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Study of applications of parabolic trough solar collector technology in Mexican industry

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Abstract

In Mexico, a local enterprise has developed a parabolic trough solar collector to produce thermal energy. This collector has modular characteristics and it has been installed in some industries around the country to meet the thermal load for their processes or diminish the consumption of fossil fuels. Besides this, a local university has made a computational program that predicts the energy output of system with this type of solar collector. This paper presents the results of two systems installed comparing the results with computational and experimental data.

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Keywords: Thermal efficiency; solar collector; parabolic trough; industrial applications; numerical model.

1. Introduction

Inventive Power® is a mexican enterprise that has been participating on the renewable energy market around the country since 2010. It started as an initiative of two Master in Energy Engineering Program students of Instituto Tecnológico y de Estudios Superiores de Monterey, Campus Monterrey, with the support of CONACYT (the National Secretary of Science and Technology in Mexico). Aldo Agraz and Angel Mejía made a technical and economical analysis of a parabolic trough solar collector (respectively) as their thesis project [1,2]. For the thecnical analysis, the ASHRAE 93 standard was used. The solar collector was entirely manufactured by them. The results of their investigation shows that the collector can get a thermal efficiency up to 60% with a feasible economical investment and including its modularity, ideal characteristics for small and medium enterprises (SME`s). After, Agraz and Mejía continued with the enterprise they founded, entering to the energy market in Mexico with the solar collector system they developed as the principal product, and also started a relationship with the University

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Graduate Program as an extension of their Research Department.

Later, Pablo Tagle realized a technical analysis using the SRCC standard 600, which is different than ASHRAE 93 [3]. SRCC standard evaluates both reliability of the entire system (collector and control devices) and thermal efficiency and ASHRAE 93 only make the thermal efficiency analysis for solar collectors. A second part of this study consisted on a numerical evaluation of the collector under different conditions using a computational software, the same that is used to compare the numerical analysis with experimental data on thermal efficiency. The results show that the collector has a good reliability but its fabrication can be improved to make both reliability and maintenance better, so some improvements were proposed. For the thermal analysis it was found that the software predicts the behaviour of the collector with good accuracy. The improvements proposed were realized on a new collector model, and this is now commercialized by the enterprise.

This study presents the results of comparing two cases of systems installed by the enterprise and the computational model. Both the collector system and computational model is explained in detail.

Nomenclature

ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
SRCC	Solar Rating and Certificate Corporation
SME	Small and medium enterprise

A	Effective area of collector (m^2)
C_p	Heat capacity (J/kgK)
D_i	Diameter of surface i (m)
I	Solar irradiance (W/m^2)
K_{ij}	Thermal conductivity of material between surfaces i and j (W/mK)
L	Length of collector (m)
$\dot{m}$	Mass flow (kg/s)
Nu	Nusselt number (dimensionless)
Pr	Prandtl number (dimensionless)
q'	heat flux per unit of length (W/m)
T_i	Temperature (ºK)
α_i	Absorptance of surface i (dimensionaless)
ε_i	Emittance of surface i (dimensionaless)
η_N	Thermal efficiency of a system of N collectors (dimensionaless)
η_{opt}	Optical efficiency of collector (dimensionaless)
τ_i	Transmittance of surface i (dimensionaless)
σ	Stefan-Boltzmann constant (5.67×10^{-8} W/m^2K^4)

Subscripts

1 - 5	Surface of measurement
in	inlet
out	outlet
w	measurement at wall

2. Description of the system

The solar collector system has 3 components: the collector, the solar tracking and the data measurement device. The principal product is the solar collector, but in order to increment the efficiency of the collector the enterprise has developed their own control devices. Each of the components is detailed below.

2.1. Solar collector

Table 1 shows the principal data about the collector. One of the principal characteristics is its modularity due to its dimensions and materials. These characteristics make the collector feasible for SME's because it does not need special machinery for transportation or maintenance. It is also shown that the collector is designed for working temperatures between 60ºC and 180ªC covering a huge range of industrial applications that use temperatures in their processes.

