ANALISYS OF THERMAL EFFICIENCY OF A MODIFIED SOLAR COLLECTOR TYPE EVACUATED TUBE

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ABSTRACT

The need of renewable energy sources due to climate change and thus the search for clean energy sources, justify the growing investment on new types of solar collectors. The research has contributed to this expansion in the scope of solar concentrator collectors, with the efficiency as the main goal. Many works have been developed in order to optimize the thermal stratification of the fluid inside the tubes and heat reservoirs, as well as mathematical modeling considering the problem as transient heat flow as boundary condition. In this work is studied experimentally, the heating of the water by solar collector modified from the conventional evacuated tube, focusing on efficiency. With the help of CFD software, a theoretical analysis is done to visualize the phenomenon, assuming the same boundary conditions and geometric experimental problem. An important approach concerns the physical separation of the flows of both cold and hot water inside the evacuated tube. The system performance was analyzed using experimental tests performed outdoors with sunlight.

Keywords: heat Solar Energy, Solar Colector, Evacuated Tube, Thermal Efficiency.

NOMENCLATURE

A	Surface area of the side of the square parallelepiped tube, m^2
cp_{water}	Specific heat at constant pressure, J/(kg.K)
m	Mass, kg
$\dot{m}$	Mass flow, kg/s
$\dot{Q}_a$	Heat flow absorbed by water, W/m^2
$\dot{Q}i$	Incident heat flow, W/m^2

Greek symbols

η	Thermal efficiency, %
ρ	density, kg/m^3
α	Slope, (°)

INTRODUCTION

In 2011 the researchers Liang et al., (2011) analyzed a modified evacuated tube with a copper tube format "U" getting an increase in efficiency of 12% compared to conventional evacuated tube.

The main application of solar power is heating water for domestic use that allows a significant reduction in energy consumption on a large scale, reducing the load on conventional energy matrices (Mathioulakis and Belessiotis, 2002).

According to Cabanillas et al, (1995) the quantification of the solar radiation incident on collector tube is more difficult compared to flat plate solar collector. Due to the geometry of the cylinder, the solar radiation becomes a function of angle of incidence and sunlight hours, as well as analyzed Kalogirou, (2009) and Kim e Seo, (2007) comparison between flat plate collectors and evacuated tubes. Yan Gao et al., (2010) studied the effect of vacuum thermal insulation.

Based on experimental results Shah and Furbo, (2004), studied a prototype of a evacuated tube collector, installed vertically, allowing solar radiation across the cylindrical surface of the tube. The system is based on forced circulation of the fluid inside the tube, having a numerical model to simulate the thermal performance of the system and the same authors Shah and Furbo, (2007) conducted numerical simulations with the same solar collector.

Budihardjo and Morrison, (2009) and Budihardjo, (2005) analyzed a solar collector evacuated tube for several variables, such as slope angle, geometry characteristics and distribution of radiation on the tube. Results of numerical simulation also developed in this study were compared with good agreement with experimental data obtained from profiles of temperature and water flow.

OBJECTIVES

The main objective of this work is the efficiency analysis of a modified conventional solar collector with concentric glass tubes. The proposed modification is to introduce a third tube of different material inside the inner glass tube for injection of cold water into the system. The heating and hot water outlet occur in the space between the inner glass tube surface and the external surface of the new inserted tube. The physical flow separation of cold and hot water in counterflow in the same space produces a better fluid stratification and increases thermal efficiency by the Second Principle of Thermodynamics, when compared to the conventional model. In this study, besides the improvement of thermal liquid flow stratification, is seeked greater thermal performance of the modified collector compared to the conventional model collector.

MATHERIALS AND METHODS

The modified solar collector evacuated tube system consists on a conventional solar collector evacuated tube increased by a tube fixed to the inner tube concentric glass. The purpose of this modification is to inject cold water into the bottom internal glass, avoiding direct contact and mixing between flows in counterflow of the hot water exiting the system and cold water entering the glass tube. The physical separation of water flows at different temperatures, improves thermal stratification and increases the thermal efficiency of the system, by the second law of thermodynamics, as compared to the conventional system.

