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Comparative experimental analysis of thermodynamic performance of heat pipe and water in glass solar collectors

Comparative experimental analysis of thermodynamic performance of heat pipe and water in glass solar collectors

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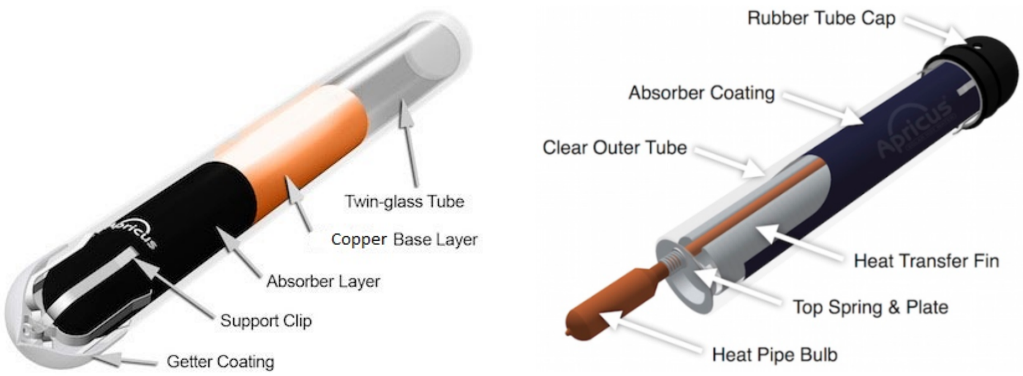
Abstract. Solar energy plays an important role in the alternative energy mix. Solar thermal energy is used in many processes such as domestic water heating, pasteurization, desalination, ambient heating and power generation. There are many devices designed to make use of the radiation coming from the Sun. Evacuated tube solar collectors are one of them. They can be classified according to the employed heat transfer mechanism: direct transfer (water in glass) and indirect transfer (heat pipe). This ongoing work aims to characterize both types of collectors and make an experimental comparative of the thermodynamic performance under the environmental conditions of Porto Alegre, Brazil. An experimental rig was set up with two collectors, one water-in-glass and the other a heat pipe type. Both collectors were connected in series on a tilted plane, together with a global radiation sensor and temperature sensors on interest points namely: inputs and outputs of collectors, air temperature and storage tank. These sensors were connected to a data logger system. Preliminary results show that the heat pipe collector has an average efficiency of 20% superior to the water-in-glass collector.

1. Introduction

Water heating has an important place on the development of solar energy. The world market has multiplied over the years. According to the Institute for Sustainable Technologies [1] the installed power jumped from 62 GW in 2000 to 480 GW in 2018. Evacuated tube collectors are devices constituted by two concentric tubes with an evacuated gap between them. The outer surface of the inner tube is coated with spectral selective materials. The vacuum between tubes highly reduces the convection losses while the selective surface (with high absorptance to the solar spectrum and low emittance in the long wavelength range) optimizes the radiant thermal exchange processes. The evacuated tube collectors can be grouped in two main classes: water-in-glass (direct contact) or heat-pipe (indirect contact). The former is the simplest format, with the tubes filled directly with the working fluid and the fluid circulation is provided by the thermosyphon phenomena [2]. On the other hand, the heat pipe uses a copper tube filled with a phase changing material that uses latent heat to transfer energy to the working fluid [3]. Figure 1 details the construction of both tubes, where the Figure 1(a) show the water-in-glass and the Figure 1(b) show the heat pipe.

Many studies have been carried out aimed at comparing the performance of different collector technologies. Ayompe, *et al.* [4] monitored the energy production of two types (heat pipe and flat plate) solar heaters over the course of one year. He found that the heat pipe was 12% more efficient than flat plate. Al-Joboory, *et al.* [5] made an experimental analysis of two types of collectors, one water-in-glass and the other heat pipe, under different kinds of loads (no-load, intermittent and continuous loading), in order to simulate the hot water consumption habits in the local community in Iraq. He found that the heat pipe collector had a performance of 22.5%, 42.5%, and 32.4%, superior to water-in-glass, respectively. Hayek, *et al.* [6] tested two collectors during winter, one heat pipe and other water-in-glass. The results show that the heat pipe type achieved a superior efficiency in the range of 15% to 20% over the water-in-glass. David, *et al.* [7] made a comparative analysis between a flat plate collector and a tube-type collector evacuated from direct contact, both submitted to the same environmental conditions. They found that the vacuum tube collector was able to reach a temperature of upper output in a range between 2 °C and 4 °C concerning the flat plate collector.

