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Output Temperature Control of a Flat Plate Solar Collector Subject to Time-Varying Environmental Conditions

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Abstract: Solar collectors are heat exchangers that transfer solar energy to a fluid in the form of heat; however, the problem is that solar energy is not constant, and it is essential for industrial applications the deliver a continuous thermal load or constant temperature. In this paper, we avail of a nonlinear mathematical model developed by us. Such a model predicts the collector's output temperature subject to time-varying, unknown solar irradiance, ambient temperature, and wind speed. To deliver a constant temperature at the collector outlet, we designed a PI control, considering the derivative of the input flow ($d\dot{m}/dt$) to the collector as a manipulated variable. We show its applicability through simulation but considering natural environmental conditions.

Keywords: Solar energy, solar collector, modeling, control, outlet temperature.

1. INTRODUCTION

Solar energy is considered a viable alternative for integrating solar thermal energy into industrial processes in applications such as heating or cooling fluids for food, textile, and room heating industries. There are equipment and devices designed to capture solar energy and deliver it to a process or service; these equipment are known as solar collectors, which are a type of heat exchanger in which energy exchange takes place between a distant source and a flux in the collector Pandey and Chaurasiya (2017). Solar collectors can supply the energy required for industrial processes; however, their challenge is to maintain the target temperature constantly in the face of climatic changes.

According to the International Energy Agency (IEA), the food, beverage, and textile sectors are the main industrial sectors that could use solar thermal energy to couple it in their processes Vannoni et al. (2008).

Solar collectors have been implemented in the dairy industry, such as the powdered milk plant in New Zealand. The potential of integrating a solar thermal system to meet the heat demand of the process was investigated, demonstrating that they can achieve savings in utilities. The pasteurization (62 °C - 85 °C) and sterilization (130 °C - 150 °C) processes consume 23 percent of the energy in the dairy industry Atkins et al. (2010). In the process of making beer in a Spanish company, it has used solar thermal energy to generate low-pressure steam that requires temperatures of 100 °C - 110 °C Schweiger et al. (2013). Thermal solar energy has been used in the textile industry for heating liquid baths that require temperatures of 100 °C for washing, bleaching, and dyeing. The heat supply to such a liquid bath is a major energy consumer in this industry Frey et al. (2015).

Mathematical model studies have been carried out to predict the collector's behavior. Hamed et al. (2013), developed a dynamic model keeping constant the ambient temperature and the wind speed. He found that the outlet temperature and the heat loss coefficient decreased if increased the water flow. Sun et al. (2016), presented a mathematical model based on finite differences, keeping radiation, ambient temperature, and wind speed constant. He found that an increase in mass flow had a negative effect on the outlet temperature. Silviano Mendoza and Martínez Rodríguez (2018), developed a mathematical model in a transient state that would predict the outlet temperature considering the heat loss coefficient and the mean plate temperature as a variable, finding that the model could predict the outlet temperature. Sarwar et al. (2020), developed a model to analyze the performance of a solar collector by varying the angle of inclination of the collector, finding that the efficiency was greater than 70 percent with angles of inclination between 12° and 50°.

The industrial sectors that couple solar thermal energy to their processes are non-linear systems that are usually complex because different variables and parameters that affect the system's behavior are considered. Control studies have also been carried out in the area of solar energy. For example, Álvarez et al. (2009), proposed a repetitive control to a PD controller manipulating the fluid flow to improve the control of the fluid outlet temperature in distributed solar collector fields, assuming that the irradiance, the ambient temperature, and the inlet temperature were constant. On the other hand, Guzmán et al. (2020), presented a PID control with parallel feedback, finding that with this approach, the control system reacted instantly to changes in irradiance and input temperature disturbances, improving the response of the control scheme.

In this paper, we avail of a mechanistic, one-dimensional, dynamic model developed by us Uribe-Mora et al. 2021. Such a model predicts the behavior of the flat plate solar collector. Unlike other studies, we have considered environmental variations such as irradiation, ambient temperature, and wind speed. Finally, a control scheme was designed to mitigate environmental effects and achieve the target temperature required for the processes, regardless of weather conditions. Such a model requires online knowledge of the irradiation, ambient temperature, and wind speed. To achieve such a constant temperature at the collector's output, we chose the time derivative of the collector's influx rate as the control variable. Due to the choice of the control variable, the collector's output flux is time-varying.