The evacuated tube is attached to a connector at the entrance of the glass tube, which purpose is prevent mixing of cold water and hot water. The layout system studied is shown in Figure 1.

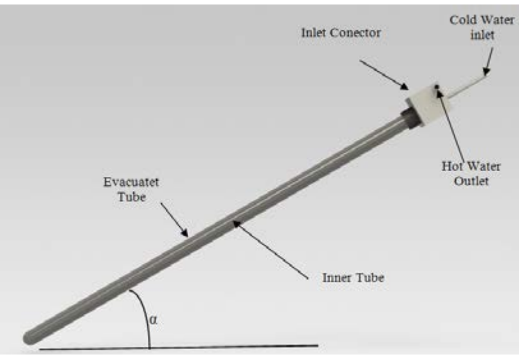

Figure 1. Schematic Modified Model.

The system geometrical characteristics are: evacuated tube external diameter 57mm, internal diameter 45mm and length 1800mm; connector with 127 x 127 x 200mm; steel and CPVC (Chlorinated Polyvinyl Chloride) tube with diameter 19mm and length 2000mm; slope $\alpha = 32°$.

To solar power measurement was used a solar meter TES, Model 1333 with 0.1 W/m2 and maximum intensity 2000 W/m^2.

Air speed was measured by an anemometer Airflow Model LCA 6000 with read range of 0.25 to 30 m/s.

The hydrostatic pressure at the inlet valve, which controls the cold water flow to the system was held constant and measured the mass flow water with the help of a digital precision balance accurate in 10^{-2} grams, by OHAUS Adventurer Pro.

Temperatures were obtained using type "T" thermocouples, calibrated in accordance with international standards calibration measurement. The thermocouples were connected to the bridge NIDAC National Instruments, NI 9213 model, 16 channels for thermocouple inputs and recording of temperature data at Sign Express software.

The mass flow is a function of the incident solar radiation intensity on evacuated tube. The mass flows were measured at each 5 minutes and plotted by averaging every 30 minutes, as the air speed, solar radiation and the output heated water temperatures, recorded by the data acquisition system NIDAC and software Sign Express.

The thermocouples were installed in the cold water inlet, hot water outlet, ambient air and the evacuated tube outer surface glass for measuring the respective temperatures.

The Figure 2 shows the experimental assembly with the modified evacuated tube at an angle of 32 ° (the latitude of the city Bauru - 22 º 21'06, 69 "S - 49º 01'57, 37" W with an elevation 613 meters) absorptive surface oriented to north.

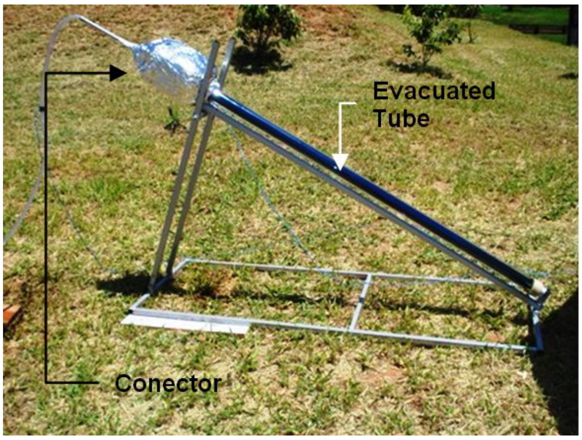

Figure 2. Evacuated tube overview with slope of 32° face north.

The total solar radiation incident measurement on the outer surface of the evacuated tube was obtained by partial sum of incidences measures the positions shown in Figure 3. It is proposed in this work to divide the total glass outer surface tube in 4 absorbing surfaces, one upper, one bottom and two lateral to quantify the distribution of incident sunlight radiation during the day. The absorption surfaces areas, corresponding to the four positions 1, 2, 3 and 4, according to Figures 3 and 4, are established by the parallelepiped inscribed in a cylinder of inner diameter 45 mm, as shown in Figure 3. The reason for the measurements at each cross-sectional area outer tube, is the need of the CFD-Open Foam simulation software.