In order to determine the performance of a solar collector it is necessary to follow one of the international established standards, such as ASHRAE 93-2003 [8]. In general, the main focus of these standards is to determine an instantaneous efficiency curve, which is necessary to predict the collector performance and calculate its energy production. However, this type of test is difficult to carry out in outdoor conditions due to high thermal capacity of evacuated tube collectors. Furthermore, it is very hard to get constant wind speed, irradiance and ambient temperature conditions. As the objective of this work is only to make a comparative performance between two technologies (heat pipe and water-in-glass collectors), it was decided to use the results of two collectors operating under exactly the same conditions. Thus, many of the experimental errors that occur in individual measurements can be neglected.



(a) (b)

Figure 1. Evacuated tube schemes [9]: water-in-glass (a) and heat pipe (b).

2. Methodology

The analysis of thermal system is performed applying the thermodynamic laws. The theoretical analysis of solar heaters is carried out through an energy balance applying the first law of thermodynamics for control volumes [10], this approach is applied on analysis of heat pipe solar water heaters [11] and water in glass solar water heaters [12]. The Figure 2 shows the energy flux that passes through the collector area.

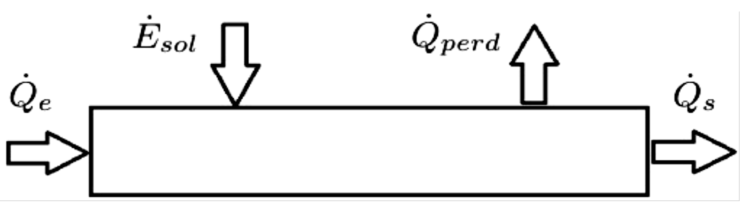


Figure 2. Energy flux on a solar collector.

Applying the first law the thermal balance on the collector is described by the Equation (1).

$$\dot{E}_{sol} + \dot{Q}_a = \dot{Q}_s + \dot{Q}_{perd}, \tag{1}$$

where $\dot{E}_{sol}$ is the solar irradiance, $\dot{Q}_a$ is the water energy in the collector inlet, $\dot{Q}_s$ is the water energy at the outlet and $\dot{Q}_{perd}$ is the energy transferred to the ambient. In this case, the analysis was performed on operating conditions on a clear day monitoring the heat gain of the water all day along, without taking into account the standards methods [5,13]. Then for calculate the thermal power for each collector it is used the Equation (2):

$$\dot{Q} = \dot{m}\, Cp\, \Delta T, \qquad (2)$$

where $\dot{Q}$ is the useful gain, that is, the converted power of solar radiation that is effectively aggregated to the water, $\dot{m}$ is the mass flow rate, Cp is specific heat capacity and ΔT is temperature difference of the water between outlet and inlet of each collector.

A workbench was set up for testing purposes in the solar energy laboratory facilities at the "Universidade Federal do Rio Grande do Sul", located in Porto Alegre, Brazil. The city is the southernmost capital of the country and has four well defined seasons during the course of the year. Both collectors were installed in the same tilted plane (at 30º, equivalent to the local latitude) and oriented towards the equator line. The bench has been mounted to support two series connected evacuated tube collectors. Thus, in each test period, it can be stated that solar radiation, wind speed, ambient temperature and mass flow are exactly the same for both collectors. The only parameter that is different in each solar collector is the inlet temperature, because in the second collector the water has already been heated by the first. The temperatures at the inlets and outlets of the collectors, the ambient air and at the thermal tank were sensed by thermo-resistors (PT100). The irradiance on the plane of the collectors was monitored by a thermal pyranometer EKO MS-80. The fluid flow was evaluated by means of a visual flow indicator (rotameter). Since the vacuum tubes were built by two different manufacturers (although visually indistinguishable), they were submitted to a preliminary test to check for eventual differences in the thermal performances between the two brands, with the tubes mounted in two identical manifolds in water-in-glass configuration, each one with the tubes of one different manufacturer. Thus, any difference between the heat transferred to the water would be due to constructive differences of the tubes. Figure 3 depicts the experimental rig.

