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HYBRID SOLAR HEAT PUMP SYSTEM FOR WATER HEATING

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KEYWORDS

heat pump, solar collector, thermal energy.

ABSTRACT

A comparative test of water heating between the hybrid system - solar collector with heat pump - and a system with conventional supplementary heating - with high electric power - was performed. For this, a small capacity heat pump was installed, which was later installed together with a solar heating system, composed of a 250 L thermal reservoir and three thermoplastic collector plates. Tests were carried out to evaluate the COP of the heat pump and the energy consumption of the solar heating system operating with the heat pump and with an electrical resistance of 3000 W. In the laboratory tests, the heat pump presented an average COP of 2.15. In the field tests, the energy consumption of the solar system with heat pump was 54.9% lower when compared to the tests in which electrical resistance was used as a source of supplementary heating.

INTRODUCTION

Demand for energy has been continuously increasing, whether due to population increase or growth in individual needs, as well as strong dependence regarding on non-renewable sources (Zafar & Dincer, 2014). In fact, according to IEA (2016), the energy matrix of the energies consumed in the world is predominantly non-renewable, mainly petroleum, coal and natural gas, corresponding to 66.50% of the energy consumed on the planet. Kyoto and Montreal Protocols (Reis, 2012), which aims to persuade signatory countries reducing the damage to the ozone layer and the carbon dioxide emission into the atmosphere, so that the use of renewable energy be intensified.

In Brazil, until 2014, the industrial sector experienced a relative stability; while in the commercial and residential sectors there was an increase in electricity consumption. Between 2005 and 2014, the commercial sector demanded an increase of 5.9% in electric energy, while the residential sector increased by 13% compared to other energy sources, such as natural gas and charcoal (Brasil, 2015). In addition, the increase in residential population, estimated by the Ministry of Mines and Energy, could lead to an increase of about 15 million households by 2020. This increase has an impact on the greater possession of domestic equipment, with consequent increase in residential electric consumption (Brasil, 2011).

With this in mind, companies and researchers seek the most efficient and optimized use of energy (Akbulut et al., 2016), aiming to the more intense use of renewable energies, in order to reduce previously mentioned environmental impacts. Solar (Yadav et al., 2014), geothermal (Ratlamwala et al., 2012; Safa et al., 2015), and wind Systems (Li et al., 2013) are used individually or together in hybrid systems in order to reduce the impacts to the concessionaire conventional electricity network and, of course, reducing the costs of those who propose to use such equipment.

The heat pump has been introduced in several researches of hybrid systems, such as in Li et al. (2013), Tagliafico et al. (2012), Kim et al. (2013) and Zhao et al. (2014). The heat pump is more efficient when compared to other sources for heating, such as direct use of electricity and combustion. Although the heat pump is not a recent technology, its concept is still less widespread in some parts of the world (Staffell et al., 2012). And according to Hepbasli & Kalinci (2008), water heating is one of the most responsible for the consumption of electricity, along with lighting and air conditioning.

The heat pump performance coefficient depends on the following factors (Jordan et al., 2016; Zhao et al., 2014, Safa et al., 2015, Akbulut et al., 2016): heat source temperature, condenser and water for consumption temperature, refrigerant fluid used, as well as constructive characteristics of the heat pump.

Solar panels and heat pumps are very promising systems for heating air and water, and can form hybrid systems, in serial or in parallel. The hybrid system can seek efficiencies balancing of the solar panel and the coefficient

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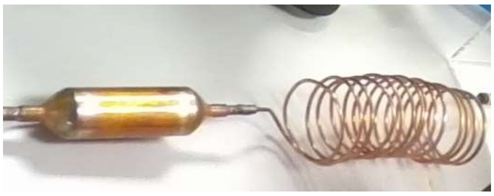
of performance (COP) of the heat pump. Most studies deal with direct expansion systems, for the production of water at temperatures of 45 ° C, for air conditioning or water heating (Tagliafico et al., 2012).

In this context, the present study presents the assembly, in the field, of a prototype for water heating using solar collectors, using two configurations distinct and parallel for the supplementary heating. This prototype was tested in both configurations, obtaining data on final water temperature and energy consumption of the supplementary heating, making possible the comparative performance of each configuration.

