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ECONOMIC ANALYSIS OF A CO_2 SMALL DIRECT EXPANSION SOLAR ASSISTED HEAT PUMP FOR A DOMESTIC WATER HEATING

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Abstract. *Water heating for bath occupies a large portion in energy consumption in Brazil, since the most used device for this application is the electric water heater. In this paper experiments were conducted to evaluate the use of a direct expansion solar assisted heat pump (DX-SAHP) operating with CO_2 as coolant fluid to heat water for bath, comparing to the electric heater. The experimental tests were conducted in Belo Horizonte (Brazil) during April to June of 2018.A PID control system was used to control the water outlet temperature at 60ºC, to any valve opening position. In that way, take the data from INMET, it could take the average temperature and radiation for each day to estimate the payback period of this device. A survey of the prices of the components needed to make the DX-SAHP was also carried out. The results obtained were a payback period of 240 months to water heater of four people in a family and 58 months considering the best case, two houses with six people.*

Keywords: *Economic analysis, Experimental analysis, DX-SAHP, Water heating, CO_2.*

1. INTRODUCTION

In the past decade, the concern of energy resources has been attracted the attention of many researches about ways of saving energy. In that context, in Brazil, water heating occupies a large portion of the electricity consumption, it considering the second one consume of use electrical energy, second largest in this matter (FEDRIGO *et al.*, 2009). Vasconcellos and Limberger (2012) presented that the electricity-heated showers are the most used for this application, which are found in 73.5% of Brazilian's homes. Gathering all this data, a way to cause a positive impact on the country's energy saving would be to substitute the electricity-heated showers for more efficient ways of water heating (WILLEM *et al.*, 2017).

Heat pumps are a suitable alternative for water heating, since those equipment can use clean energy from the environment. According to Willem *et al. (2017)*, the average coefficient of performance (COP) of a regular heat pump varies between 1.8 and 2.5. It represents about twice of electric heater's efficiency. In addition, there are many ways to increase the COP by doing some modifications on the refrigerant's thermodynamic cycle. One them is use solar energy, since it is a renewable source, clean and readily available energy, especially in a country such as Brazil. A solar assisted heat pump (SAHP) achieves greater COP than the air source heat pumps (SUN *et al.*, 2014), since it can absorbs, besides the heat provided by the solar radiation, the heat from air convection and the water vapor condensation. (PAULINO *et al.*, 2017).

There are several configurations of a solar assisted heat pump. Although, it can highlight the one that it operates with a direct assisted solar energy, it known as direct expansion solar assisted heat pump (DX-SAHP) (WANG et al., 2017). In that equipment the evaporator is the solar collector, which the primary fluid on the system receives directly the energy provide by the sun, increasing the COP (LI *et al.*, 2007; DUARTE et al., 2019; PAULINO et al., 2019).

However, for the substitution of electric showers for heat pumps, it is very important to also associate the economic factor, analyzing initial investments and return time. Duarte *et al.* (2018) reported an economic analysis of R134a DX-SAHP operating in Belo Horizonte (Brazil) with a collector size of 2.3 m^2 collector and average COP of 2.8, which achieved a 3.4 years of payback period. In addition, the authors proposed that the collector size, geographic location and energy price directly affects payback period.

In this context, the aim of this paper is to present a detailed economic analysis of a DX-SAHP to heat domestic water operating in the Belo Horizonte region, but with a more environmentally friendly fluid such as CO_2. In the past decade, this fluid has been outstanding since it is a natural refrigerant, readily available fluid with low environmental impact. It has the lowest GWP (Global Warming Impact) among all well-known refrigerants and ODP (Ozone Depletion Potential) equal to zero (Nawaz *et al*. 2018). The costs of all the devices that composed the DX-SAHP are analyzed, as well as the average monthly radiation in the region. Then, the performance and the payback of the equipment are achieved.

