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EXERGETIC ANALYSIS OF FLAT-PLATE PHOTOVOLTAIC/THERMAL SOLAR COLLECTORS COMBINED WITH A LOW-TEMPERATURE LIBR/H_2O ABSORPTION REFRIGERATION CYCLE

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Abstract. *In this work, the application of hybrid flat plate photovoltaic/thermal (PV/T) solar collectors coupled to a low-temperature indirect-fired single-effect LiBr/H_2O absorption refrigeration chiller as a solar cogeneration system is discussed. Its main purpose is to provide auxiliary air conditioning in order to lessen electricity costs associated with thermal comfort for residences in warm climates. Moreover, the hybridization of the solar collectors increases the PV module efficiency and can decrease the total area needed for the installation of PV modules and solar flat plate collectors for use in distributed generation, especially on residential rooftops. A thermal circuit model is used to simulate heat transfer through the PV/T collector. This study describes the performance of the absorption refrigeration system, its constraints due to the lower temperatures achieved with the flat plate PV/T collectors and the increase in the PV module electric conversion efficiency due to their cooling through heat transfer to the thermal cycle, which is especially high during the sunny season in Brazil, with high rates of solar radiation. An exergy analysis is applied to the system under steady state conditions and its total efficiency and electrical power output and savings are evaluated and compared to a simple PV/T cogeneration system with hot water production and a standard vapor compression refrigeration cycle with the same thermal load removal for air conditioning.*

Keywords: *solar cogeneration, solar thermal, solar photovoltaic, PV/T, absorption refrigeration, LiBr-H_2O*

1. INTRODUCTION

It is well known that standard photovoltaic panels can only convert a fraction of incident solar irradiation into electricity, with the remaining energy is discarded in the form of waste heat. Hybrid photovoltaic/thermal (PV/T) solar collectors, still relatively rare in today's solar energy market, combine solar thermal collectors and photovoltaic panels in the same building area where they are installed.

This type of system has numerous advantages such as a more regular thermal power output with the option of thermal storage in tanks and cooling of the photovoltaic panels, improving their efficiency and lifespan. It also has disadvantages, such as lower thermal efficiencies due to the solar collector's geometry (usually non-concentrating, flat plates) and higher initial costs.

There are today some demonstrative projects that use hybrid PV/T collectors for photovoltaic power generation and water heating, one of them located at Massachusetts, USA, of which first study results imply that this kind of system is significantly more viable economically in hot climate locations with higher and steadier solar irradiation, as well as high electric rates (Dean *et al.*, 2015).

Another possible application of the PV/T panels is the use of liquid water and other heat transfer fluids as the energy input of an absorption cycle, since the low temperature achieved by flat plate solar panels can be compatible with this kind of thermal cycle, such as absorption cycles using a mixture of lithium bromide and water. Therefore, this could decrease the energy use in air conditioning systems. It is also important to highlight that the highest demand of air conditioning is when the radiation achieves its highest values (Lizarte *et al.*, 2012).

The pair water-lithium bromide is recommended in residential and commercial air conditioning systems because as water is the fluid that passes through the evaporator, it limits its temperature to values higher than 0ºC. Nevertheless, there can be a problem with the crystallization of lithium bromide even in intermediate values of concentration (Hernandez *et al.*, 2004) in temperatures close to environment temperature (Chen *et al.*, 2017), but as this problem is solved there can be advantages to this type of thermal cycle such as higher reliability, smaller maintenance costs, silent and vibration-free operation and compact installation size (Palacios-Bereche *et al.*, 2009).

2. METHODS

To simulate the proposed system, system modeling is divided in three parts – the first comprising of the photovoltaic panels, the second of the thermal collectors and the third of the absorption refrigeration cycle. Simulation will be performed under steady-state conditions using climate and solar irradiation data from Campinas, State of São Paulo, Brazil, compiled from CRESESB (2016) and INMET (1990).