Table 1. General Characteristics of the collector

Design	
Aperture (m)	1.1
Length (m)	3
Efective area (m2)	3.3
Mirrors	Anodized aluminum
Structure	Galvanized steel
Receiver	AISI 304, 1" nom. Diam.
Cristal cover	Borosilicate
Selective coating	Solkote
Weight (kg)	55
Estimated lifespan	>20
Thermal Performance	
Thermal efficiency (%)	60
Mean Power (W)	1815
Temperature (ºC)	50 – 200

2.2. Tracking system

This device is used to make the collector follow the sun during the day to maximize its efficiency. It works with sensors that determine the position of the sun and send signals to an electronic board that controls the movements of the collector. The tracking system also can be installed in other solar systems, with thermal or electric output, and for one or two axis control.

2.3. Monitoring device

Due to that the cost of energy is not the same through the day, the monitoring device reduce the demand of the system in high-cost schedules. Besides this, it measures electric parameter (active and reactive power and energy, voltage and amperage used) and can be controlled by web.

3. Description of the computational model

The computational model is based on a one-dimensional steady-state thermal-resistance heat transfer model, where all heat transfer modes involved on the physical phenomena are considered. The computational model was first developed by Forristall [4], and was used to determine the thermal efficiency of parabolic solar collectors. This model was improved and it can predict the behavior of any parabolic collector design under any ambient condition and with a variety of work parameters. The software used to simulate the thermal model is Engineering Equation Solver, a software that can solve a non-linear system equation, just like the heat transfer correlations.

The heat transfer model considers radiation, convection and conduction heat transfer modes. Figure 1 shows the thermal resistance diagram used to simulate the phenomena. The model use theoretical equations to determine radiation and conduction heat transfer and correlations to determine the heat transfer coefficient by convection. Table 2 describes the equations and the considerations of each heat transfer involved.

Table 2. Heat transfer model description.

Heat Transfer	**Considerations**	**Equations or Correlations**
To working fluid (q'12 conv) [a]	Interior-forced convection in long cylinder with constant heat flux	Laminar flow: $Nu = 4.36(Pr/Pr_w)^{0.11}$ Transitional Flow: Churchill correlation with modified Reynolds number * Turbulent Flow: Gnielinsky correlation *
Through receiver (q'23 cond)	Conduction in long isothermal cylinder	$q'_{23\,cond} = 2\pi K_{23}(T_3 - T_2)/ln(D_3/D_2)$
Convection in annulus (q'34 conv)	Natural convection	Raithby-Hollands correlation *
Radiation in annulus (q'34 rad)	Radiation in annular cavity for isothermal surfaces	$q'_{34\,rad} = \pi D_3\sigma(T_3^4 - T_4^4)/\{1/\varepsilon_3 + D_3/[D_4(\varepsilon_4 - 1)]\}$
Through cover glass (q'45 cond)	Conduction in long isothermal cylinder	$q'_{45\,cond} = 2\pi K_{45}(T_4 - T_5)/ln(D_5/D_4)$
Convection to ambient (q'5a conv) b	Natural or forced convection (depending on wind velocity)	Natural convection: long horizontal isothermal cylinder (Churchill-Chu correlation *) Forced convection: long isothermal cylinder in external cross flow (Zhukauskas correlation *)
Radiation to ambient (q'5c rad) [b]	Small gray-body in long cavity (sky)	$q'_{5s\,rad} = \varepsilon_5\pi D_5\sigma(T_5^4 - T_s^4)$
Through supports (q'3s cond) [b]	Infinite extended surface with constant cross area under natural or forced convection (depending on wind velocity)	Natural convection: Churchil-Chu correlation * Forced convection: Zhukauskas correlation *
Heat flux in receiver (q'3) [c]	Heat flux in external cylindrical surface	$q'_3 = \eta_{opt}\tau_5\alpha_3 IA$
Heat flux in cover glass (q'5) [c]	Heat flux in external cylindrical surface	$q'_3 = \eta_{opt}\alpha_5 IA$