MATERIAL AND METHODS

The heat pump used was a prototype assembled exclusively for the research, using the following components (Figure 1): a) compressor, Embraco manufacturer, EMI 60HER model, 1/6 HP, 220 V voltage, 60 Hz, hermetic, piston compression; b) capillary tube with drier filter; c) evaporator (¼ HP of commercial reference) with 1/30 HP air forcing; (d) a shell-tube condenser, mounted with a 15 m of copper tube ¼” diameter, coiled in a serpentine form, enclosed in a 50 mm diameter PVC tube shell. The refrigerant used was the R134a.

a) Compressor EMI 60 HER



b) Capillary tube with drier filter

c) Evaporator

d) Shell-tube condenser

FIGURE 1. Components used in the heat pump.

After assembly, the heat pump was tested in the laboratory to determine the heating capacity and the coefficient of performance (COP), under thermosiphon circulation conditions (Figure 2). This stage was carried out in the Laboratory of Energy and Thermodynamics of the Faculty of Agrarian Sciences (Faculdade de Ciências Agrárias, FCA), Federal University of Grande Dourados (Universidade Federal da Grande Dourados, UFGD). For this purpose, the heat pump was connected to a 184 L reservoir, insulated with a 10 mm thick expanded polyurethane blanket. Three trials were carried out, with a duration of 5 hours, always starting with the same temperature value (22 ºC), measured with a PT100 probe. At the end the homogenized temperature of the tank was measured. The coefficient of performance (COP) was obtained through [eq. (1)].

FIGURE 2. Laboratory heat pump test.

$$\text{COP} = \frac{Q_H}{W} \quad (1)$$

Where,

COP = coefficient of performance;

Q_H = heat stored in the water of the thermal reservoir (kJ),

W = Heat pump work (kJ).

$$Q_H = ww.C_p.(T_f - T_i) \quad (2)$$

Where,

ww = water weight of the reservoir (kg);

C_p = water specific heat at constant pressure (kJ kg^{-1} $°C^{-1}$);

T_f = homogenized final water temperature (ºC),

T_i = initial water temperature (ºC).

The work was determined based on the energy consumption (Equation 3). For the measurement of electricity, an hour meter ampere, model AH3, brand Valexcell was used. The energy consumed in kWh was determined by [eq. (4)]. Therefore, the power factor of the heat pump was corrected to 1, with the installation of a capacitor of 15 μF.

$$W = C_E.3600 \quad (3)$$

$$C_E = \frac{\text{Ah}.V}{1000} \quad (4)$$

Where,

C_E = energy consumption (kWh);

Ah = ampere-hour measured during the test (Ah),

V = network voltage (V).

After the laboratory tests, the heat pump was installed together with the solar heating system for the field tests (Figure 3), at coordinates 22° 11’ 45” S and 54° 55’ 18” N. The solar heating system, manufactured by Alpina Thermoplastics, was composed of three flat plastic collectors, model 1003, of 1.05 m^2 each, connected to a thermally insulated reservoir (boiler) with a volume of 250 L.

Initially, it was attempted to install the heat pump in series with the solar collectors - hybrid system. However, as the condensation pressure became very high, it was necessary to switch to the parallel installation with forced circulation, using a small water pump, used in washing machines (model BAV220, manufacturer Honewell, of 34 W of power), which was installed at the condenser output (Figure 4).