Figure 3. Experimental rig.

The test showed that both brands have almost identical characteristics. To demonstrate these results, a two hours' period was selected, with solar irradiance ranging from 740 W/m² to 800 W/m² ± 2% and a constant mass flow rate of 0.0417 kg/s ± 2%. In the last 30 minutes of this period, the collectors could be considered thermally in quasi-steady state. The temperature gain (difference between the inlet and outlet temperatures of each collector) for both collectors fluctuated around 6.4 °C, as can be seen in Figure 4. Any difference ends up being smaller than the experimental uncertainties. Similar results were observed in other days of experimentation. After confirming that the optical characteristics of the tubes of different manufacturers were the same, the comparative test of collector technologies was performed. In this new assembly, the first collector was mounted with heat pipes while the second collector remained with water-in-glass technology. In the comparison tests the water pump was started in the morning and monitoring was performed from sunrise to sunset. The tests were performed on sunny days with few clouds.

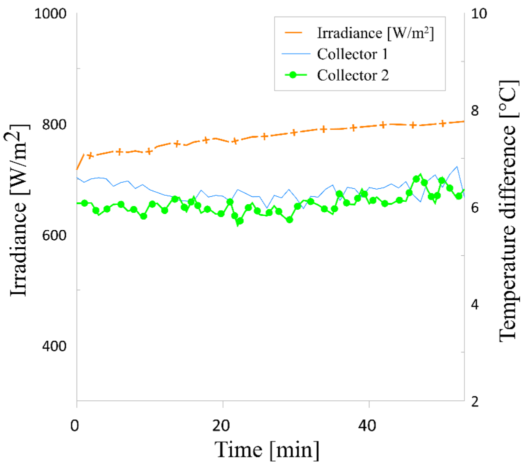


Figure 4. Temperature gain of two different brands water-in-glass collectors.

2.1. Experimental procedure

The experiment for the comparison of the collector thermal performances involves measuring the inlet and outlet water temperatures of each collector, the ambient temperature and the incident solar irradiance. The water flow (kept constant throughout the day by means of a circulation pump) was evaluated with a visual flow indicator (rotameter). Even if the measured flow value might not be very accurate, the way the two collectors were connected (in series) ensures that the flow is exactly the same for both collectors. The experimental procedure steps were:

- The collectors were kept initially shielded from solar radiation.
- A constant water flow was imposed to the collectors while the temperatures at the inlet and outlet of the collectors were monitored.
- When the temperature sensors reached the same temperature, the collectors were uncovered, and the test began. The data was collected at 30 s intervals.
- The test continued while the system remained at a quasi-steady state.
- The uncertainties in the measurements were 0.1 °C for temperatures and 3% for solar irradiance.

The energy calculation was made by applying the first law of thermodynamics for control volumes, ruling out the losses to the environment, with the Equation (2). The experiments were performed between the end of winter and the beginning of spring and all tests were repeated on days with similar conditions.

3. Results

Figure 5 shows the evolution of irradiance along one of the test days. The useful gain converted from solar radiation in each collector was calculated from the measurements performed on this day. The green line in Figure 5 shows the ratio between the useful gains of both collectors. At first sight, a remarkable difference between the heaters can be observed in beginning of the day. Apparently, the heat pipe shows a much higher thermal performance during this period. This is due to the higher heat capacity of water-in-glass collector, as a consequence of the larger mass of water contained in it. The consequence is that it needs more energy (and therefore more time) to reach the working regime. On the other hand, the heat pipe collector does not heat directly the water but the fluid inside the copper tube. As this fluid has much smaller mass, less energy and time it is needed to achieve the steady state. An opposite behavior can be observed at the end of the day. The thermal capacity of water-in-glass heater makes it seem that it delivers more energy with little irradiance, making it more efficient. Again, this enhance performance is not true so, for analysis purposes, those data points were neglected.

The Figure 5 show the useful gain ratio between heat pipe and water-in-glass collectors. It was observed that the heat-pipe collector has an average energy production 20% superior to the water-in-glass. The experiment was repeated on other days with similar meteorological conditions with alike results.