2. EXPERIMENTAL SETUP

2.1 Experimental device

A CO_2 DX-SAHP installed in Belo Horizonte, Minas Gerais - Brazil was used in this study, as presented in Fig. (1a). The experimental device has a reciprocating compressor with 1.75 cm³/rev displacement, manufactured by SANDEN model SRCaDB. The counter current gas cooler has 24.3m with 4.66 mm, 6.34mm inner and outer diameter. The needle valve used as expansion device has 1.6mm² orifice area manufactured by Swagelok model SS-31RS4. The device's evaporator is a solar collector made with a copper tube of 7.6mm and 6.0mm inner and outer diameter, 16.3m in length and 0.1m distance between the tubes attached on 0.5mm copper flat plate of 1.57m² area. The hot water storage has a capacity of 200 liters.

2.2 System Monitoring

The Schematic of the DX-SAHP is shown in Fig. (1b), where T represents a T-type thermocouple (calibrated with an accuracy of ±0.5°C), PT represents a pressure transducer and PI represents a pressure indicator (calibrated with an accuracy of±0.5 bar for both). The numbers 1, 1′, 2, 3, and 4 are the CO_2 cycle position and the letters a and b are the water inlet and outlet in the gas cooler respectively.

Furthermore, two pyranometers (manufactured by BLACK & WHITE) model 8-48, with a range spectral 295 to 2800nm and an accuracy of +/-5% were used to measure the solar radiation flux, one of them on the horizontal plane and the other was fixed at 30° in relation to the horizontal. The power consumption in the compressor was measured using an ABB ETP 30 power meter, with an accuracy of +/- 5% and range of 0 to 1039 W.

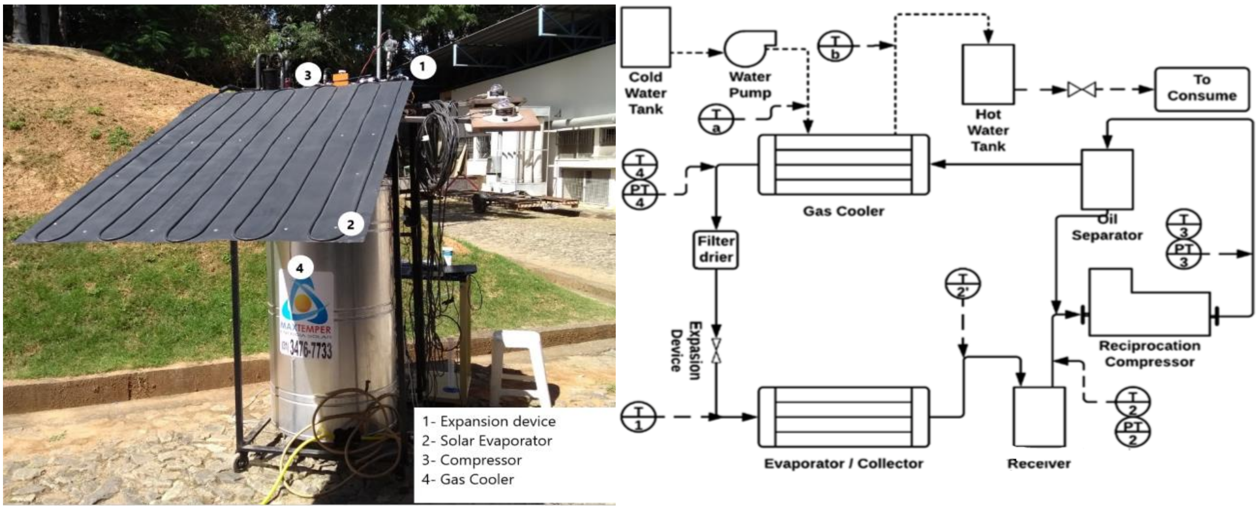

Figure 1. (a) Picture of the experimental setup (b) schematics of the DX-SAHP

2.3 Experimental procedure

Experiments were conducted during the months of April, May, and June from 10am to 15pm at Belo Horizonte time, Brazil. The average temperature during the test was 25.28°C and an average deviation of 0.56°C with wind speed characterized by light breezes. For all tests, a PID control system keeps the water outlet temperature at 60ºC, adapting the entire system according to the expansion valve opening and the radiation intensity. For a continuous admission of data, the Labview software was used. Then, it was possible to evaluate when the equipment reached the steady-state condition, which occurs about 20 minutes after each parameter variation. Through results evaluation, it was observed that the expansion device of two turns gives the best COP result, as presented by Paulino (2019). In that way, the economic analysis is performed considering this position of two turns opening of the expansion valve.