2. CHARACTERISTICS OF FLAT PLATE SOLAR COLLECTOR

The collector considered for this project is a flat plate solar collector that uses water as the working fluid and consists of five main elements as shown in Fig. 1:

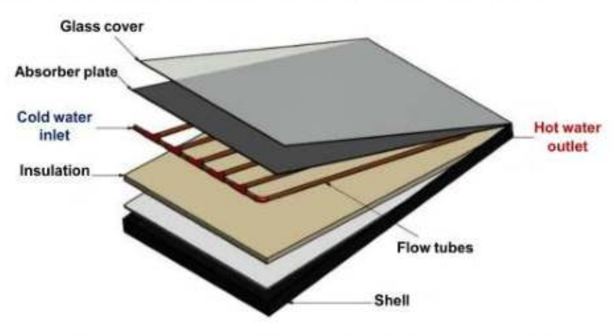

Fig. 1. Flat plate solar collector Abril Ortega et al. (2017).

- Glass cover: must have the appropriate thermal conductivity and transmission coefficients to cause the greenhouse effect and reduce losses.
- Absorber plate: receives solar radiation and converts it into heat to transmit it to the working fluid.
- Flow tubes: carries the working fluid.
- Insulation: used to reduce thermal losses at the bottom and edges of the collector. The materials can be fiberglass, rock fiber, cork, polyethylene or polyurethane.
- Shell: made of aluminum or stainless steel, protects and supports the collector's elements, allowing the collector to be anchored and fixed to the mounting structure. Must resist temperature changes and must resist corrosion Tiwari and Sahota (2017).

3. MATHEMATICAL MODEL

3.1 Energy balance equations

The following describes the mathematical model of heat transfer for a flat plate solar collector. The useful energy output of a collector is the difference between the absorbed solar radiation and the thermal loss. The global energy balance for a solar collector is Uribe-Mora et al., 2021:

$$Q_{useful} = Q_{absorbed} - Q_{lost} \tag{1}$$

where Q_{useful} is the energy gained by the working fluid, $Q_{absorbed}$ is the total energy absorbed by the collector surface and Q_{lost} is the energy lost to the ambient by convection, conduction and radiation.

Defining each term of the global balance we have:

$$Q_{useful} = \dot{m}C_p(T_o - T_i)$$
$$Q_{absorbed} = A_s G_s \alpha\tau$$
$$Q_{lost} = A_s U_L(T_{pm} - T_a)$$

Replacing each term in the global balance we obtain:

$$\dot{m}C_p(T_o - T_i) = A_s[G_s\alpha\tau - U_L(T_{pm} - T_a)] \tag{2}$$

where $\dot{m}$ is the mass flow (kg/s), C_p is the specific heat (kJ/(kg°C)), T_o is the fluid outlet temperature (°C), T_i is the fluid inlet temperature (°C), A_s collector area (m^2), G_s solar radiation (W/m^2), α selective layer absorbance, τ glass cover transmittance, U_L overall heat loss coefficient (W/(m^2°C)), T_{pm} mean plate temperature (°C), T_a ambient temperature (°C).

Deriving (2) as a function of time, we obtain the mathematical model of dynamic heat transfer for a flat plate solar collector to calculate the change in the fluid outlet temperature concerning time, considering the variations in irradiation, wind speed, ambient temperature, overall heat loss coefficient, fluid inlet temperature, mass flow and the mean plate temperature is the plate's temperature that absorbs radiation, and this is transferred to the fluid in the form of heat.

Selective layer absorbance α and glass cover transmittance τ are considering constant.

