Single phase natural circulation flow through solar evacuated tubes collectors on the equatorial zone.

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Abstract

Thermal performance of water inside of a glass evacuated tubes solar collector under the action of solar radiation in the Equator Andean high lands is presented. The aim is to deepen the understanding of the relations between the water temperature in the tubes and the inclination of single-ended tubes. A salient feature of this study is the employment of temperature sensors located inside of manifold. A data logger was used to collect data during the experiment from early in the morning till the boiling point of the water. The data collected during the experiment shows the highest values of water temperatures for larger inclination angles at earlier stages of the experiment. A consequence of the location of the solar collector is a larger incidence area for solar radiation. This fact results in larger values of water temperature despite the fact that floatability is lower for horizontal tubes. This observation gives important insights for the design of the topology of solar thermal devices for the equatorial zone.

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1. Introduction

The energy crisis due to the prolonged use of fossil fuels mainly in power generation is reflected in the negative impact on global warming, the degradation of the ozone layer, and the presence of acid rain that results in environmental degradation and poor quality of life. Solar collectors as alternative devices for energy conversion, transform solar radiation into thermal energy, replace electricity, and reduce...
greenhouse gas emissions. Manifolds with evacuated tube have a better behavior than its counterparts the flat plate solar collectors when they are used for water heating [1], [2]. These particular characteristics in addition to lower the costs and simplicity have made these devices the best choice for home use. In recent years, research has been conducted in order to develop technology and improve performance and understanding of these heating systems. Several studies have focused on the development of radiation models for vacuum collectors with tubular absorber. Experimental programs have been conducted in order to determine numerical correlations for natural circulation flow on glass evacuated tubes with an opening and tubes mounted over a diffuse reflector, studies concluded that in order to maximize the accumulated annual heat differential in solar water heaters, the device should be tilted at a certain angle to maximize the capture of solar radiation [3]. In addition, the experiments showed that in the case of North-South oriented tubes tilted an angle from the horizontal, cold water will return directly to the tank without reaching the sealed end of the tube. This water fraction will increase if the inclination angle of the tubes is larger. Nevertheless, neither of the above studies are suitable for low latitudes, where the area of incidence of solar radiation is maximized by tilting the collectors, in angles close to the horizontal. Also some mathematical models suggest that the thermosyphon effect is impossible with slopes close to the horizontal, when the rate of natural circulation through the tubes is proportional to the cosine of the inclination angle to vertical [1].

As a result from the previous analysis in this work, the thermal behavior of solar collectors with evacuated tubes was investigated. Three experiments were conducted at different days. Temperature was measure over time and along the tubes inclined at different angles. Small angles to the horizontal increases the amount of the absorption of solar radiation, which is converted into heat inside vacuum tubes.

2. Methodology

Necessary to estimate \( \theta_z \) the direction and \( q \) amount of beam radiation over a single tube along the day, but this can not be directly measured by a pyrometer due to the need of a solar tracker, however it is known that \( q \) is proportional the cosine of \( \theta_z \). Assuming that the \( \beta \) collector tilt-angle from the horizontal; azimuth angle \( \gamma \); where \( \phi \) is the site latitude, \( \omega \) is the solar hour angle, \( \delta \) is the declination of the sun [4].

\[
\cos \theta_z = \sin \delta \sin \phi \cos \beta - \sin \delta \cos \phi \sin \beta \cos \gamma + \cos \delta \cos \phi \cos \beta \cos \omega + \cos \delta \sin \phi \sin \beta \cos \omega + \cos \delta \sin \beta \sin \gamma \sin \omega
\]  \quad (1)

Knowing that diffuse radiation prevails in the morning hours, measures were performed from 10 a.m., in days with negative, positive and little solar declination according to Table 1. Three K temperature sensors previously calibrated were positioned into two solar evacuated tubes, those tubes were arranged with two different inclination angles with respect to the horizontal: 30° and 60°; 20° and 45°; 10° and 50°; located on the terrace of a four-story building. Table 1 shows the results of the experiment conducted on three different days, 28 November, 2013; 11 March and 21 May 2014. Temperature profiles were monitored, at intervals of three minutes, until the boiling point of water was reached. A data logger was used to collect in a digital format the information, where \( T_1 \) is the temperature measured near the open end of the tubes, \( T_2 \) right at the middle of the tubes, and \( T_3 \) is measured at a point near the sealed end.

The experiment took place from morning to early afternoon on days with clear sky. The intensity of global solar radiation was measured in 2013 with a solar pyranometer that belongs to the weather station located at the National University of Chimborazo. The station is located at a distance of 4 Km from the site where the experiment of the evacuated tubes is conducted. Finally on March and May 2014 an automatic Vaisala ISO 9060 pyranometer, first class classification that belongs to the weather station or
the Polytechnic School of Chimborazo was used in the process. It was located 300 m from the terrace where the evacuated tubes experiment took place. The fluid in the tubes was heated by conduction and natural convection. This process depends on the intensity of solar radiation and activates the thermosiphon circulation.

3. Results and discussion

The variables considered in the experiment are: azimuth angle, $\gamma=160^\circ$, the collector tilt-angle $\beta$, inclination with respect to the horizontal. The direction of beam radiation obtained from a model show that solar radiation hits from north to south with $\delta$ solar declination angle of -21.2° and -4° first and second experiment respectively. These facts explain why direct solar radiation, in the early hours of the morning, hits the bottom part of the solar evacuated tubes, explaining the temperature values at the beginning of monitoring, and subsequent change, as shown in Fig. 1.

Fig. 1. Behavior of temperature versus time.

