Design, construction and evaluation of a system of forced solar water heating.

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Abstract. The main purpose of this project was to design, construct and evaluate a system of forced solar water heating for domestic consumption, at the Universidad Pontificia Bolivariana-Bucaramanga, Colombia; using solar energy. This is a totally system independent of the electrical grid and an important characteristic is the heating water doesn’t mix with the consumption water. The system receives the solar radiation through a flat-plate collector, which it transmits the heat to the water that it flow with impulse from the centrifugal pump of 12VDC, the water circulates toward helical serpentine it is inside of the tank of the storage whose capacity is 100 liters of water. The temperature of the tank is regulated with a controller in such a way that de-energized the pump when it gets the temperature required. The performance thermal or efficiency of the system was evaluated like a relationship between the delivered energy to the water in storage tank and the incident energy in the flat-plate collector.

1. Introduction

In the publication by Chuck Marken, 2009 [1], a foundation on solar energy exchanger is made, which transfer heat from one fluid to another without contact between them. The most important design parameters are the wall material should be a good conductor, the contact area, the physical configuration of coil or flat pipe, the flow rate, and the type of fluid, generally water depending on the weather will additives added. Brian Mehalic [2], speaks of the need to install pressure relief valves in the tank, because the water temperature increases and pressure causing a possible rupture of the tank, therefore keep a good coating for long periods of time the temperature in the tank and the material must be resistant to maintain suitable conditions, water consumption is required. In 2007 an American professor builds a forced flow heater (system that was implemented in this project) and James Dontje [3] describes step by step each of the determinations that led to the construction of this system. The first step was the choice of system, he ruled out direct systems which will expose a pipe to freeze. The thermosiphon system was out of reach for the need to place the tank below the collector, he thought of a photovoltaic system powered by a DC pump, closed loop which used distilled water and create drains pipe to prevent damage when the water freezes. One of the big challenges was to reach the desired pump head, as already being in the maximum height, beat other resistance is relatively easy. There is little head is expected to pump current and usually more striking pumps AC found in greater quantity, variety and low cost, but the ultimate goal was the independence of the network, so it had to work to find the DC pump indicated. Prior to mounting the pump, the required maximum height was measured and was a test to see if the pump was able to reach it. Indeed he did, including the
bypass, which served to beat other resistance. The rest was working plumbing, electrical installations and protection. Getting to the end of the first day at 90 gallons of water at 50 °C.

Numerous studies have investigated the performance of solar water heaters operating by thermosiphon [4-7]. Burbano et al. [4] they built a thermosyphon solar water heater with an interesting design process. Zerrouki A. et al. [5] found experimentally that the rate of mass flow increases in the hour of greatest radiation (11 am-2pm). Sakhrieh and Al-Ghandoor [6] presented an experimental study of the performance of different types of solar collectors and conclude that the vacuum tube collector is the top performer with respect to efficiency, with a maximum value of 72%. Gupta and Garg [7] experimentally proved that the flow rate of a thermosyphon water heater can be increased if the relative height between the collector and the storage tank is increased, but the efficiency is not increased.

2. Theory
2.1 Energetic balance of a flat collector

\[ Q_1 = Q + Q_2 \]  \hspace{1cm} (1)

\( Q_1 \): is the incident energy (direct + diffuse + albedo) in the unit time.
\( Q \): is useful energy, by collecting the heat transfer fluid.
\( Q_2 \): is the energy lost by dissipation to the environment.

Given the definition of intensity of radiant energy, \( Q_1 \) is the product of the intensity and the surface. Not all the incident energy \( Q_1 \) will be absorbed in the absorber. First, if there is deck, you have to have the transmittance in a count, which will leave to flow part of this energy (\( \tau SI \)). Moreover, the absorption coefficient \( \alpha \) or absorptance of the absorber plate never becomes equal to unity, so that the fraction of energy actually absorbed is:

\[ Q_1 = \tau \alpha SI \]  \hspace{1cm} (2)

As for the energy lost \( Q_2 \), detailed calculation is very complex because, must be taken into account simultaneously and in different proportions losses by radiation, convection and conduction. However, in order to be able to use a simple formulation, it has been agreed to include these influences in the overall loss coefficient called \( U \), which is measured experimentally and is data supplied by the manufacturer. Experience has shown that supposing losses per unit of surface proportional to the difference between the average temperatures \( t_c \) of the absorber plate and the environment \( t_e \), being the proportionality factor the coefficient \( U \), is a good approximation. So that:

\[ Q_2 = SU (t_c - t_e) \]  \hspace{1cm} (3)

Substituting (2) and (3) in (1) is obtained:

\[ Q = S [I(\tau \alpha ) - U(t_c - t_e)] \]  \hspace{1cm} (4)

