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TRANSIENT ANALYSIS OF A HEAT PUMP SOLAR EVAPORATOR THROUGH A TEMPERATURE STEP

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Abstract. *The superheating degree of a refrigerant fluid in a vapor compression cycle, applied in refrigerating and heating systems, is fundamentally important for the good operation of the compressor and consequently the good performance of the system. This work aims to analyze the superheating degree control of the refrigerant fluid R134a in the solar evaporator of a heat pump operating with vapor compression to heat water, when a temperature step is applied in its evaporator. The experiment proposed simulates the behavior of a direct expansion solar evaporator in situations of sunny and cloudy days, that is, when the solar radiation on the evaporator is intense and when it is reduced due to the clouds. The behavior of thermodynamic parameters of the refrigerant fluid and parameters of the system was analyzed by applying a temperature step in the solar evaporator to simulate experimentally the sudden variation of solar radiation incident on the evaporator. The transient behavior of the heating system has been studied and it has been found that when the evaporator is heated, the refrigerant flow rate in the suction of the compressor increases. The thermostatic expansion valve acts on the system until a new equilibrium point is found, stabilizing the flow of the refrigerant fluid.*

Keywords: *Heat pump, solar evaporator, thermostatic valve, temperature step.*

1. INTRODUCTION

Energy is fundamental to human life, but the way it is being used and thought of by society has been changed over the years, promoting researches that investigate its use in a more sustainable and renewable way. Refrigerating and heating systems are essential to humanity survival, guaranteeing quality of life promoted by thermal confort and food preservation. Extensive works about these systems are cooperating for their inovation regarding efficiency, safety and sustainability. In this scenario, the heat pump (HP) is an equipment applied to heat ambients, water pools, water baths, and water to consume in general, beside other specific applications. This equipment has the same configuration of a refrigerating machine, as the air conditioner, for example, that operates in vapor compression cycle, the most used method for heating and refrigerating.

A heat pump is basically composed by a compressor, a condenser, an expansion valve and an evaporator. In a closed cycle, the refrigerant fluid (primary fluid) runs through the heat exchangers, receiving or giving heat to secondary fluids. Initially in the compressor, the primary fluid has its pressure and temperature increased, becoming superheated vapor (Çengel, 2013). Afterwards, this fluid is sent to the condenser, where it looses its energy in the form of heat, going to the liquid state, giving heat to the secondary fluid (heat source) that, in the specific case of this work, is water. After the condenser, the primary fluid goes through the expansion valve, decreasing its pressure, and part of the liquid turns into vapor, that is, in the valve outlet there is a liquid vapor mixture. This fluid is then sent to the evaporator, that is under low pressure and temperature. The refrigerant fluid receives heat from the cold source, leaving the evaporator as superheated steam, thereby acquiring heat from the secondary fluid which, in the specific case of the heat pump of this work, is ambient air. Next, the primary fluid is conveyed to the compressor, initiating the entire cycle again. Thus, the heat pump studied acts by supplying heat to water through its condenser and acts by withdrawing heat from the environment through its evaporator. The heated water is stored in a thermal reservoir and intended for domestic use.

A thermostatic expansion valve acts in the sense of controlling the temperature at the evaporator outlet, dictating this fluid to superheat and ensuring its entry as superheated vapor in the compressor. This preserves the compressor's life, once it works only with vapor (Fabris,2006). The superheating degree, that is, the difference between the evaporation temperature and real temperature at the evaporator outlet is maintained in a determined range. It is because, as it is safe to keep the fluid entirelly vapor at the inlet, from the other side, the exagerated superheating decreases the compressor efficiency, that decreases the system performance (Diniz, 2017).

In this study, the superheating control through a thermostatic valve was evaluated, simulating different conditions. A temperature step was applied to the evaporator from different levels of solar irradiation, increasing the temperature of the evaporator. The inverse process was also performed and studied. Thus, the performance of the thermostatic valve was investigated and the behavior of the mass flow inside the evaporator was quantified.

1. METHODOLOGY

The experimental prototype used is a heat pump using R134a as the working fluid, according to Fig. 1 and Tab. 1, consisting of a compressor, a thermostatic expansion valve, a serpentine flooded condenser, a coaxial condenser, a solar evaporator, a conventional evaporator of finned tubes with forced convection of air and a thermal reservoir of water (tank). The prototype has two condensers and two evaporators, however, only the the flooded condenser and the solar evaporator are used in this work.

