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Experimental Analysis of the Influence of Water Mass Flow Rate on the Performance of a CO_2 Direct-Expansion Solar Assisted Heat Pump

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***Abstract*—**Energy use is one of the main indicators for the economic and social development of a country, reflecting directly in the quality of life of the population. The expansion of energy use together with the depletion of fossil resources and the poor efficiency of energy systems have led many countries in recent years to invest in renewable energy sources. In this context, solar-assisted heat pump has become very important in energy industry, since it can transfer heat energy from the sun to water or another absorbing source. The direct-expansion solar assisted heat pump (DX-SAHP) water heater system operates by receiving solar energy incident in a solar collector, which serves as an evaporator in a refrigeration cycle, and the energy reject by the condenser is used for water heating. In this paper, a DX-SAHP using carbon dioxide as refrigerant (R744) was assembled, and the influence of the variation of the water mass flow rate in the system was analyzed. The parameters such as high pressure, water outlet temperature, gas cooler outlet temperature, evaporator temperature, and the coefficient of performance were studied. The mainly components used to assemble the heat pump were a reciprocating compressor, a gas cooler which is a countercurrent concentric tube heat exchanger, a needle-valve, and an evaporator that is a copper bare flat plate solar collector designed to capture direct and diffuse radiation. Routines were developed in the LabVIEW and CoolProp through MATLAB software's, respectively, to collect data and calculate the thermodynamics properties. The range of coefficient of performance measured was from 3.2 to 5.34. It was noticed that, with the higher water mass flow rate, the water outlet temperature decreased, and consequently, the coefficient of performance of the system increases since the heat transfer in the gas cooler is higher. In addition, the high pressure of the system and the CO_2 gas cooler outlet temperature decreased. The heat pump using carbon dioxide as a refrigerant, especially operating with solar radiation has been proven to be a renewable source in an efficient system for heating residential water compared to electrical heaters reaching temperatures between 40 °C and 80 °C.

***Keywords*—**Water mass flow rate, R-744, heat pump, solar evaporator, water heater.

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I. Introduction

In the recent decades, the issues about energy saving, energy efficiency and environmental improvement are among the concern objectives as related to heating and cooling systems. In this context, the heat pump is an attractive alternative, especially for water heating, which is the fourth largest energy option in the commercial and residential sector [1].

The current heat pump water heaters (HPWHs) offer efficiencies that are at least twice of conventional electric water heaters [2]. The advantages of the use of the HPWHs are the reliable in terms of performance and durability of those systems, besides the reduced environmental impacts by lowering carbon emissions compared to electric water heaters [2], [3]. Aiming to increase the efficiency and performance of the heat pumps water heaters systems, recent studies are also focused on systems that led to use of solar energy, since it is one of the most viable renewable energy sources. A DX-SAHP system, which employs a solar collector as an evaporator, is an interesting technique because it converts and transports heat energy directly from the sun to water. Compared to the air-source heat pump system alone, the DX-SAHP system operates at higher evaporating temperature due to effective absorption of solar thermal energy, which therefore results in a higher heat pump performance and high yields of collector efficiency [4].

Because of the high thermodynamic performance compared to conventional water heaters, in the past years, many theoretical and experimental studies have investigated DX-SAHP systems worldwide applied to water heaters. Omojaro and Breitkopf [5] reported that 75% of researches about DX-SAHP have the purpose of water heaters.

Kuang et al. [6] made a theoretical and experimental about performance of DX-SAHP system for domestic water heater using R-22. The monthly averaged COP was found to vary between 4 and 6, while the collector efficiency ranged from 40 to 60%. Chow et al. [7] proposed a numerical model of the DX-SAHP systems for residential water heater in the city of Hong Kong. The results are found to be way better than the conventional heat pump system performance with an average coefficient of performance (COP) of 6.46. Kong et al. [8] developed a theoretical and experimental study of a direct expansion solar heat pump with R-22 to supply hot water for a domestic use. The experiments results showed good agreement with those predicted by the simulation with only 1% of deviation. In addition, the authors concluded that the mains factors that affect the performance of the system were:

solar radiation, ambient temperature and compressor speed.