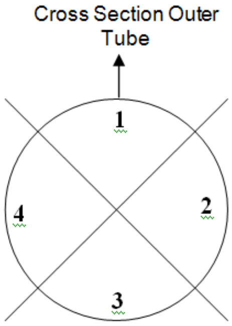

Figure 3. Positions measurement points.

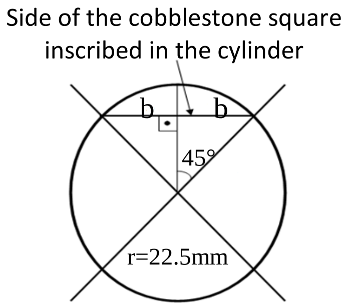

Figure 4. Side of the cobblestone square (2b), for each inner tube region.

Each surface area is obtained by multiplying the segment 2b by the length of the evacuated tube:

Of trigonometry: $r = 0.0225m$, has $2.b = r.\sqrt{2} = 0.0318198$ m, resulting in areas:

$A = A1 = A2 = A3 = A4 = 0.0318198m \times 1.8m = 0.0574164\ m^2$.

Therefore the overall solar heat incident on the inner surface tube is the sum of four products incident solar heat, at each position, the axial area of the parallelepiped at the same position.

RESULTS PRESENTATION

Table 1. Heated water flow, air speed and incident solar radiation versus time.

Times	Mass Flow		Volumetric Flow	Air Speed	Radiation [W/m^2]			
	[g/min]	[kg/s]	[ml/min]	[m/s]	1	2	3	4
11:00	364.56	0.004311000	258.66	0.33	908	520	187	128
11:30	356.39	0.004174833	250.49	0.29	970	410	208	120
12:00	352.55	0.004110833	246.65	1.63	1095	355	235	158
12:30	351.91	0.004100166	246.01	0.78	1097	320	235	160
13:00	350.02	0.004068666	244.12	0.37	1249	217	264	219
13:30	348.32	0.004040333	242.42	0.23	1260	223	268	366
14:00	348.80	0.004048333	242.9	1.52	1180	363	265	218
14:30	342.05	0.003935833	236.15	0.42	1147	172	252	547
15:00	340.24	0.003905666	234.34	1.96	1010	152	229	702
15:30	337.31	0.003856833	231.41	1.85	936	160	224	840
16:00	333.59	0.003794833	227.69	0.42	839	130	202	870
16:30	330.54	0.003744000	224.64	1.10	750	132	182	930
17:00	326.84	0.003682333	220.94	1.16	550	112	148	1055
17:30	326.93	0.003683833	221.03	1.07	480	91	108	1050
18:00	324.44	0.003642333	218.54	0.83	180	19	41	504
18:30	321.10	0.003586666	215.20	0.35	95	27	19	180

Table 1 shows the volumetric and mass flows of heated water, air speed and solar radiation in sections 1, 2, 3 and 4 on the tube as a function of time.

The experiment was conducted on 28/11/2012 and data collection at each time interval of 30 minutes for the period from 11:00 to 18:30.

Table 2 shows the hot and cold water temperatures, the environment temperature, the absorbed heat flow, incident solar heat flow and system thermal efficiency. In the same table the maximum temperature difference between hot (outlet) and cold (inlet) water was 8.7°C;

Table 2. Water temperatures, ambient temperature, absorbed heat flow, solar incident heat flow and system efficiency.