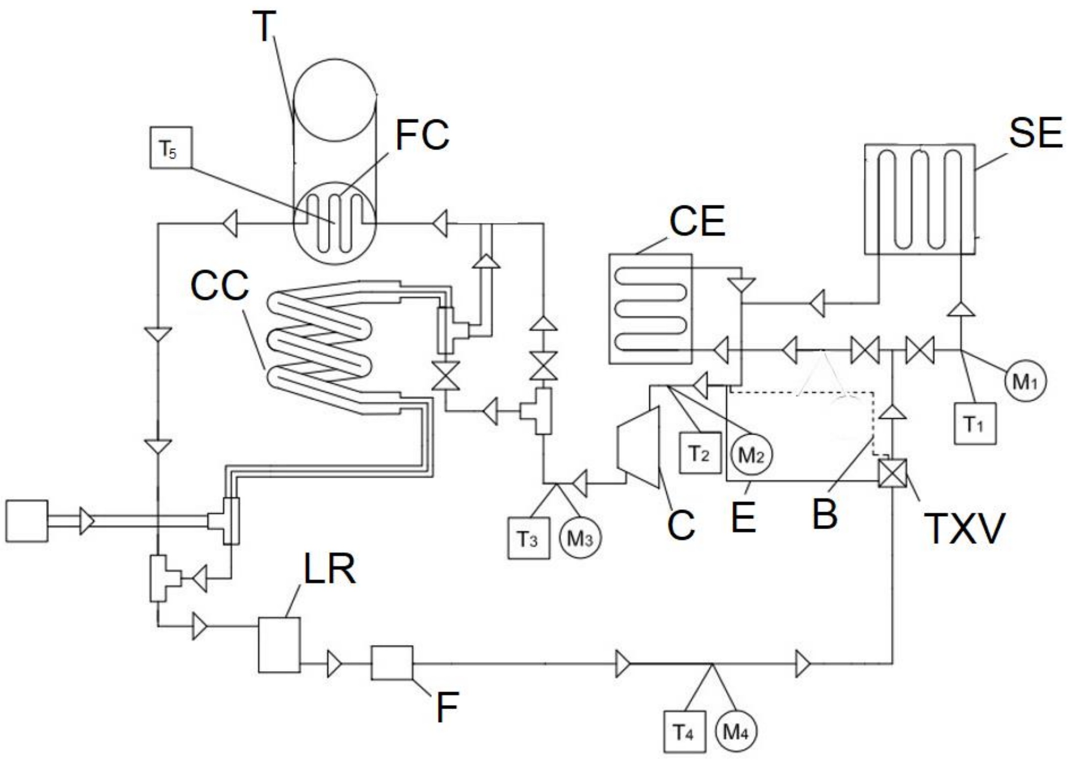

Figure 1. Heat pump schematic design

Table 1. Description of heat pump equipment

Labels	Thermocouples (Temperature)
TXV - Thermostatic Expansion Valve	T1 - SE Inlet
SE - Solar Evaporator	T2 - C Inlet
CE - Conventional Evaporator	T3 - IC Inlet
C - Compressor	T4 - TXV Inlet
FC/CC – Flooded/Coaxial Condenser	T5 - IC Water
B - Bulb	**Manometers (Pressure)**
LR - Liquid Receiver	M1 - SE Inlet
E - Equalizer	M2 - C Inlet
F - Dryer filter	M3 - IC Inlet
T - Tank	M4 - TXV Inlet

The machine is instrumented with four pressure gauges (bourdon type), two low and two high pressure gauges. It also has five thermocouples, four of which are installed near the manometers, making possible the determination of the four points of the refrigeration cycle. The fifth thermocouple is intended for the measurement of water in the tank (where the flooded condenser is located).

The machine has also a flow meter at the condenser outlet and a pyranometer (solar irradiation measurement - W/m²) on the evaporator plane. All measurements except pressures are recorded at one tenth of a second intervals in LabView software via data acquisition boards. The full description of the prototype can be found in Diniz (2017).

For the simulation of the temperature step, the tests were performed on a sunny day in the city of Belo Horizonte - MG. A tent was used, according to Fig. 2, in order to cover up the solar evaporator, thus simulating low solar irradiation. As soon as the system goes into operation in the permanent regime (in the shade), the tent is removed, increasing the intensity of irradiation on the evaporator (the amount of heat has increased up to 9 times).