Furthermore, another issue face to the refrigeration industry is the great impact of the refrigeration fluid use on those heat pump systems causes on climate change. The Montreal and Kyoto Protocols, and more recently the Kigali's amendment, established goals to reduce greenhouse emissions by developing and using refrigeration fluids with low ODP and GWP [9], [10]. In this context, the dioxide carbon has shown to be a potential natural fluid replacement, since it has zero net impact on climate change with OPD=0 and GWP=1. CO_2 is not toxic, flammable or corrosive fluid; it is compatible with many lubricants oils and has high thermal exchange coefficients and low-pressure ratio [10], [11]. Many works in the literature such as Neská, Sarkar et al., Sarkar and Bhattacharyya, Yokoyama et al., Minetto, Checchinato et al., Yamaguchi et al., Xu et al., Lin et al., Purohit et al., Rawat et al. investigated various configurations, parameters and components of air source HPWHs using CO_2 operating in a transcritical cycle [12]-[24]. There are just a few works of heat pumps employing solar radiation and CO_2 as refrigeration fluid, and those are focused more on simulation systems. Oliveira et al. developed a dynamic modeling with experimental validation for a CO_2 heat pump gas cooler. The model was based on the conservation equation of energy, mass, and momentum. The results showed a maximum deviation of 2 °C between the numerical model and experimentally data [25]. Faria et al. proposed a model to analyze the behavior of the solar evaporator and the expansion valve for a DX-SAHP operating with CO_2 in transcritical cycle for a transient and steady state condition. The mathematical model showed to be a promising tool to perform simulations, since it included atmospheric conditions parameters such as solar radiation, ambient temperature, and wind speed [26].

In this way, the present work aimed to investigate the influence of the mass flow rate at the thermal performance of a direct-expansion assisted solar heat pump water heater operating with CO_2 in a transcritical cycle.

II. Experimental of a Transcritical CO_2 Heat Pump

A. Experimental Device

The experimental set layout of the heat pump operating with CO_2 is shown in Fig. 1. The hermetic reciprocating compressor used in this study was manufactured by SANDEN model SRCaDB with cooling capacity of 819 W, 110-127 V, constant speed and displacement of 1.75 cm^3/rev. The gas cooler is a countercurrent concentric cooper tube heat exchanger disposed around a polyvinyl chloride (PVC) tank with insulation as seen in Fig. 2. Water flows in the outer annular channel, while CO_2 flows in the inner tube. The total length of tubing of the gas cooler was 24.2 m with outer tube diameter of 6.34 mm and 12.5 mm, respectively for CO_2 and water. The water is provided by a bath and a small pump incorporated at the gas cooler, and another tank with capacity of 200 liters is used to storage the hot water. A pulse width modulation control (PWM) was developed to provide a control of the outlet water temperature and to vary the mass flow rate.