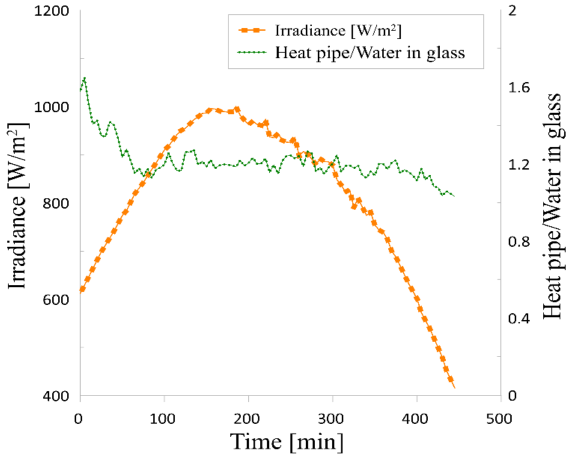


Figure 5. Useful gain ratio between heat pipe and water-in-glass collectors.

4. Conclusions

A comparative experimental analysis of two schemes of heat transfer employed in solar evacuated tubes collectors was made. One collector was provided with water-in-glass (direct contact) tubes and the other with heat-pipe (indirect contact) tubes. The experimental assembly proved to be suitable to carry out the desired performance comparison. The results indicated that under the environmental conditions of Porto Alegre, Brazil, heat-pipe tubes offer a better thermodynamic performance, transferring heat efficiently (about 20% higher) when compared to water-in-glass tubes. As the water-in-glass collector has a much greater thermal capacity (and thus greater response time), care has to be taken when analyzing daily data.

References

[1] Weiss W, Spörk-Dür M 2019 *Solar Heat Worldwide* (Austria: Solar Heating & Cooling Programme International Energy Agency)

[2] Morrison G L, Budihardjo I, Behnia M 2004 Water-in-glass evacuated tube solar water heaters *Solar Energy* **76(1-3)** 135

[3] Kalogirou S A 2014 *Solar Energy Engineering, Second edition* (San Diego: Elsevier Inc.)

[4] Ayompe L M, Duffy A, McCormack S J, Conlon M, Mc Keever M 2011 Comparative field performance study of flat plate and heat pipe evacuated tube collectors (ETCs) for domestic water heating systems in a temperate climate *Energy* **36(5)** 3370

[5] Al-Joboory H N S 2019 Comparative experimental investigation of two evacuated tube solar water heaters of different configurations for domestic application of Baghdad-Iraq *Energy and Buildings* **203** 109437

Journal of Physics: Conference Series **1587** (2020) 012031 doi:10.1088/1742-6596/1587/1/012031

[6] Hayek M, Assaf J, Lteif W 2011 Experimental investigation of the performance of evacuated-tube solar collectors under eastern mediterranean climatic conditions *Energy Procedia* **6** 618
[7] David J S, Viveckraj J, Seralathan S, Sivamani S, Varatharajan K 2016 comparative study of solar water heating systems - flat plate collector (FPC) with evacuated tube collector *International Journal of Engineering Research in Africa* **26(1)** 76
[8] American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) 2003 *Methods of Testing to Determine the Thermal Performance of Solar Collectors* (USA: American Society of Heating, Refrigerating and Air Conditioning Engineers)
[9] Manea T 2012 *Desenvolvimento de Uma Bancada para Ensaios de Coletores Solares de Tubos de Vidro a Vácuo* (Porto Alegre: Universidade Federal do Rio Grande do Sul)
[10] Duffie J A, Beckman W A 2013 *Solar Engineering of Thermal Processes, Fourth edition* (New Jersey: John Wiley & Sons, Inc.)
[11] Shafieian A, Khiadani M, Nosrati A 2019 Thermal performance of an evacuated tube heat pipe solar water heating system in cold season *Applied Thermal Engineering* **149(1)** 644
[12] Budihardjo I, Morrison G, Behnia M 2002 *Development of TRNSYS Models for Predicting the Performance of Water-in-Glass Evacuated Tube Solar Water Heaters in Australia* (Sydney: The University of New South Wales)
[13] Mazarrón F, Porras-Prieto C, García J, Benavente R 2016 Feasibility of active solar water heating systems with evacuated tube collector at different operational water temperatures *Energy Conversion and Management* **113(1)** 16