Times	$T_{hot\ water}$ [°C]	$T_{cold\ water}$ [°C]	$T_{enviroment}$ [°C]	Absorbed Flow [W]	Incident Flow [W]	Efficiency [%]
11:00	27.34016	27.42436	28.87438	0	99.83137	0
11:30	28.15775	27.71141	29.78087	7.78546	97.82672	7.95842
12:00	30.40661	29.57653	31.39821	14.25655	105.55893	13.50577
12:30	32.18733	31.37953	32.45184	13.83799	103.78338	13.33353
13:00	32.07765	31.76511	31.79934	5.31287	111.63014	4.75935
13:30	32.35399	31.76695	31.64468	9.90948	121.25244	8.17261
14:00	32.46605	31.65668	32.68244	13.68975	116.04036	11.79741
14:30	34.68218	33.19686	33.98890	24.42437	121.30972	20.13389
15:00	35.44226	33.82068	34.16144	26.46072	119.87783	22.07307
15:30	35.91603	34.23142	34.45792	27.14561	123.71529	21.94200
16:00	36.12763	34.23978	33.96811	29.93139	116.89949	25.60438
16:30	36.08375	34.01303	33.62202	32.39127	114.20754	28.36176
17:00	35.37323	33.21214	33.19967	33.24799	106.81899	31.12554
17:30	34.27284	32.13089	32.53043	32.96679	99.02951	33.28986
18:00	32.71916	31.36146	31.67875	20.66100	42.61304	48.48516
18:30	31.42965	30.68233	31.20696	11.19870	18.38546	60.91062

In Figure 4 are shown as a function of time, temperatures profiles on the outer wall tube, inlet cold water, outlet hot water, bottom inner tube water and ambient temperature.

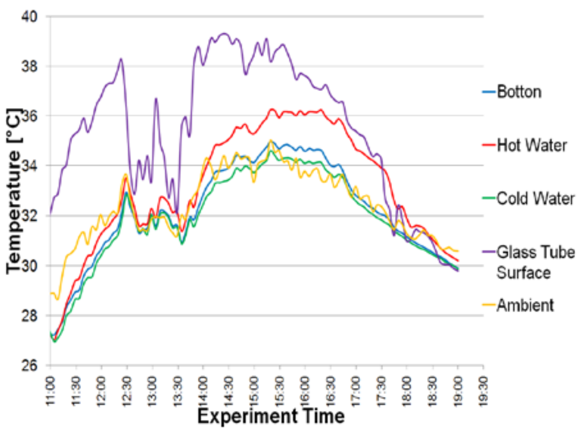

Figure 4. Temperatures profiles output signals versus time.

It is observed in Figure 4, from the start to 13:30, the difference in temperatures of the water which enters and exits the inner tube are practically paltry, since the heat from the incident solar radiation on the outer tube is still not enough to change the temperatures.

During this period the air temperature is higher due to the lower floor thermal inertia which heats the air relative to water.

From 13:30 the water temperature that entering and leaving the inner tube increases considerably reaching a maximum of 36.24°C at 15:20, when it stabilizes until 16:20. From that moment begins a decrease in these temperatures due to drop in solar intensity.

From 13:50 occurs a greater variation in temperature of the water leaving the inner tube relative to in the bottom tube water due to the greater intensity of sunlight during that period.

From 15:20 to 16:20 stabilization occurs on the differences in temperatures between the entering and leaving water of the inner tube.

From 14:00 until 18:25 the hot water temperature is significantly higher than the ambient air due to the high intensity of the solar radiation on the evacuated tube.

After at 18:25 solar activity drops generating a rapprochement between the profiles of the air temperature higher due to less ground thermal inertia.

In periods of 12:33 to 13:00 and from 13:20 to 13:35 there were clouds on the experimental site.

From 17:30 to 19:00 solar intensity was drastically reduced causing a drop in the glass surface temperature but the profile temperatures of the hot water kept higher due to the water thermal inertia.

The Figure 5 shows the incident solar heat flow on the outer surface of the tube and the portion of the same flow absorbed by water inside the tube versus time.