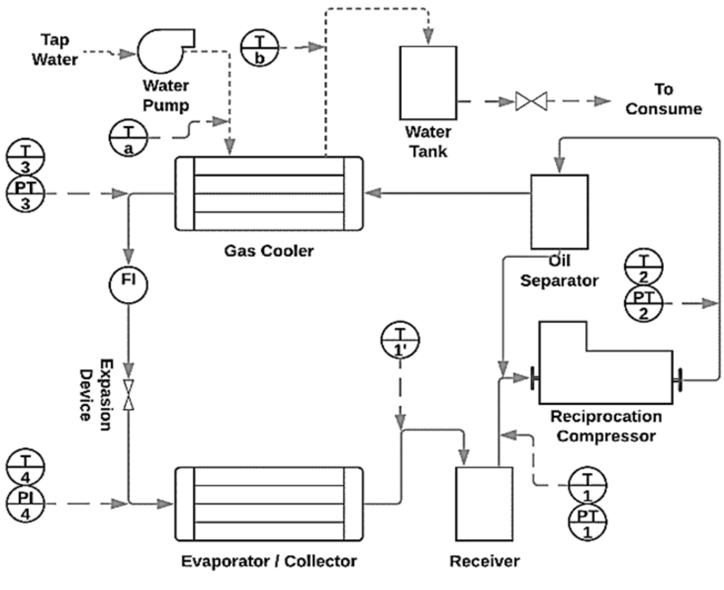

Fig. 1 Experimental set layout of the transcritical CO_2 heat pump

A Swagelok integral bonnet needle valve (model SS-31RS4) with orifice area of 1.6 mm^2 was used as the expansion device, which can be used to regulate flow rate and the degree of superheat of the system. The evaporator was a solar collector made by a copper tube arranged as shown in Fig. 3 and attached at a 0.5 mm copper flat plate with total length and collecting area of 16.3 m and 1.57 m^2, respectively. The inner and outer diameters are 4.66 mm and 6.34 mm, and the distance between the tubes is 100 mm as shown in Fig. 3. The collector was installed with a fixed angle of 30°. According to Duffie and Beckman [27], there is an optimum slope that favors the solar radiation absorbed at the plate during all seasons of the year. For the region that the DX-SAHP was installed, in at the south hemisphere, Belo Horizonte – Brazil, considered the latitude as 20° added by 10°.

Fig. 2 Gas cooler assembly

Fig. 3 Solar collector

B. Test Procedure and Test Conditions

In the experimental study, the effects of water mass flow rate in gas cooler, the ambient temperature and radiation were the mainly parameters investigated. For all the measurements, steady state condition was assumed, and data were collected. The total mass of CO_2 in system for all test was 560 g. The CO_2 temperatures in the inlet and outlet of each component, the water temperature inlet and outlet, the ambient temperature and the walled compressor housing temperature were measured with T-type thermocouples. All thermocouples were located outside the cooper pipe with a layer of silicon sealant coated between the sensor and the pipe to offer excellent heat conductivity and insulation. The high pressure of the system was measured by two pressure sensors, one at the compressor discharge and the other at the gas cooler outlet. A mechanical pressure gauge installed at the compressor suction measured the low pressure of the system. Two pyranometers were used to measure the solar radiation flux, one fixed at 30° and other at the horizontal plane. All the instruments were calibrated, and their uncertainties are summarized in Table I. The LabVIEW program data acquisition instrument was used to monitor and record all data, and the MATLAB with Coolprop toolbox software to calculate the thermodynamics parameters.

TABLE I
ACCURACY OF THE MEASUREMENT DEVICES

Sensors	Measured Variable	Range	Calibrated accuracy
T-type thermocouple	Temperature (°C)	-270-370 °C	0.5 °C
Pressure transducer	Pressure (Bar)	0- 102 Bar	0.5 Bar
Pressure gauge	Pressure (Bar)	0,1 - 200 Bar	0.5 Bar
Pyranometers	Flux of solar radiation	295-2800 nm (spectral range)	5%

The combined standard uncertainty of COP was calculated using the method described by BIMP [28], in which the highest and the lowest value were, ±0.26 for COP equal to 3.3, and ±0.64 for COP equal to 4.65, respectively.