The dynamic energy balance as a function of time can be expressed as:

$$\frac{dT_o}{dt} = \frac{A_s}{\dot{m}C_p}\left[\alpha\tau\frac{dG_s}{dt} - (T_{pm} - T_a)\frac{dU_L}{dt}\right] - \frac{A_s}{\dot{m}C_p}U_L\frac{d(T_{pm} - T_a)}{dt} + \frac{dT_i}{dt} - \frac{T_o - T_i}{\dot{m}}\frac{d\dot{m}}{dt} \quad (3)$$

The collector overall loss coefficient U_L is the sum of the top, bottom, and edge loss coefficients Duffie and Beckman (1982):

$$U_L = U_t + U_b + U_e \quad (4)$$

U_t is the top loss coefficient from the collector plate to the ambient, and it is defined as:

$$U_t = \left(\frac{1}{h_{c,p-c} + h_{r,p-c}} + \frac{1}{h_w + h_{r,c-a}}\right)^{-1} \quad (5)$$

where $h_{c,p-c}$ is the convection heat transfer coefficient from the plate to the cover $(\mathrm{W}/(\mathrm{m}^2\,{}^\circ\mathrm{C}))$, $h_{r,p-c}$ is the radiation heat transfer coefficient from the plate to the cover $(\mathrm{W}/(\mathrm{m}^2\,{}^\circ\mathrm{C}))$, h_w is the wind heat transfer coefficient $(\mathrm{W}/(\mathrm{m}^2\,{}^\circ\mathrm{C}))$, and $h_{r,c-a}$ is the radiation heat transfer coefficient from the cover to the ambient $(\mathrm{W}/(\mathrm{m}^2\,{}^\circ\mathrm{C}))$.

U_b is the bottom loss coefficient and it is defined as:

$$U_b = \frac{k}{L_b} \quad (6)$$

where k is the insulation thermal conductivity and and L_b is the bottom insulation thickness.

U_e is the edge loss coefficient and it is defined as:

$$U_e = \frac{kP_cE_c}{L_eA_s} \quad (7)$$

where k is the insulation thermal conductivity $(\mathrm{W}/(\mathrm{m}\,{}^\circ\mathrm{C}))$, P_c is the collector perimeter (m), E_c is the collector thickness (m), L_e edge insulation thickness (m), and A_s collector area (m^2).

3.2 Environment data

For the study of this paper, experimental data of environmental variables such as irradiance, ambient temperature, and wind speed were collected, provided by the Solar Testing Laboratory of the University of Guanajuato. We analyzed 600 data/day for each of these variables for the days of January.

- We consider the fit to a second-degree polynomial for the irradiance data, as shown in Fig. 2, finding that the equation of the polynomial function is $y = -25.173x^2 + 646.5x - 3549.2$ $(\mathrm{W/m^2})$ with a fit $R^2 = 0.8443$. We integrate this time-varying polynomial and determine the incident irradiation in a period of time per square meter for each day in January. We found that the 13th of January was the day with the lowest irradiation, with a value of 3600 $(\mathrm{W\,h/m^2})$.

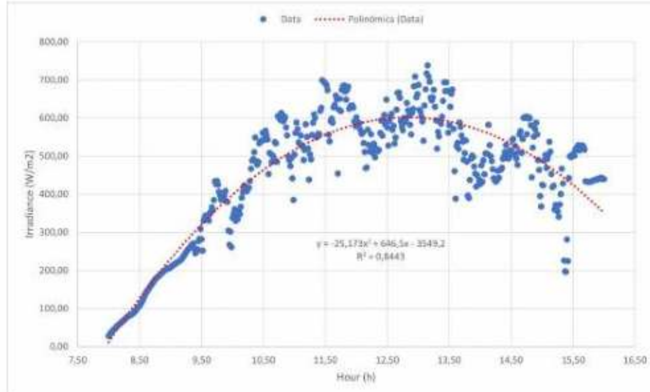

Fig. 2. Irradiance on January 13.

- We consider the fit to a third-degree polynomial for the ambient temperature data, as shown in Fig. 3, finding that the equation of the polynomial function is $y = -0.0326x^3 + 1.191x^2 - 13.208x + 62.357$ (°C) with a fit $R^2 = 0.9714$.

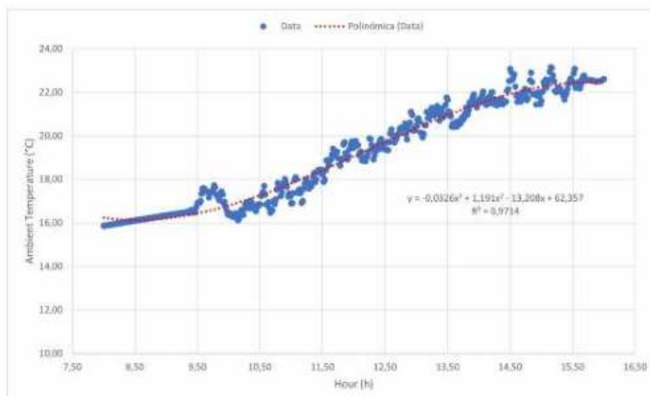

Fig. 3. Ambient Temperature on January 13.