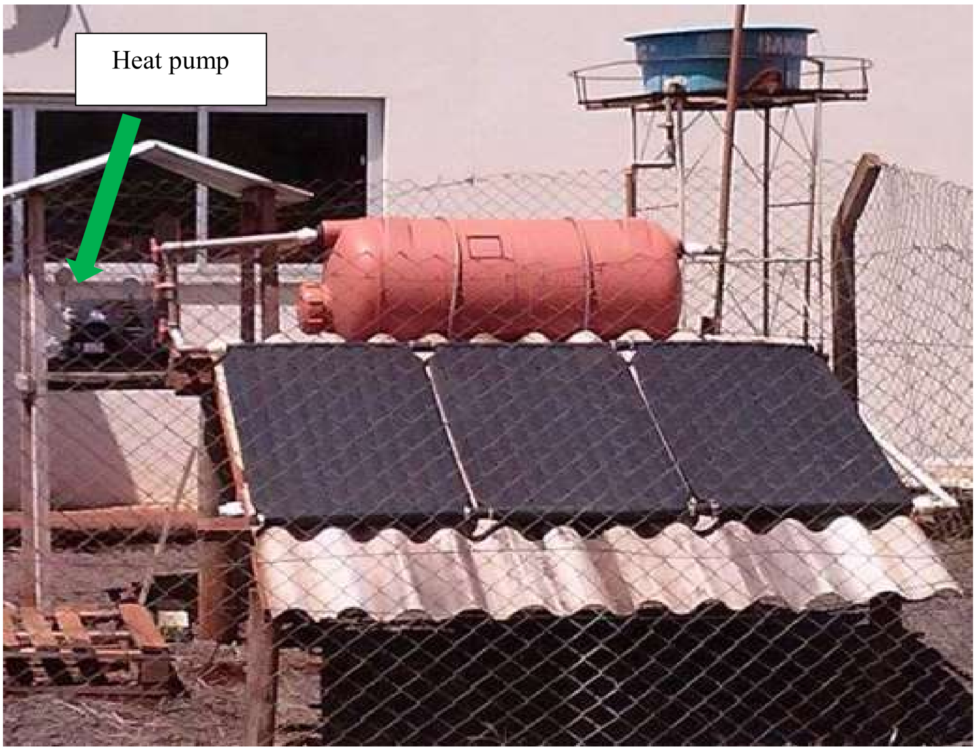


FIGURE 3. Complete system assembled for field testing.

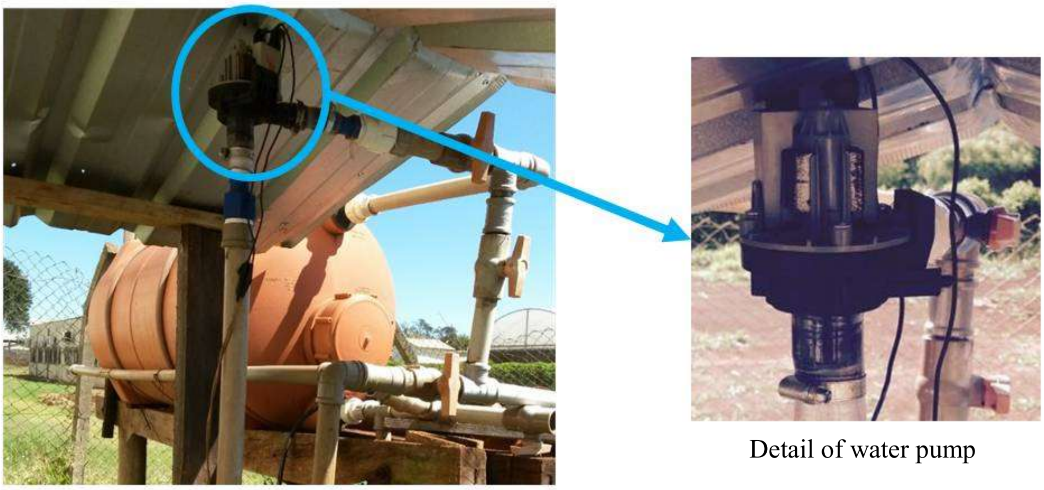


FIGURE 4. Water pump for forced circulation.

The installation of the heating system was done in a way that enabled four operating configurations: without supplementary heating with natural circulation, with supplementary resistive heating, with supplementary heating by heat pump with forced circulation and without supplementary heating with forced circulation. For this, the hydraulic installation was provided with valves at specific points to enable these changes (Figure 5).