The heat pump COP was defined as:

$$COP = \frac{\dot{Q}H}{W} \quad (1)$$

The heat received by water at the gas cooler ($\dot{Q}H$) and the compressor power (W) were given by:

$$\dot{Q}H = \dot{m}(h_3 - h_2) \quad (2)$$

$$W = \dot{m}(h_1 - h_2) \quad (3)$$

where $\dot{m}$ is the refrigerant mass flow rate, the subscripts h_1, h_2, h_3 represent the specific enthalpy at the suction of the compressor, the outlet of the compressor and the outlet of the gas cooler, respectively. The refrigerant mass flow rate was obtained from the energy balance in the gas cooler. Then, the heat transfer received by the refrigerant in the evaporator ($\dot{Q}L$) was given by:

$$\dot{Q}L = \dot{m}(h_1 - h_4) \quad (4)$$

where h_4 refers to the specific enthalpy at the evaporator inlet.

III. RESULTS AND DISCUSSION

The results showed that the variation of the water mass flow rate interferes some parameters of the refrigeration system such as the water outlet temperature, COP, evaporator temperature, outlet gas cooler temperature, high pressure and heat transfer rates.

For all tests, the water inlet temperature and the ambient temperature was approximately 25 °C. The solar radiation has a maximum deviation about 11% with average 783 W/m^2. In addition, the electronic expansion valve was maintained with the same aperture. All measurements were done in steady-state condition. Fig. 4 shows the variation of the water mass flow rate relate to the water outlet temperature and the system COP.

As expected, the increase of the mass water flow rate of the system decreases the water outlet temperature and increases the COP of the system. A larger mass in the gas cooler increases the capacity of heat exchange with the CO_2. The higher water mass flow rate of 0.0217 kg/s results in a COP of 5.34. The values of COP obtained are similar to others works in the literature that used a DX-SAHP with a R-314a such as Kuang et al. [6] and Chow et al. [7].

In Fig. 5, it can be noticed that the higher water mass flow rate, the lower is the high pressure of the system. This effect occurs since the water outlet temperature decreases with a higher mass flow rate, causing a reduction of the high pressure in the gas cooler. Because of that, the gas cooler outlet temperature also is slightly reduced as it is seen in Fig. 6.

In addition, as discussed by Wang et al. [29], the high pressure and the outlet temperature of the gas cooler are two factors that have a great influence on the performance of a system operating with CO_2 in the transcritical cycle. The thermophysical properties of carbon dioxide above the critical point have a differentiated behavior. The specific heat in the transcritical region decreases with an increase of the pressure and temperatures, which contribute to decrease of coefficient of heat transfer. Then, a higher water outlet temperature provides from a lower mass flow rate, increases the high pressure of the system leading to a lower COP.

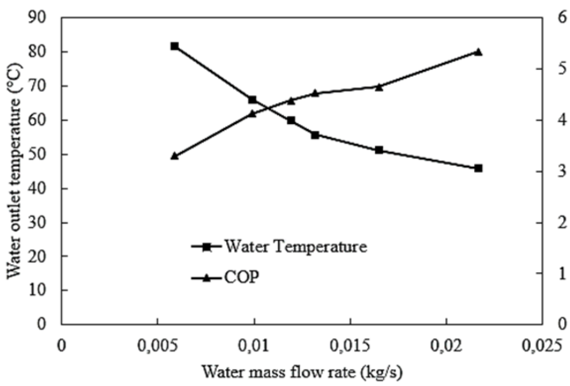

Fig. 4 The variation of water mass flow rate function of the COP and the water outlet temperature

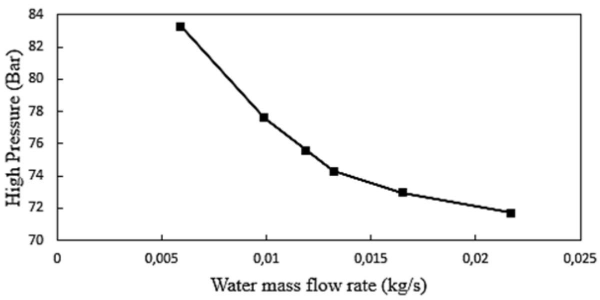

Fig. 5 The variation of water mass flow rate function of the high pressure of the system

Fig. 7 shows the effect of the water mass flow rate at the evaporator temperature. As it can see, the temperature has a slightly decreased as the water mass flow rate increased. Since the global coefficient and the area of the evaporator are practically constant for an increase of the heat transfer, the delta of temperature in this heat exchanger needs to be higher. Then, the evaporation temperature tends to decrease. Wang et al. [29] related the same behavior in their experimental results. In addition, as expected, the heat transfer rates in the solar evaporator (QL) and in the gas cooler (QH) increased for a higher mass flow rate as demonstrated in Fig. 8. Since the solar radiation changed little, its influence was not considered at the heat transfer rates.