3. METHODOLOGY

Using the DX-SAHP to heat water is far more interesting them the electric resistors, due to it absorb the environment energy as a primary source as well as the work provided by an electrical source. Considering this characteristic an economic study is carried out to calculate the payback of the equipment. The climate and irradiation data are calculated by taking the average of temperature and irradiation for each day of the month in 2018, the data were obtained in the web site of Brazilian National Institute of Meteorology (INMET), as well as the interest for value correction over the time. It will be considered four operation conditions, heating water for four and six people in a house as well as two houses with the same amount of people, four and six each, considering that each individual per day uses 40L of hot water at 40°C, the DX-SAHP provides water at 60°C and the average room temperature is 20°C, for a more conservative perspective, for each kg of water at room temperature is necessary 1kg of hot water, so the average is 40°C.

By the average radiation flux obtained in the INMET website Tab. 1 was made. The electric energy provide to the DX-SAHP to heat water (Q_1) is calculate by Eq. (1), where the M is the water mass, c is the water specific heat and Δt is the water temperature variation. In this analysis it considered that the water is stored and at the time needs, it is mixed with room temperature water considered 20°C. Table 2 shows the average temperature during the year (provided by INMET website). Also, the efficiency of the electric resistor is considered 100% and the electrical energy necessary (Q_2) is calculated by Eq. (2). Then, comparing these two sources of energy it's possible to calculate the energy saved monthly (ΔQ) by Eq. (5). The energy saved monthly (P) is described by Eq. (6) using the value of kWh (E) and the factor of conversion from kJ to kWh.

$$Q_1 = (M_1 c \Delta t_1)/COP \tag{1}$$

$$Q_2 = M_2 c \Delta t_2 \tag{2}$$

$$M_2 = nl \tag{3}$$

$$M_1 = M_2/k \tag{4}$$

$$\Delta Q = Q_2 - Q_1 \tag{5}$$

$$P = \Delta Q j E \tag{6}$$

As expressed in Eq. (7), that relates the DX-SAHP initial investment (Bc), Selic taxes value (Ts), the income tax (Ir) and the value saved monthly(P) to the amount (m), and an Excel routine the payback is calculated for each case, considering the Selic of 2018 as a monthly income, and an Ir of 25%.

$$m = Bc(1 + Ts) - BcTsIr - P \tag{7}$$

Table 3 shows the estimated prices that compound each devices of the DX-SAHP, the values considered the Belo Horizonte market.

Table 1. Average solar radiation in Belo Horizonte in 2018.

	Solar radiation (W/m²)											
Hour daily	Jan	Feb	Mar	Apr	Mai	Jun	Jul	Ago	Sep	Oct	Nov	Dec
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	5	28	0	0	0	0	0	0	0	0	0	0
7	92	50	27	18	15	6	5	27	18	15	6	5
8	282	208	211	173	144	105	128	211	173	144	105	128
9	477	377	438	357	326	251	318	438	357	326	251	318
10	683	554	639	546	495	395	502	639	546	495	395	502
11	826	624	750	664	576	515	630	750	664	576	515	630
12	851	723	821	724	622	551	699	821	724	622	551	699
13	778	733	819	701	624	552	690	819	701	624	552	690
14	759	645	777	592	542	498	624	777	592	542	498	624
15	679	541	581	485	450	413	503	581	485	450	413	503
16	473	440	423	328	316	283	341	423	328	316	283	341
17	340	298	298	193	127	114	159	298	193	127	114	159
18	168	133	95	33	8	6	13	95	33	8	6	13
19	43	13	62	0	0	0	0	62	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0

Table 2. Average Temperature in Belo Horizonte in 2018.