Figure 2. Tent and prototype studied

1.1 Determination of parameters inside the evaporator

The mass and internal energy variation of the refrigerant inside the compressor are negligible, so the mathematical models used for the compressors are the same both in the transient regime and in the permanent regime (Koury, 1998).

The quantification of the mass flow rate in an evaporator has been the object of several studies. Currently, several studies use Eq. (1) to Eq. (3), that determine the mass flow at the outlet of the expansion valve (evaporator inlet) and at the suction of the compressor (evaporator outlet). These equations were obtained from the global balance of mass, energy and momentum. Eq. (1) relates the flow at the compressor inlet, Eq. (2) deals with the volumetric efficiency of the compressor and Eq. (3) shows the flow imposed by the thermostatic valve.

$$\dot{m} = NV\rho_{asp}\eta_v \tag{1}$$

$$\eta_v = 1 + c - c\left(\frac{P_{cond}}{P_{ebul}}\right)^{cv/cp} \tag{2}$$

$$m_{v\,exp} = C_d\sqrt{(P_{cond} - P_{ebul})\rho_{ent}} \tag{3}$$

In Eq. (1), $\dot{m}$, N, V, ρ_{asp} and η_v are, respectively, the compressor mass flow, rotational speed, displaced volume, inlet specific mass and volumetric efficiency. In Eq. (2), c, P_{cond} , P_{ebul}, cv and cp are, respectively, dead space coefficient, condensation pressure, boiling pressure, specific heat at constant volume and at constant pressure. In Eq. (3), $m_{v\,exp}$ is the mass flow imposed by thermostatic valve, C_d is the expansion valve characteristic constant (passage section area times an adimensional friction coefficient) and ρ_{ent} is the fluid specific mass at the expansion valve inlet. These equations were used in the works of Machado (1996), Koury et al. (2001), Maia (2000), Maia (2007), Nunes (2010) and Nunes (2013).

1.2 Experimental procedure

The behavior of the variables influenced by the operation of the thermostatic expansion valve (TXV) was analyzed, being them the temperature in the evaporator, the variation of mass flow in the evaporator and the superheating control in the evaporator. A tent was used to cover the solar evaporator, to simulate a cloudy day. The temperatures, mass flow and irradiation were recorded in this situation. Subsequently, the tent was removed causing the solar radiation on the evaporator to increase significantly (up to nine times). With this, a temperature step in the evaporator was carried out, allowing the change of the evaporation temperature of the fluid. The temperature variations at the inlet and outlet of the evaporator and the mass flow as a function of time were analyzed, as well as the high and low pressures of the system. As the main result, charts representing the behavior of the mass flow over time as well as the variation of the evaporator temperatures are plotted against time.

2. RESULTS

The test was performed in July 2018 (winter in the southern hemisphere) in the morning. The sky was clear and sunny. The irradiation intensity reached close to 1000 W/m². All data except pressures were collected at 0.1 second time intervals and recorded in LabView software. The test lasted 1 hour and 34 minutes.

The experiment starts by connecting the heat pump compressor with the solar evaporator covered by the tent. When the system reaches the permanent regime, the tent is removed and a temperature step is observed in the solar evaporator, increasing the flow imposed by the thermostatic valve. The system reaches a new operation point, and finally the tent is relocated to the original position, casting shadow over the evaporator again. Figure 3 shows the behavior of the mass flow during this process, remembering that the flow meter is located at the inlet of the thermostatic expansion valve, what means that only compressed liquid passes in this instrument.