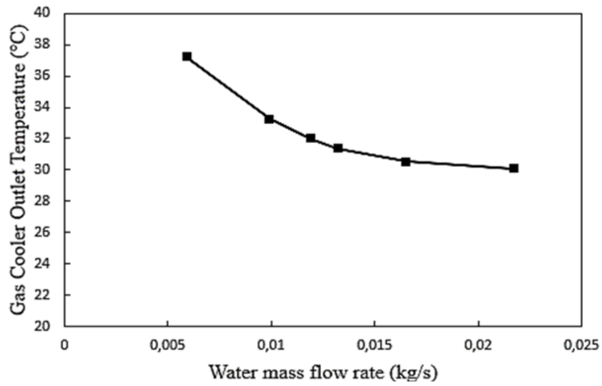

Fig. 6 The variation of water mass flow rate function of the gas cooler outlet temperature

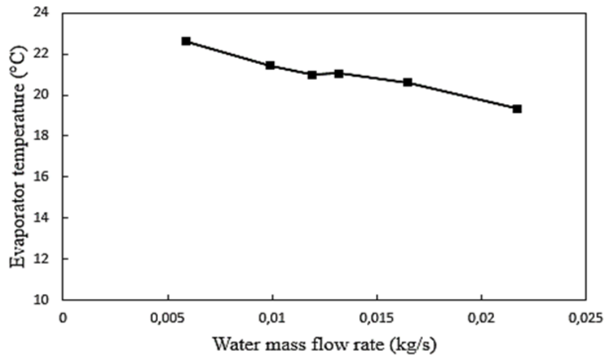

Fig. 7 The variation of water mass flow rate function of the evaporator temperature

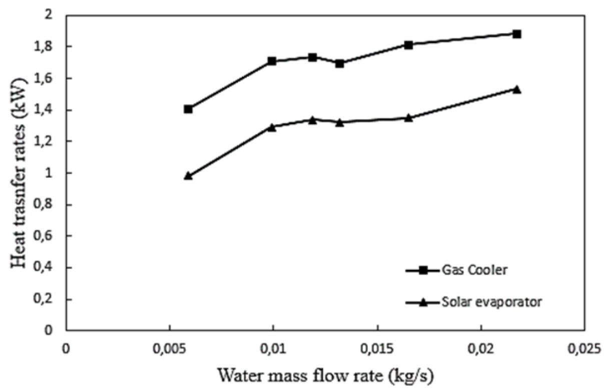

Fig. 8 Water mass flow rate versus the heat transfer rate from the solar evaporator (QL) and the gas cooler (QH)

IV. Conclusion

It is observed that the DX-SAHP using a CO_2 as refrigerant is a very promising technique to heat domestic water. The system was able to heat water with 25 °C up to 80 °C with a great performance compared to electrical heaters. The water mass flow rate demonstrated to be an important parameter on this system since it influences the water outlet temperature, the high pressure, the gas cooler outlet temperature and the COP of the system. For higher water mass flow rate, the COP of the system increased, while the water outlet temperature, the high pressure and the gas cooler outlet temperature decreased. In addition, as expect, the heat transfer rates increased as higher water mass flow rate. For those experimental, the solar radiation was almost constant, but whenever it changed, the DXSAHP other analyzes must be carried out in order to verify the influence of all parameters on the system performance.

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