	Average Temperature (°C)											
Hour daily	jan	Feb	Mar	Apr	Mai	Jun	Jul	Ago	Sep	Oct	Nov	Dec
1	22.11	20.78	20.78	20.19	18.67	16.63	17.46	18.34	20.39	20.95	20.02	20.30
2	21.75	20.66	20.49	19.85	18.24	16.12	16.90	17.97	19.88	20.63	19.70	20.28
3	21.50	20.44	20.06	19.48	17.87	15.85	16.37	17.62	19.54	20.33	19.52	20.09
4	21.09	20.24	19.77	19.20	17.49	15.55	15.94	17.21	19.28	19.99	19.26	19.77
5	20.87	20.05	19.45	18.93	17.40	15.54	15.57	16.44	18.90	19.84	19.13	19.64
6	20.80	19.82	19.36	18.80	17.19	15.31	15.32	16.17	18.59	19.90	19.34	19.87
7	21.86	20.78	20.27	19.25	17.64	15.52	15.40	16.62	19.47	21.04	20.53	21.45
8	23.25	22.04	22.30	21.25	19.59	17.43	17.67	18.69	21.18	22.42	21.59	22.59
9	24.69	23.09	23.67	22.53	21.46	19.06	19.94	20.74	22.97	23.60	22.60	23.63
10	25.92	24.42	24.93	23.95	22.83	20.26	21.72	22.28	24.46	25.07	23.73	24.74
11	26.95	25.08	25.97	24.84	23.85	21.54	23.23	23.90	26.00	26.32	24.82	25.75
12	27.65	25.86	26.96	25.55	24.91	22.48	24.33	25.00	27.34	27.18	25.57	26.17
13	28.20	26.33	27.77	26.44	25.38	23.11	24.95	26.16	28.32	27.75	25.80	26.94
14	28.75	26.19	28.15	26.40	25.73	23.34	25.52	26.93	28.70	28.45	25.81	27.30
15	28.31	26.28	27.79	26.54	25.60	23.34	25.53	26.75	28.66	28.19	26.26	26.99
16	28.05	26.11	27.10	26.03	25.11	22.93	25.26	26.27	27.93	27.43	25.31	26.26
17	27.40	25.28	26.49	25.20	23.71	21.52	23.92	25.16	26.72	26.20	24.49	25.95
18	26.34	24.46	24.99	23.56	22.40	20.12	22.00	23.33	25.06	24.94	23.25	24.87
19	25.19	23.29	24.09	22.83	21.65	19.49	21.14	22.18	24.05	24.09	22.46	23.54
20	24.40	22.84	23.43	22.29	21.06	18.91	20.25	21.38	23.15	23.35	21.80	22.69
21	23.87	22.42	22.88	21.89	20.50	18.53	19.48	20.46	22.29	22.84	21.49	22.13
22	23.33	22.12	22.40	21.47	20.04	17.90	18.79	19.86	21.69	22.34	21.02	21.63
23	22.79	21.67	22.08	20.97	19.56	17.52	18.40	19.52	21.17	21.96	20.57	21.24
24	22.51	21.16	21.49	20.58	19.17	17.19	17.85	18.86	20.77	21.35	20.30	20.83

Table 3. DX-SAHP cost devices based on regional values.

Compressor	R$1,125.00
Liquid separator	R$150.00
Oil separator	R$650.00
Evaporator plate	R$473.74
Expansion device	R$1,559.00
Water pump	R$130.00
Drying filter	R$50.00
Pressure switch	R$795.00
Thermostat	R$50.00
CO_2 (refrigerant fluid)	R$20.00
Labor	R$910.00
Total	R$5,912.74

Note: The values were estimated by prices in the local market in Belo Horizonte

4. RESULTS AND DISCUSSIONS

4.1 Experimental results

Considering the environment conditions described in 2.3, five operation conditions were obtained experimentally, for the radiation flux range between 610.49 (W/m^2) and 816.25 (W/m^2). Figure 2 shows the experimental results obtained of the COP function of the radiation flux. The average COP obtained was 2.67 and this value is used at Eq. (1).