2.1 PV Panel Efficiency model

One point that must be evaluated in the present article is the calculation of the average energy conversion efficiency in the photovoltaic panel as a function of the operation temperature. The efficiency equation of the PV panel models is usually selected from literature for the simulation and is proportional to its surface temperature. Therefore, in order to properly evaluate the PV efficiency, this physical quantity was evaluated as a function of the panel's surface temperature. This temperature is a function of climate data and irradiation level on an inclined surface obtained for the Campinas city in Brazil.

The surface temperature of the photovoltaic panels can be calculated with the help of the following simplified equation, one of many described by Skoplaki e Palyvos (2009):

$$T_s = T_a + \frac{I}{I_{NOCT}}\left(T_{NOCT} - T_{a,NOCT}\right)\ [^\circ\mathrm{C}] \tag{1}$$

In this Equation T_{NOCT} is the nominal operation temperature of the panel (NOCT), given by the manufacturer and defined as the temperature achieved by the PV panel in open circuit subject to a irradiation of 800 W/m^2 (I_{NOCT}) when the environment is at ambient temperature $T_{a,NOCT}$ of 20ºC and wind speed of 1 m/s. The other terms such as T_a and I are the maximum average temperature of the environment and the solar radiation in W/m^2, respectively.

The choice of Equation 1 was made because of its simplicity in relating solar irradiation with environmental temperature, without the necessity to estimate other values such as reflectivity and absorptivity. Moreover, the energy losses and wind speed are not accounted in equation since it is necessary higher precision in these data which was not obtained for the present research. The efficiency numbers will be compared with the nominal values of efficiency by manufacturers of common photovoltaic panel models available today for purchase, under standard test conditions. The system inverter efficiency will also be considered in these calculations.

2.2 Photovoltaic-Thermal Solar Collector model

There have been multiple proposed models of hybrid PV/T solar collectors for water heating and electrical power production, (Dean *et al.*, 2015), but their presence in the market is still very limited to this day. This work will use a thermal circuit model similar to **Figure 1**'s, below, to simulate heat transfer throughout the PV/T collectors, from the PV panels through the interior of the collectors and finally to the heat transfer fluid that will flow through the indirect-fired generator in the absorption refrigeration cycle. For simplification purposes and due to the nature of the steady state simulation, this work won't consider the option of energy storage.

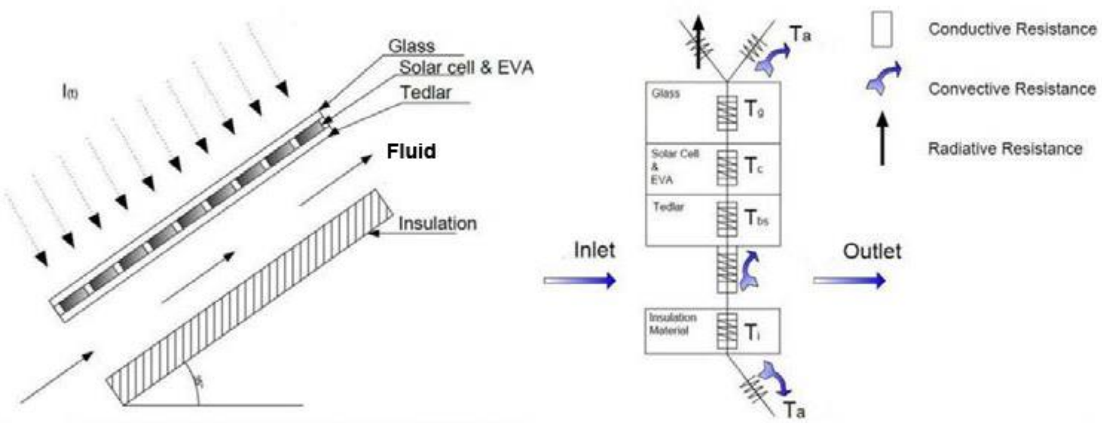

Figure 1. Simplified cross-sectional view and thermal resistance circuit of a PV/T collector. Adapted from (Pauly *et al.*, 2016).