[a] Useful heat flux
[b] Heat looses
[c] Income heat flux
* Correlations from reference [5]

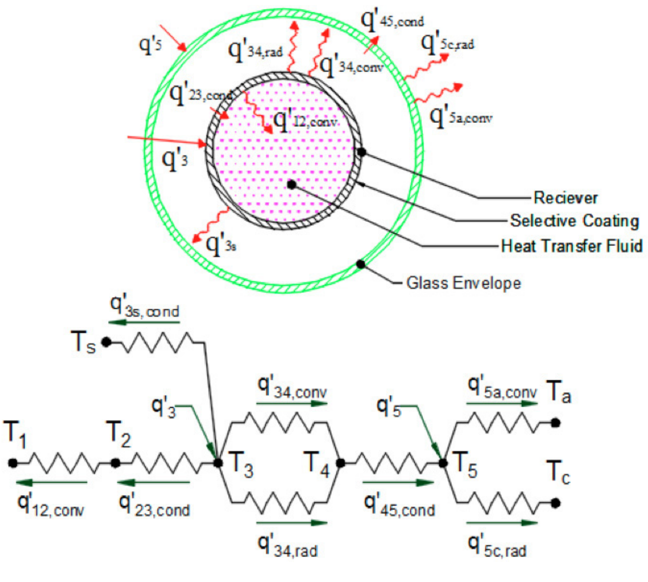

Fig. 1. Thermal model with its thermal resistance circuit equivalence.

After to compute the useful heat transfer, in combination with an inlet temperature and the length of the collector, an output temperature is calculated as shown in equation (1). For collectors in series the output temperature of a collector is taken as inlet temperature for the next one, and so on for the others. Then, a net thermal efficiency and output temperature for the system can be obtained.

$$\eta_N = \frac{\sum_{i=1}^{N}(q'_{12\,conv})_i}{INA} = \frac{\dot{m}C_P(T_{out} - T_{in})_N}{INA} \qquad (1)$$

4. Cases of study

For this study, two different systems installed by Inventive Power® were analyzed, each is described below and both systems are for water-heating purposes. The principal purposes in the systems installed are: pre-hetated water for boiler, cleaning machinery, pasteurization and other processes with water heated up to 95ºC. The weather conditions and general data of the systems are also shown. The results obtained are based on input and output data from the computational model.

4.1. Chicken food production industry

In Morelia (Michoacán state), there is a factory that produces food for chicken. The vapor needs of the factory were estimated in 12150 l/day. For meet this load, they use a common boiler with LPG as fuel. Table 3 shows the principal data about the needs of the factory taken before installing the system and the proposed solar collector system. With this data, an estimation of 920W/m2 of mean solar radiation during approximately 6h of sun was simulated on the system. The results show that under this conditions the system can heat the water up to 85ºC obtaining 140kW as maximum thermal output with a mean net efficiency of 58%. Figure 2 shows how temperature and efficiency varies through each collector in the system.

Table 3. Data for chicken food factory

General Information	
Location	Morelia, Michoacan
Mean annual direct solar insolation (kWh/m2day)	5.784
Source of energy	Boiler
Water heating information	
Initial temperature (ºC)	20
Required temperature (ºC)	150
Total volume (l/day)	12150
Fuel consumption and CO2 emissions	
Fuel consumption (kg/day)	105
Aprox. Emissions (Ton/year)	155.5
Solar collector system (proposed)	
Number of collectors	80
Inlet Temperature (ºC)	25
Outlet temperature (ºC)	95
Total Power (kW)	126.30
Water flow rate (GPM)	9

