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Comparison of Transcritical and Subcritical Heat Pump Systems for Domestic Hot Water Production in Energy Recovery Applications

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ABSTRACT

Water-to-Water heat pump (WtWHP) is an efficient alternative to the current technologies used in Domestic Hot Water (DHW) production. However, this application is characterized by high secondary temperature lifts and irregular demands that define critically its design. In order to maximize the efficiency, transcritical cycles coupled to stratified storage tank has been the preferred solution. Nevertheless, recently subcritical cycles with a subcooling control system has been also considered also as a promising alternative because of the cost with the right desing the efficiencies could be in the range of transcritical system. The objective of this work is to compare the performance of both heat pump systems for DHW production in a heat recovery application where there is no restriction in the low temperature energy source availability. This situation could correspond to a source coming from sewage water or a system of low temperature district heating. The comparison has been made for the optimum configuration of both system which has implied the definition of the proper control strategy, proper sizing of the WtWHP and the tank and incorporation of a primary recovery heat exchanger in order to compare both systems in what is considered as the optimum working conditions. Results show that while both systems are able to operate with similar SCOPs, the CO2 system is more sensitive to water temperature lifts variations and temperature of the heat source than the propane WtWHP resulting in lower performances.

1. INTRODUCTION

The European Union (EU) has settled the objective of reducing the global warming emissions of the residential sector to a level of 90 %, regarding the levels of 1990, for 2050 (Comission, 2018a). Currently, the residential sector is responsible for 40 % of the total energy consumption of the EU and 36 % of the CO2 emissions in Europe (Comission, 2018). The average EU household accounts for a 65 % heating consumption and 14 % Domestic Hot Water (DHW) consumption. In this way, the EU defined for first the concept of Near Zero Energy Building (NZEB) in the EPBD Directive 2010/31/UE. The NZEB concept intends to reduce the heating consumption to a near zero value. Thus, the DHW will play a key role in the near future in the issue of decarbonization of the residential sector. Not only because it will take a higher importance within the NZEB concept, but also because of the high energy potential savings.

R744 based on its thermodynamic characteristics is seen as an efficient way to satisfy the DHW demand in buildings using natural refrigerants and R744 heat pump (Cecchinato et al., 2005, Nekså, 2002, Nekså et al., 1998) and has been introduced in the market since 90's with good efficiency results (Zhang et al., 2015). One of the important factors for the R744 is related to the high water temperature lift required by the DHW production in community installations. Some studies have been done comparing this technology with subcritical heat pumps from the system point of view (Nawaz et al 2018) but in energy recovery applications the tap water is pre-heated and this advantage is reduced and the conclusions can change in a significant way. Recently some work has been done in order to develop heat pumps working in subcritical conditions for DHW production based on heat recovery from a source of heat of low temperature (Hervas-Blasco et al 2019a, Hervas-Blasco et al 2020).

In this manner, this research aims to deeply analyze and compare both options commented from the point of view of the system performance. The cases compared are the transcritical CO2 cycle coupled with a stratified storage tank that represents the CO2 commercially available option and a subcritical cycle using propane and coupled with a variable-volume storage tank. The propane case corresponds with the innovative system presented in (Hervás-Blasco et al. 2019b). The cases are compared under a heat recovery application, working as booster HP with a hot water network at 20 ºC. This network could correspond with a sewage water recovery system as well as with an Ultra Low District Heating Network (ULTDH).

2. SYSTEM DESCRIPTION

This section describes in detail the different cases analyzed and the simulation procedure. A first subsection introduces and explains the features of the different cases considered and the next includes the optimization variables and model assumptions.