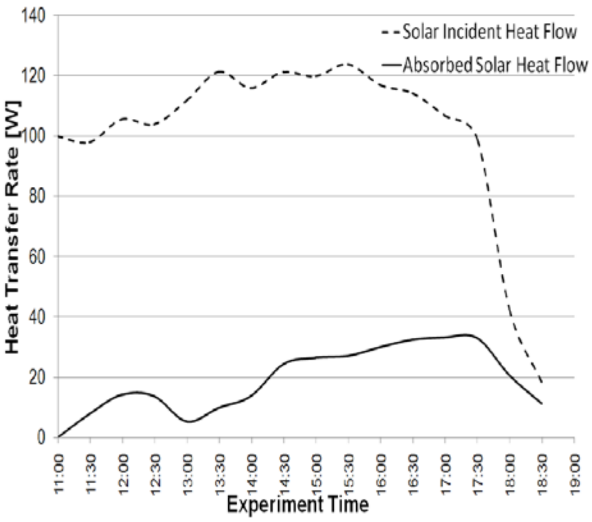

Figure 5. Incident solar heat flow and absorbed heat flow versus time.

On the same figure is observed that even with a drop in solar intensity between 15:30 and 17:30 the system continues to show increases on absorbed power. This is due to the thermal inertia system, and, from 17:30 there is a decrease in both powers.

The portion of the lost total incident energy and not recovered by the system is represented by the total area between the profiles of the solar incident heat flow and the absorbed heat flow plotted in Figure 5.

Figure 6 shows the gradual decrease in mass flow at the system output versus time due to the increase of water temperature for an initial flow rate of 0.004311 kg/s.

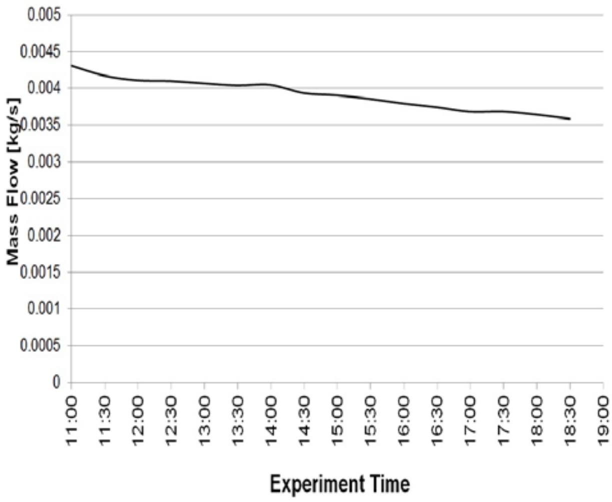

Figure 6. Mass Flow (Initial Flow: 0.004311 kg/s) versus time.

It was observed experimentally that for an initial flow 0.002 kg/s at time 15:30 the water flow interrupted. It was necessary to increase the initial flow rate to restore the flow system. It follows that for low flow rates produce increases on water temperature generating steam bubbles inside the tube interrupting the flow. This experiment was carried out with a steel pipe injecting cold water into the bottom evacuated tube.

Experiments conducted with steel central tube, with the initial flow rate of 0.004311 kg/s, there was obtained a uniformly flow because steel has a thermal conductivity greater than the CPVC. Thus, the point of best balance of hot water production was obtained with CPVC pipe for an initial flow of 0.004311 kg/s, as shown in Figure 6.

The thermal efficiency [(Chang et al., 2004), De Marchi Neto et al., (2009) and (Yang and Wang, 2012)] system is calculated as

$$\eta = \frac{\dot{Q}a}{\dot{Q}i}, \qquad (1)$$

where the heat absorbed by the water flow inside the tube ($\dot{Q}a$) is given by

$$\dot{Q}a = \dot{m}.cp_{water}.(T_h - T_c) \qquad (2)$$

and the evaluation of experimental solar heat incident flow ($\dot{Q}i$) is measured on the outer surface of glass tube.

The Figure 7 shows the thermal efficiency of the modified evacuated tube versus time by measuring the solar incidence in each of the positions 1, 2, 3 and 4, according to Figs. 3 and 4.