The experimental results show that water temperature measured in three different points on the evacuated tubes inclined 30°, 20° and 10° are larger than those measured for the tubes inclined 60°, 45°
The temperature differences measured in the top and bottom of the tubes can be explained by the buoyancy effect. An analysis of the behavior of water temperature along the tubes during midday shows that tubes inclined smaller angles have greater capacity to convert solar radiation into thermal energy. The larger area available in the tubes to catch solar radiation explains it.

3.1. The heat transfer and natural circulation flow rate

The relationship between the heat transfer and fluid flow rate in water-in-glass evacuated tube solar collectors a rectangular thermosyphon loop is still a very complicated phenomenon (Budihardjo, 2007). The flow rate and heat transported by natural circulation are affected by the inclined angle $\beta$, fluid properties, temperatures, the vertical distance between the heat source and the heat sink. However, the mass flow rate can be decoupled from the other parameters. Then, the natural circulation in evacuated tube solar collectors can be predicted.

The energy equation, for one dimensional steady state and single phase circulation,

$$ q = c_p \, \dot{m} \, \Delta T $$

Momentum equation,

$$ \Delta \rho g H = 2 \frac{1}{\xi} \frac{\dot{m}^2 \rho H}{\Delta A^2} $$

Where $c_p$ is the specific heat, assumed to be a constant; $\dot{m}$ is the mass flow rate; $\Delta T$ is the temperature difference between the heat source and the heat sink; $\rho$ is the density; $g$ is the gravity; $H$ is the vertical distance between the heat source and the heat sink; $f$ is the coefficient of flow resistance; $L$ total length of thermosyphon loop, $d$ tube diameter and $A$ is the cross sectional area of the tube. For small values $\Delta T$, the density difference between the cold and the hot fluid columns can be calculated by

$$ \Delta \rho \approx \tilde{\rho} \, \xi \, \Delta T $$

where $\xi$ is the normalised thermal expansion coefficient for water. Substituting the density difference into momentum equation provides the mass flow rate.

$$ \dot{m} = \left( \frac{\tilde{\rho} \, \xi \, A^2 \, d}{2} \right)^{\frac{1}{2}} \left( \frac{H \Delta T}{L} \right)^{\frac{1}{2}} $$

Equation 5 indicates that if $H$ decreases, the temperature difference for the same mass flow rate must increase. Replaced the equation of mass flow rate into the energy equation, where $H/L$ corresponds to the cosine of $\beta$,

$$ q = k \left( \frac{\cos \beta}{f} \right)^{\frac{1}{2}} (\Delta T)^{\frac{3}{2}} $$

$$ k = c_p \left( \frac{\tilde{\rho} \, \xi \, A^2 \, d}{2} \right)^{\frac{1}{2}} $$
Considering $k$ the same for each of the tests, the rate of the heat absorbed by the couple of evacuated tubes is, with $\beta_1$ lower than $\beta_2$ for the three tests.

$$1 < \frac{q_1}{q_2} = \left( \frac{f_2 \cos \beta_1}{f_1 \cos \beta_2} \right)^{1/2} \left( \frac{\Delta T_1}{\Delta T_2} \right)^{3/2}$$

(8)

In the equatorial zone when the angle inclination of the evacuated tubes decreases, so does $H$, however $q$ increases, the experiments show that increased uptake area produces higher water temperatures. Besides the ratios $q_1/q_2; (\cos \beta_1/\cos \beta_2)$ the angles of each test, and $(\Delta T_1/\Delta T_2)$ the difference between the maximum and minimum temperatures in each evacuated tube. In all the study cases, the influence of $f$ coefficient of flow resistance changes, decreases with increasing temperature.

### Table 1. Comparison of results for the three cases tested in the experimental program

<table>
<thead>
<tr>
<th>Date</th>
<th>28/11/13</th>
<th>11/03/14</th>
<th>21/05/14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start Hours</td>
<td>10h00</td>
<td>10h54</td>
<td>11h01</td>
</tr>
<tr>
<td>Solar Declination $\delta$ (°)</td>
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<td>-4</td>
<td>20</td>
</tr>
<tr>
<td>Average global solar radiation W/m²</td>
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<td>1047</td>
<td>1003</td>
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<tr>
<td>Tilt tube $\beta$ (°)</td>
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<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Higher Temperature (C°)</td>
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<td>88</td>
<td>88</td>
</tr>
<tr>
<td>Less Temperature (C°)</td>
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<td>21</td>
<td>21</td>
</tr>
<tr>
<td>$q_1/q_2$</td>
<td>10</td>
<td>1,3</td>
<td>1,1</td>
</tr>
<tr>
<td>$(\cos \beta_1/\cos \beta_2)$</td>
<td>0,6</td>
<td>0,5</td>
<td>0,2</td>
</tr>
<tr>
<td>$(\Delta T_1/\Delta T_2)$</td>
<td>1,3</td>
<td>1,1</td>
<td>1,1</td>
</tr>
</tbody>
</table>

### 4. Conclusions

Experimental results of the behavior of water temperature on inclined evacuated tubes show that the heat and mass transfer, that result from the natural circulation in evacuated tubes with small inclination, occurs due to the increase incidence area of solar radiation and increased captured energy. This fact has a direct impact on natural circulation. This fact is an important observation that should be considered in the design of the topology of solar thermal devices for the equatorial zone.

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### References


**Biography**

**Dr. C. Recalde** is working as Professor, ESPOCH and UNACH, Ecuador. He had his Bachelor degree in Physics, Master degree in Environmental and Dr. student. He has executed several projects in the fields of environmental and solar energy. With over twenty scientific papers and posters at international events; with several publications.