\( S \): collector surface
\( I \): radiant intensity [W / m²]
\( \tau \): transmittance of the transparent cover
\( \alpha \): absorptance of the absorber plate
\( U \): overall loss coefficient [W / (m² °C)]
\( t_c \): average temperature of the absorbing plate [°C]
The efficiency ratio of the collector, $\eta$, is defined by the relationship between energy captured and received at a given instant according to the equation (5).

$$\eta = \frac{Q}{[SI]} \quad (5)$$

Substituting (4) in (5) is obtained (6)

$$\eta = F_R[(\tau a) - U(t_m - t_a)] / I \quad (6)$$

Where $t_m$ is the mean temperature of the collector according to the equation (7).

$$t_m = \frac{(t_e + t_s)}{2} \quad (7)$$

For a flat plate collector, the equation (6) is approximate to the equation (8) [8].

$$\eta = 0.83 - 6.8(t_m - t_a) / I \quad (8)$$

### 2.2 Efficiency of the system

$\eta$ = Delivered Energy / Received Energy from collector

$$\eta = \frac{qt / t}{Ac * Gt} \quad (9)$$

qt : Quantity of received heat by stored water

$t$ : Time where hot is received (was taken 1 h)

Ac : collector Area

Gt : Average radiation during the time that tank received radiation

qt = m*Cp*(Tf – To)

Tf: End Temperature of water in the tank.

To: Initial Temperature of water in the tank.

### 3. Methodology

The system built solar heating forced shown in Figure 1. The solar collector has the dimensions 2.0 m * 1.2 m * 0.13 m with stainless steel plates and copper according to Figure 1. Internally the collector has twelve copper tubes. The collector has a tempered glass dimensions 1.6 m * 0.8 m, which determines the catchment area of solar radiation.

The water heating system shown in Figure 1, is performed in a cycle that involves two stages, in the first water from the external tank it flows through the pump to the flat plate collector and take heat from it in the second stage will he sent water to a helical coil that is inside the storage tank, there while the water flows through the coil transmits heat acquired in the collector to the drinking water, finally the water is discharged into the external tank. This process is carried out in a loop driven by a 12V DC centrifugal pump and de-energizes the pump controlled by a pyrometer that when the temperature is ideal. Table 1 shows the results of calculating the efficiency of the system of the Figure 1.
Figure 1. Implemented forced solar water heating system

| Day | $T_o$ [°C] | $T_f$ [°C] | $A_c$ [m$^2$] | $\dot{Q}$ [W/m$^2$] | $\Delta T$ | $q_t$ [J] | Efficiency [%] |
|-----|------------|------------|---------------|----------------|-----------|---------|---------------|
| 24  | 32.2       | 35.2       | 2.4           | 786            | 3         | 368.2   | 19.5          |
| 25  | 40.8       | 44.5       | 2.4           | 874            | 3.7       | 454     | 21.6          |
| 26  | 44.9       | 47.8       | 2.4           | 1877           | 2.9       | 354     | 18.9          |
| 27  | 46.4       | 49.5       | 2.4           | 1097           | 3.1       | 380     | 14.4          |
| 28  | 49.3       | 55         | 2.4           | 1125           | 5.7       | 700     | 25.9          |
| 31  | 37.4       | 39.4       | 2.4           | 574            | 1.9       | 233     | 16.9          |

Efficiency in Table 1, is the best obtained efficiency that day, calculated according the equation (9) and the experience was made from 24 to 31 August of 2015.

| $T_e$ [°C] | $T_s$ [°C] | $T_a$ [°C] | $I$ [W/m$^2$] | Efficiency [%] |
|------------|------------|------------|---------------|----------------|
| 38         | 39         | 28         | 618           | 71.0%          |
| 42         | 44         | 28.5       | 624           | 67.0%          |
| 45         | 48         | 27         | 624           | 61.7%          |
| 47         | 49         | 29         | 652           | 63.0%          |
| 50         | 51         | 28         | 650           | 59.0%          |
| 50         | 52         | 26         | 648           | 56.0%          |

Efficiency in Table 2, was obtained every 15 minutes and is showed because was obtained the best efficiency of 71.0%, calculated according the equation (8).

4. Conclusions
The system of forced solar water heating was implemented, which provides hot water for domestic use with a capacity of 106L of water, raising the temperature from room temperature to 55 °C. The maximum efficiency for the system was 25.9 % and for the collector was 71 % this are good results because the accepted commercially efficiencies are approximated [8-10]. The storage tank maintains the isolation because the left over a time of 18 hours at environment temperature, water temperature decreased 4 °C.
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