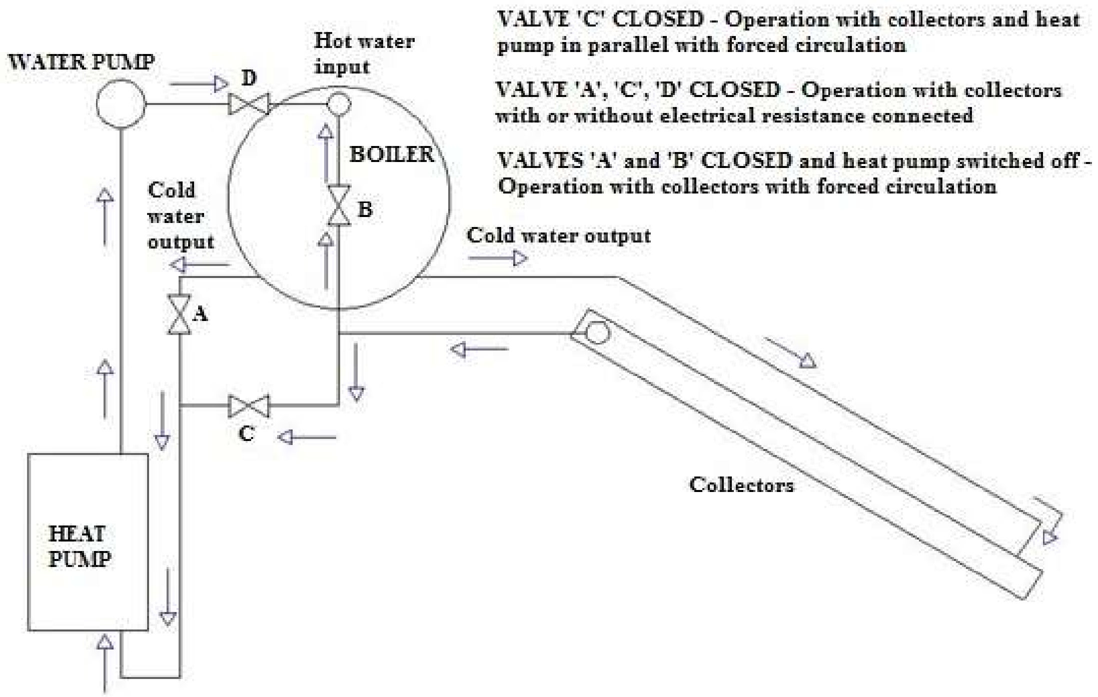


FIGURE 5. Hydraulic configuration of the hybrid system.

In addition, an electric control panel was set up to select the electrical components in each configuration. In this frame was installed a digital temperature controller, to operate both the heat pump and the electrical resistance in each mode of operation, which was set at 50 ° C.

The installation of the solar collectors was carried out following the manufacturer's recommendation (local latitude + 10º), with a north orientation, with a slope angle of 33º. The electrical resistance used in the reservoir was not offered with the set, being purchased separately, had heating power of 3000 W.

The tests in each configuration (Table 1) were repeated 4 times, performed on consecutive days, except for cloudy or rainy days, with tests beginning on 05/20/2015 and ending on 06/29/2015. All trials lasted for 9 hours, starting at 8 am and finishing at 5 pm. At the beginning of each test, the initial temperature of the water was recorded by the temperature reading of the digital temperature controller, which sensor was installed at the midpoint of the thermal reservoir. At the end of the test, the final temperature, also read in the temperature controller, was taken. The controller probe was installed in the central part of the thermal reservoir at the same point of the electrical resistance installation.

TABLE 1. Test configurations that were performed in the field.

Test	Heat pump	Water pump	Electrical resistance
T1	Active	Active	Inactive
T2	Inactive	Active	Active
T3	Inactive	Active	Inactive
T4	Inactive	Inactive	Inactive

The total heat transferred to the water by the heating system in each test was calculated by [eq. (2). To measure the energy consumption of supplementary heating systems, the same hour meter employed in the laboratory tests was used, and the total energy consumed, equivalent to the work used in the supplementary heating systems, determined by [eq. (3)].

The energy produced/energy consumed ratio (QH / W) was used as a parameter to compare the performance of the solar heating system in each configuration with support system.

RESULTS AND DISCUSSION

Table 2 shows the results for the laboratory tests with the heat pump, where the average COP was 2.05. Satisfactory value when compared to the results of Li et al. (2013), which obtained values between 1.4 and 4.4 for a heat pump installed in a solar hybrid system for water heating, considering that it had an electric power three times greater. Kim et al. (2013) obtained COP values between 2.12 and 2.77 for a 10.55 kW heat pump operating with CO_2 in a solar hybrid geothermal system for water heating.

TABLE 2. Results of laboratory tests.

Test	W (kJ)	Q_H (kJ)	COP
1	6249	11536	1.85
2	5468	11535	2.11
3	5468	11920	2.18
Average	5728	11664	2.05

Table 3 shows the average values of energy consumption for field tests, according to each operation configuration (Table 1). Table 4 shows the average values of the water temperature of the thermal reservoir in each test.

TABLE 3. Results of the average energy consumption in each test.

Test	Consumption (Ah)	Consumption (kWh)	Consumption (kJ)
T1	9.25	2.035	7326
T2	20.5	4.510	16236
T3	-	0.306(*)	1102
T4	n.a.	n.a.	n.a.