- We also consider the fit to a fourth-degree polynomial for the wind speed data, as shown in Fig. 4, finding that the equation of the polynomial function is $y = 0.0096x^4 - 0.4614x^3 + 8.1035x^2 - 61.287x + 169.04$ (m/s) witn a fit $R^2 = 0.4599$.

For ambient temperature and wind speed data, We will obtain the integral of the mean value to determine the mean ambient temperature and the mean wind speed for each day of January.

3.3 Automatic control scheme for a flat plate solar collector

In our case study, to achieve the target temperature in a solar collector and maintain this constant temperature throughout the application of the process, it is necessary to design a control scheme using the derivative of the input flow $(d\dot{m}/dt)$ to the collector as a manipulated variable and considering the outlet temperature collector

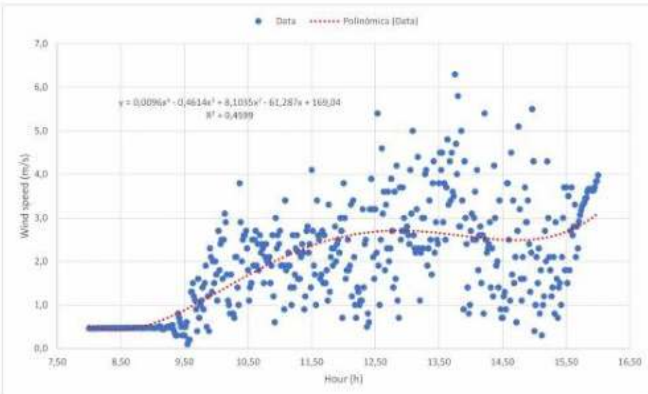

Fig. 4. Wind Speed on January 13.

as a controlled variable. This control scheme will mitigate environmental and operational disturbances such as irradiation, wind speed, ambient temperature, overall heat loss coefficient, and the mean plate temperature. Fig. 5 shows the proposed control scheme to guarantee a constant outlet temperature, using a PI control.

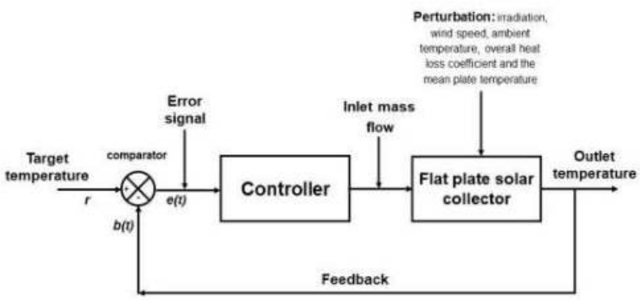

Fig. 5. Control scheme for a flat plate solar collector.

In order to achieve the regulation of the collector's output temperature, let $e(t) = T_o - T_o^*$, where T_o^* is the constant, target temperature for the output.

In order to drive $e(t) \to 0$, we avail of a PI control whose control variable is $u(t) = \frac{\mathrm{d}\dot{m}}{\mathrm{d}t}$; that is to say

$$u(t) = k_p e(t) + k_i \int_0^t e(t)\mathrm{d}t \qquad (8)$$

We apply such a control law to the dynamical model in (3). The following section we show the performance of the closed loop system under time-varying, real environmental conditions. Please notice that to perform the (closed loop) simulations we must know the time values of the time-derivatives of $G_s(t)$, $T_{pm}(t), T_i(t)$, and $U_L(t)$. Such time derivatives are computed off-line and are then fed to the model. The requirement of such derivatives, hinders the online implementation of this control scheme, since they are difficult or impossible to measure in practice.