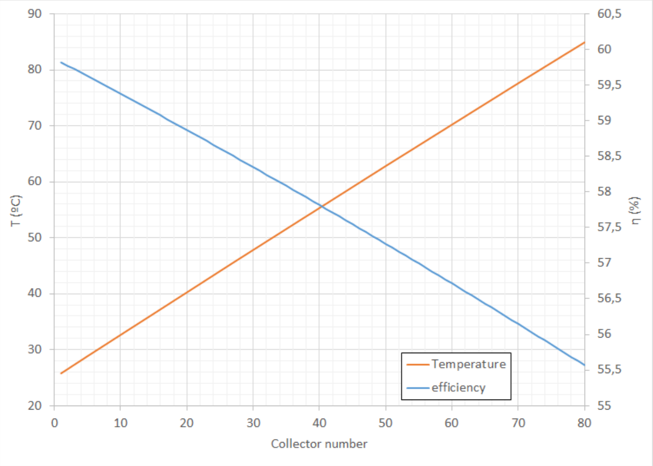

Fig. 2. Temperature and efficiency variation in system (case 1).

4.2. Shrimp food production industry

For this case, the factory is in San Miguel Zapotitlán (Sinaloa state). In the process they need an amount of 11000 l/day of heated water to meet their production. In this case a boiler is also used but with fuel oil as fuel. Similar to previous case, Table 4 shows the principal data about the needs of the factory taken before installing the system and the proposed solar collector system. For this case, a mean solar radiation of 1000W/m2 during approximately 6h of sun was simulated. The results show that this system can heat water up to 90ºC with a maximum output of 103kW and a net thermal efficiency of 57%. Figure 3 shows the variation of temperature and efficiency in the system.

Table 4. Data for shrimp food factory

General Information	
Location	San Miguel Zapotitán, Sinaloa
Mean annual direct solar insolation (kWh/m2day)	6.282
Source of energy	Boiler
Water heating information	
Initial temperature (ºC)	37.7
Required temperature (ºC)	80
Total volume (l/day)	11000
Fuel consumption and CO2 emissions	
Fuel consumption (l/month)	19800
Aprox. Emissions (Ton/year)	928
Solar collector system (proposed)	
Number of collectors	54
Inlet Temperature (ºC)	37.7
Outlet temperature (ºC)	95
Total Power (kW)	89.63
Water flow rate (GPM)	7.71

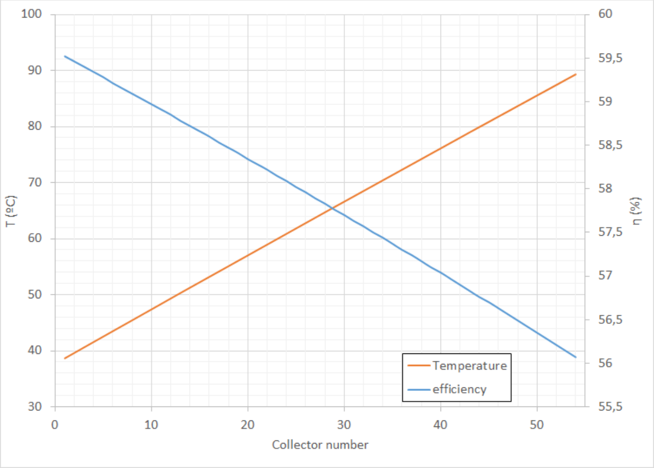

Fig. 3. Temperature and efficiency variation in system (case 2).

5. Conclusions

It was developed a computational software that analyzes a parabolic trough solar collector system and was compared with system installed by Inventive Power®. The results show that the model predicts the thermal output with around 10% of error in accuracy, this with weather data taken from internet to simulate the system in the model (due to a lack of weather data acquisition system on the site). The model also predicts the behavior of the temperature and thermal efficiency through each collector in the system.

With this results, both the computational model and the collector can be improved to get a better performance. This is a part of the future work about this study. Also, for the model, it is modifying the code to analyze a collector system that allows a change of phase in the collectors.

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