thermal efficiency up to (85 ± 10) %, which indicates improvement of efficiency of the collector compared to other solar heating systems (Fauroux, L. E., et al., 2018). Mathematical model developed in this work is justifiable because temperature results obtained from simulation approximate experimental results, there being a theoretical-experimental correlation with an error of ± 10 %.

Suggestions

To make performance of solar collector more optimal, a selective surface such as tin oxide could be used, so that all heat provided by absorbent plate is confined between glass and plate so that air can be better heated. To obtain efficiency from the simulation, it is suggested to make changes in program in such a way that temperatures from entrance to the exit of the air can be obtained.

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