4. ANALYSIS OF RESULTS

4.1 Mathematical model simulation

In the mathematical model proposed in (3), we carried out the model's programming in the Matlab mathematical software, varying the irradiation, ambient temperature, wind speed, mean plate temperature, and the overall heat loss coefficient. We use a constant water flow of 1.8 (L/min), inlet temperature of 20 °C, absorbance α of 0.96 and transmittance τ of 0.96. For the mathematical model simulation, the data for January is considered because it is the winter season. The irradiation and the temperature are lower at this time of the year. The Matlab integrator ode15s solved the system of equations.

Fig. 6, we can see the blue color curve that corresponds to the theoretical solar collector outlet temperature calculated using the proposed mathematical model, and the red color curve represents the outlet temperature from experimental data. According to Fig. 6, we can find that the theoretical model fits the experimental data and predicts the collector outlet temperature satisfactorily.

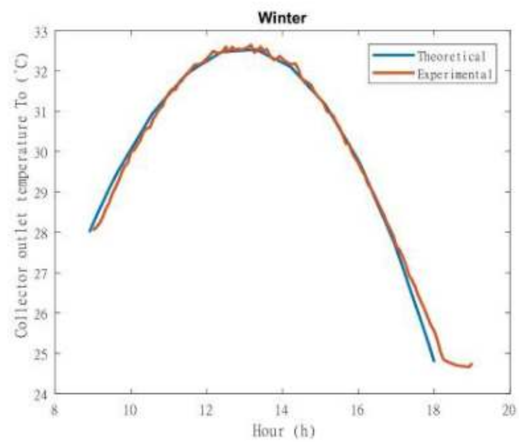

Fig. 6. Theoretical and experimental collector outlet temperature.

4.2 Automatic Solar Collector Control

With the developed mathematical model, a PI integral proportional control scheme was designed, manipulating the derivative of the mass flow to achieve the required target temperature despite environmental and operating disturbances. Fig. 7, we can see how the control reaches the target temperature and steadily stabilizes. Finally, in Fig. 8, we can observe the change of the derivative of the mass flow in the control of the solar collector.

5. CONCLUSIONS

- The proposed mathematical model was able to predict the behavior and the outlet temperature of the flat plate solar collector considering the variations in

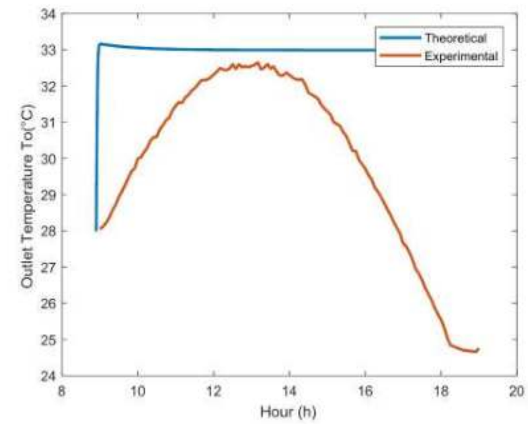

Fig. 7. PI control for solar collector.

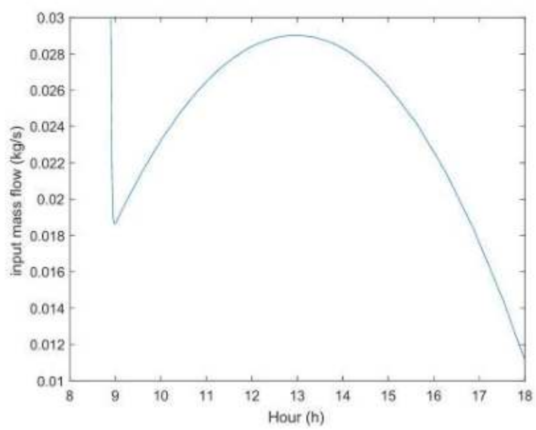

Fig. 8. Variation of the mass flow in the control of the solar collector.

irradiation, wind speed, ambient temperature, overall heat loss coefficient, fluid inlet temperature, and the mean plate temperature.

- We validated the proposed mathematical model with experimental data from a flat plate solar collector used by the Solar Testing Laboratory of the University of Guanajuato.
- With the proposed control scheme, the PI control maintains a constant temperature in the collector outlet flow, calculating the derivative of the system's mass flow and thus ensuring the required thermal load in the process.
- The simulation and control require the time-derivative of the environmental conditions, which are perhaps impossible to measure in practice.

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