Obs.: Calculated based on pump power at operating time; na.: not applicable.

TABLE 4. Temperature average values of the thermal reservoir in each test.

Test	T initial (ºC)	T final (ºC)	ΔT (ºC)
T1	24.7	49.2	24.5
T2	26.0	48.5	22.5
T3	25.0	28.9	3.9
T4	24.1	26.6	2.5

The final values of water temperature obtained in the tests with the use of supplementary heating systems (heat pump and electric resistance) were close to the value adjusted in the temperature controller. In tests 3 and 4, without supplementary heating system, these temperature values did not exceed 20 °C, demonstrating the importance of the supplementary heating system.

The use of forced circulation (T3) provided a higher temperature gain and a 56% increase in the amount of thermal energy stored (Table 5) when compared to natural circulation (T4). Jordan et al. (2015) and Pandey et al. (2015) have shown that increasing the flow up to a certain value, contributes to the increase of solar collector efficiency.

TABLE 5. Average values of energy produced and energy consumed and the relation between them.

Teste	EP - Energy Produced (kJ)	EC – Energy Consumed (kJ)	EP/EC
T1	24500	7326	3.34
T2	22500	16236	1.39
T3	3900	1102	3.54
T4	2500	n.a.	n.a.

The electric power consumption of the configuration operating with forced circulation heat pump (T1) was 54.9% lower than the configuration using the 3000 W of electrical resistance as supplementary heating (T2). This, due to the higher efficiency of the heat pump, which could generate more than double its electrical power in thermal energy (Table 2). Li et al. (2013) mention a saving potential of up to 79% with the use of heat pumps in heating systems.

In addition to reducing energy consumption, we have the benefit of power reduction, resulting in a much lower current. While the average heat pump current was 1.5 A, as demonstrated in laboratory tests, the rated current of the electrical resistance was 13.6 A, nine times higher.

Comparing the COP mean value of the heat pump obtained in the laboratory, with the result of Table 5, we verified that the heat pump was responsible for at least 60% of the thermal load accumulated in the T1 test. However, according to Jordan et al. (2016) the increase of the water flow in the condenser reduces the condensation temperature, raising the COP. Thus, forced circulation may have led to an improvement in COP, which means that the contribution of the heat pump was greater.

This can be verified when the same analysis was done for the electric resistance test (T2). Considering that all the electric energy consumed was converted to heat, which is reasonable in the case of an electric resistance, the supplementary heating was responsible for 70% of the accumulated thermal load. Thus, it is estimated that the COP of the heat pump with forced circulation was 2.34, an increase of almost 9%.

If we compare the result of the test without supplementary heating with natural circulation (T4) to the heat pump test (T1), considering that the energy accumulated in T4 test is what the solar system can generate alone, assuming that the difference for energy accumulated in T1 is the one generated by the supplementary heating, it could be stated that the heat pump can generate more than 90% of the thermal energy, which converge the results obtained by Kim et al. (2013). However, not all of this accumulated energy increase can be credited for the direct action of the heat pump, that is, the heat generated by it. But, indirectly, due to the increase of the temperature gradient in the thermal reservoir, implying an increase in thermosiphon circulation, thus improving the efficiency of the collectors.

Regarding the climatic conditions (Table 6), it is possible to assume that they were not significant, or they presented small variation among the tests. The average ambient temperature was slightly higher in the electrical resistance test (T2). But, on the other hand, the radiation was 5% lower than in the heat pump test (T1).

TABLE 6. Climatic conditions, average values, during the tests.

Test	$T_{average}$ (ºC)	$RH_{average}$ (%)	$V_{average}$ (m/s)	Radiation (MJ/m^2)
T1	20.4	82.0	0.62	6.3
T2	22.0	77.3	0.75	6.0
T3	20.6	74.8	0.70	6.3
T4	21.3	74.0	0.69	6.6

Obs.: Data from the weather station of Embrapa Agropecuaria Oeste, coordinates 22º16'30" S, 54º49'00" W, 408m. Accessed through the website http://www.cpao.embrapa.br/clima/?lc=site/banco-dados/construtor-basico (EMBRAPA, 2015).

CONCLUSIONS

The heat pump provided a significant reduction in electric power consumption for supplementary heating in the solar heating system. With a power of just over one-tenth the power of the electric resistance, the heat pump was able to produce the same temperature level at the end of the heating process, without damaging the quality of the heating.

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