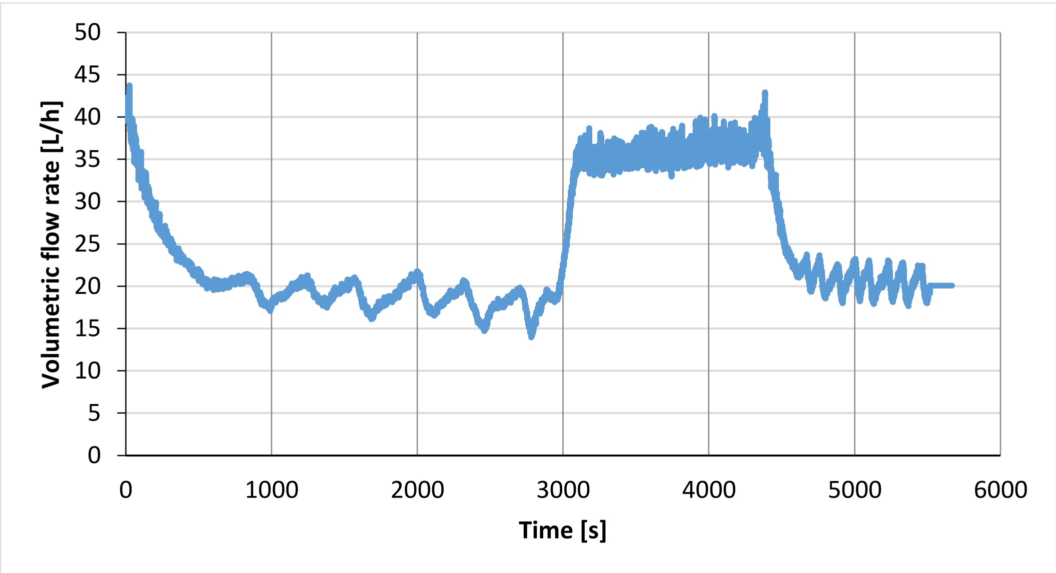

Figure 3. Mass flow behaviour in the solar evaporator

Figure 4 shows the irradiance incident on the solar evaporator during times when the tent shadows the evaporator (values close to 100 W/m²) and also at the moment the tent is removed (values close to 900 W/m²).

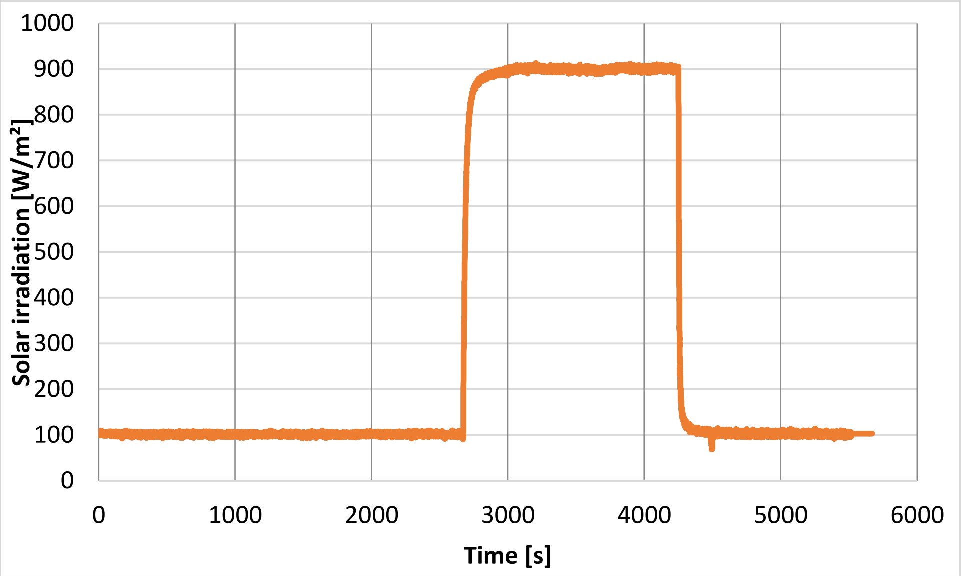

Figure 4. Solar irradiation normal to the evaporator plane

Finally, Fig. 5 shows the temperature behavior of the four points of the heat pump refrigeration cycle. It is observed that the temperature variation profile at the compressor inlet (T02) is similar to the profile of the solar irradiation flux (Fig. 4), showing the impact that the variation of this heat flow causes in the superheating degree of the system.