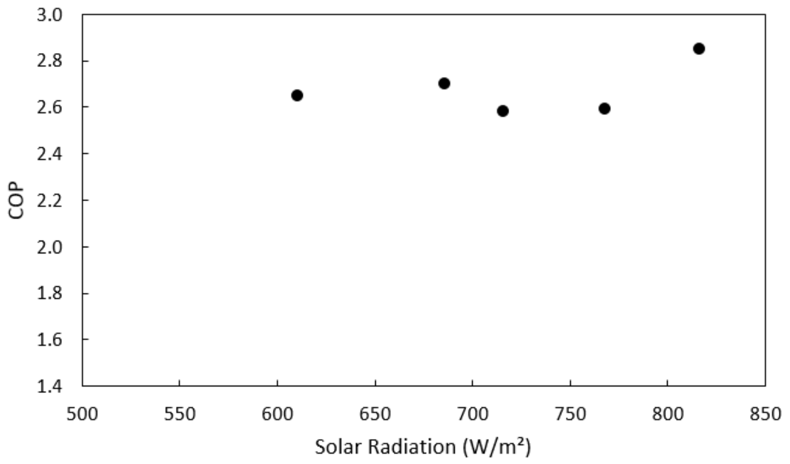

Figure 2. COP of system related to the radiation flux

4.2 Technical economic analysis

The results, shown in Fig. 3, indicates the time needed to payback the initial investment. Considering for people, 240 months are necessary, 134 months for a house of six people, 93 months for two houses with four people each, and 58 months considering the best case, two houses with six people.

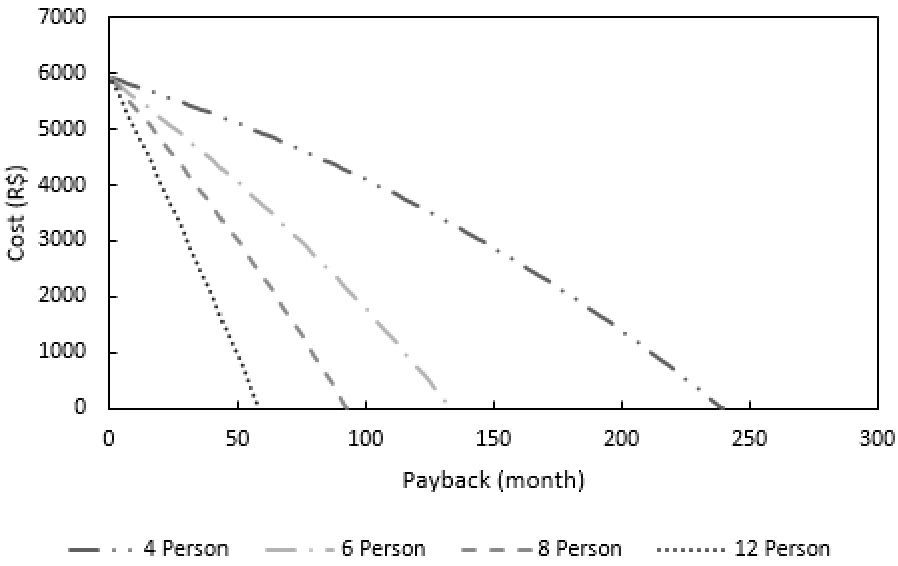

Figure 3. Amount of money X time in mounths.

5. CONCLUSION

This paper presented an economic analysis of a small CO_2 direct assisted solar heat pump for domestic water heating based on experimental data. The average COP obtained during the tests was 2.67. The total price of this equipment was estimated in about R$6,000.00. The payback can vary from 240 to 93 months, it is noticeable that the economy factor was more relevant when considering more people using the DX-SAHP as a heat resource. Considering this aspect, if the water reservoir changes by a larger one, it can increase the capacity of the equipment, however, the average COP would decrease so it's not something that can be done without further studies.

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