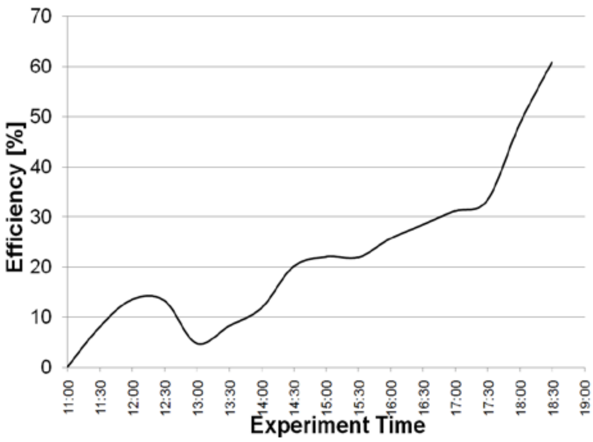

Figure 7. Thermal efficiency of the system versus time.

In the time between 11:00 to 14:00, the system shows approximately a transient heating period with a small drop in efficiency between 12:30 and 13:00 due to clouds at the experimental site. From 13:00 until about 18:30 there is a continuous increase in efficiency that the greatest solar activity in the period.

From 17:30 occurs a significant increase in efficiency due to the thermal inertia of the system. Even with the decrease in power incident solar heat is transferred also to the water for some time.

THEORETICAL ANALYS

For low initial flows (for example: 0.002 kg/s at 15:30) it was observed experimentally that with increase temperature of the water flow, a flow interruption occurred. Using CFD software Sato et al, (2011) it was possible to visualize the phenomenon theoretically assuming the same boundary conditions, geometric and experimental problem considering the installation of central tube for injecting cold water at the bottom of the inner glass tube.

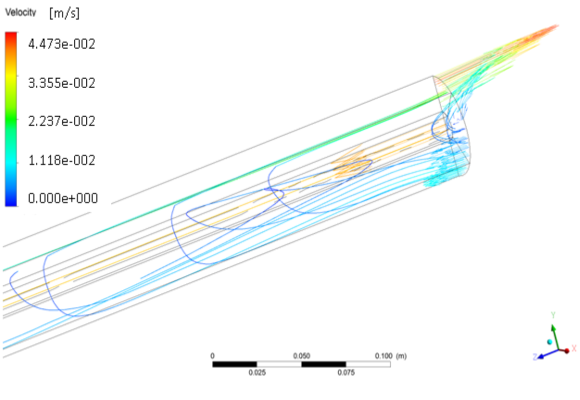

Figure 8. Recirculation water inlet evacuated tube.

The simulation result is shown in Figure 8, and shows the behavior of the water flow inside the evacuated tube. It is perceived that there is a recirculation flow, water returns from the connector into the evacuated tube producing blocking flow. The greater water flow occurred in the upper outlet tube due to contact with the surface of greater solar intensity which is the outside top of the evacuated tube.

CONCLUSIONS

Based on these results, it is concluded that:

- From Table 2, the average volumetric flow rate is 0.235074 liters/minute and so the period of 11:00 to 18:30 has a production of 105.78 liters of heated water for evacuated tube with a maximum difference temperature between exit hot water and cold water inlet from 8.7°C;
- The installation of the steel tube for injecting cold water due to its higher thermal conductivity compared to CPVC tube raises the temperature of the cold water flow at the inlet and thus decreases the temperature gradient between the inside wall of the evacuated tube and the flow of water and therefore the lower the exit temperature of the water;
- As for future works suggest themselves experiments to determine the required number of tubes in series to the water reaches its maximum temperature output;
- Another proposal is the study of the glass transmittance Theunissen and Beckman, (1985), wall thickness of the inner tube and the difference between the inner and outer diameters of the glass tubes in order to decrease the amount of incident solar heat lost over the amount of solar heat absorbed by the water;

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