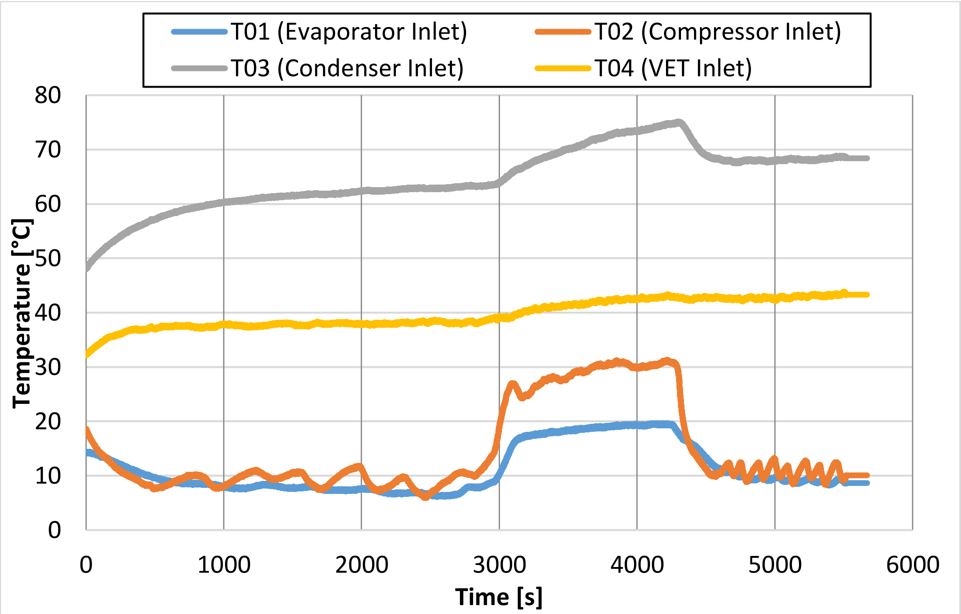

Figure 5. Temperature in the four points of the heat pump refrigerating cycle

Pressures were recorded in 3 stages, the first one with the tent casting shadow in the evaporator, the second with the solar radiation directly on the evaporator and the last stage with the tent being placed back in the original position. All steps were measured in steady state, i.e. when the machine reaches its operating point and its pressures are stable (Tab. 2).

Table 2. Pressures in the heat pump

Configuration	P1 (KPa) - SE Inlet	P2 (KPa) - C Inlet	P3 (KPa) - IC Inlet	P4 (KPa) - TXV Inlet
1° Stage – SE in shadow	260.00	190.00	1,157.18	980.66
2° Stage - SE in sun light	460.00	330.00	1,353.32	1,098.35
3° Stage - SE in shadow	300.00	220.00	1,421.96	1,225.83

Ambient temperature and air humidity were collected from a hygrometer. During the experiment, the mean ambient temperature was 21.4°C and the mean relative air humidity was 57.3%.

With the increase of the temperature in the evaporator, simulated by a step function through the removal of the tent, the evaporation temperature increased, leading to an increase of the evaporation pressure, which, as a consequence of Eq. (3), decreased the mass flow rate at the entrance of the evaporator. Then, the volumetric efficiency of the compressor increased with the increase of the evaporation pressure, according to Eq. (2), thus causing an increase in the mass flow imposed by the compressor, according to Eq. (1). This increase is intensified by the increase of the specific mass of the fluid that happens with the increase of the evaporation pressure, causing the emptying of the evaporator, which next causes an increase in the superheating degree. At this time, the thermostatic valve is activated increasing its opening section, which allows the passage of more refrigerant fluid, filling the evaporator again to a point of stability, where the temperature and the evaporation pressure are higher than the initial values. When the tent is place above the evaporator again, the system behaves inversely moving to a new operating point with the lowest pressure and temperature.

Similar results are described by Zhang et al. (2016), where the pressure and mass flow variation within an evaporator is shown through the opening and closing of an electric expansion valve. In addition, Fabris (2006) developed similar work and reached results as described above.

3. CONCLUSION

The study of the behavior of the thermodynamic and operation parameters of vapor compression refrigeration and heating machines helps to understand its operation and promotes the improvement in the systems, increasing its coefficient of performance.

In this work, it was simulated a temperature step in the primary fluid that exchanges heat with the evaporator of a heat pump, thus allowing to understand the equipment behaviour, which works changing heat with the external environment. The evaporator studied is a direct expansion solar evaporator, where the temperature and the heat coming from the sun are not constant, due to the possibility of sunny, cludy and even rainy days. The thermostatic valve was analysed in some operation situations of the evaporator, and it caused a temperature change of the refrigerant and, consequently, the evaporation pressure change. The response of the refrigerant flow rate to the temperature change as a function of time, imposed by the thermostatic valve and the compressor, are opposite. However, they stabilize immediately afterwards, thanks to the actuation of the expansion device. It is noteworthy that, as the test was performed with a flooded condenser, the third stage (tent replacement) does not return to the starting point (first stage). This happens because the temperature of the water inside the tank is being heated continuously, repositioning the equipment in a new point of operation at each moment (points very close to each other).

4. ACKNOWLEDGEMENT

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