2.3 LiBr/H_2O absorption refrigeration cycle model

A simplified simulation of the system in steady state conditions will be performed with the aid of the EES® - Engineering Equation Solver (Klein, 2013). The LiBr-H_2O cycle used for this work is based on data from (Palacios-Bereche *et al.*, 2007), with standard cooling water flows at 25ºC in the place of the flows from a cooling tower for simplification purposes, and is illustrated in Figure 2. For simulation purposes of the LiBr/H_2O cycle, the temperature of the heat transfer fluid entering the generator is previously established, since it is one of the limiting factors to the cycle's Carnot efficiency and thus its exergetic efficiency. Further simulation will determine the minimum temperature value that needs to be achieved on the surface of the PV/T collectors so that the absorption refrigeration cycle can deliver an acceptable performance for its intended purposes.

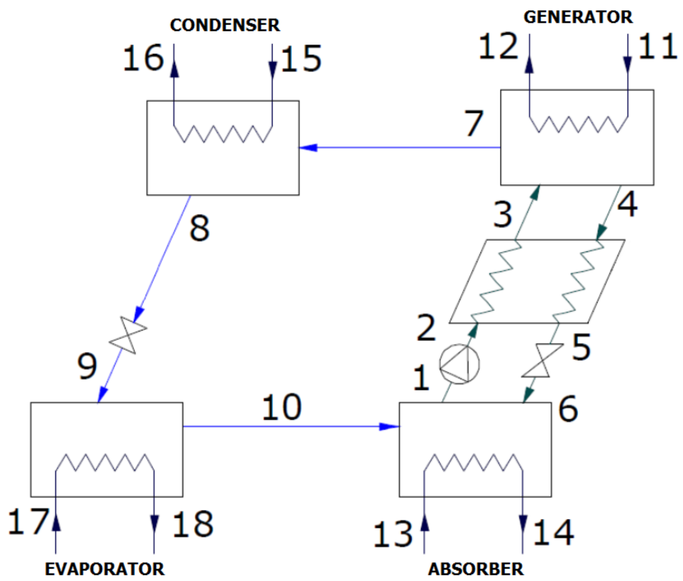

Figure 2. Simplified LiBr/H2O single-effect system. Adapted from (Palacios-Bereche *et al.*, 2009).

Initially, due to limitations such as working at steady state conditions and the maximum surface temperature of the photovoltaic panels, it is assumed that the heat transfer fluid enters the absorption refrigeration cycle's generator at 10ºC below the maximum operating surface temperature of the photovoltaic panels. Then, after modeling and simulation of the thermal circuit collector, this value will be adjusted accordingly due to climate and solar irradiation changes.

First and second-law control volume analysis in the absorption refrigeration cycle is performed on a component-by-component basis and will be detailed in the final manuscript. The exergetic efficiency of the coupled PV/T + LiBr/H_2O system during a month's interval can be given as:

$$\eta_{ex} = \frac{E_{PV} + Q_{ev}\left(1 - \frac{T_o}{T_{ev}}\right)}{IA\left(1 - \frac{T_o}{T_{sun}}\right)} \tag{2}$$

In which E_{PV} is the total electrical energy output from the photovoltaic panels' inverter during a month, Qev is the total heat removed by the absorption refrigeration cycle's evaporator from the conditioned building, I is the mean monthly solar irradiation on an inclined plane (kWh/m^2), T_o is the environment temperature, A is the total area of the photovoltaic panels and T_{sun} is the temperature of the sun, 5777K, considered a 100% black body (Joshi *et al.*, 2011).

3. ADDITIONS TO THE FINAL PAPER

The heat recovered from the PV/T collectors should be expected to power a LiBr/H2O refrigeration absorption system with the same cooling capacity as a standard residential vapor compression refrigeration system available in the market, and the number of collectors and their required installed area will be calibrated for that purpose, but it should not exceed too much the mean rooftop area dedicated to standard PV installations today in residential buildings. As the photovoltaic panels' mean surface temperature decreases due to their cooling, their conversion efficiency will increase, improving the electrical power output per installation area. The end result should give the net savings in electrical costs associated to air conditioning, especially during the summer season and in warmer climates.

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5. RESPONSIBILITY NOTICE

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