2.1 Cases analysed

The common features of both systems are described in the following. An environment constant temperature of 20 ℃, has been considered for the environment losses of the equipment. The production temperature of the HP is considered at 64 ℃ and the minimum temperature of the water in the tank has considered to be 60 ℃ as it is considered a risk installation considering legionella regulation (Comission, 1998). However, the supply temperature to the user was considered to be 45 ℃ and a tempering valve was added to the models. The insulation of the tank was considered according to the Spanish normative for the models as 0.8 W/m^{2}K and the aspect ratio considered is 4. Regarding the DHW draw-off profile, the software *DHWcalc* was used (Jordan & Vajen, 2005). As an input, the exact same conditions considered in fische(Fischer, Wolf, Scherer, & Wille-Haussmann, 2016; Hervás-Blasco et al., 2019) and shown in Table 1 have been used. The profile used corresponds to a 20 dwellings profile with an average occupation of 1.98 people per dwelling. The resulting draw-off profile is shown in Figure 1. The blue lines represent the hot water demand at every minute (litres/hour) and the orange one represents the accumulated consumption for each hour (litres). Regarding the water net temperature, a water net temperature fixed at 10 ℃ has been considered.

Table 1. Inputs considered in (Fischer et al., 2016; Hervás-Blasco et al., 2019) to DHWcalc (Jordan & Vajen, 2005).

Type of draw-off	Temperature	Mean flow	Probability	Duration	Standard deviation
-	℃	lpm	%	min	l/h
Hand-washing/cleaning	45	3	45	5	2
Shower	45	9	17	10	2
Bath	45	9	5	25	2
Cooking	45	3	33	15	2

The heat recovery unit, which is common for both cases, consists of a Braze Plate Heat Exchanger (BPHE) that takes profit from the sewage water or ULTDH network to preheat the water coming from the net. For more information about the BPHE model see (Hervás-Blasco et al., 2019). An unlimited availability of the water supply from the sewage or the DH network has been considered in this research work. The temperature of the network has been fixed to 20 ℃. This temperature could correspond with an Ultra Low District Heating (ULTDH) network as well as with a sewage water recovery application.
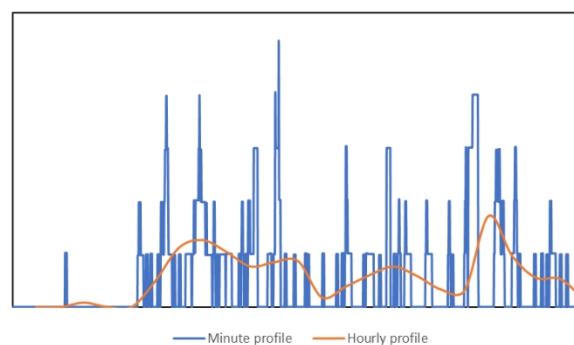

Figure 1. 1-day draw-off profile for the profile of 20 houses considered.

2.1.1 Transcritical CO2 system
The transcritical CO2 system consists of a stratified storage tank coupled with a booster HP and a heat recovery unit, as shown in Figure 2.
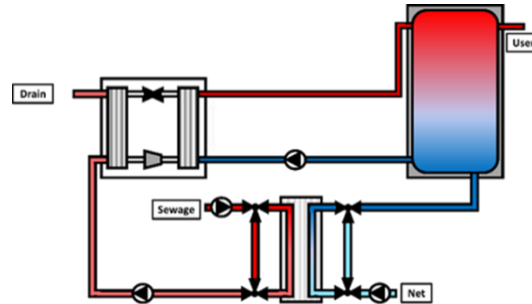
Figure 2. Illustration of the transcritical CO2 HP installation.

The storage tank in this case consists of the conventional stratified option. It has two inlets and outlets placed in the tank according to commercially available models. The control of the system consists of a hysteresis control with a set point temperature of 64 ℃ and a lower deadband of 4 ℃. In this way, the lowest temperature of the system is of 60 ℃ in order to comply with the legionella normative restrictions (Comission, 1998). This system has a peculiarity due to its topology, which differs from the subcritical case. It has to do with the hot flow circulating through the BPHE and the HP evaporator. When the WtWHP is ON, this hot flow corresponds with the flow to maintain a constant temperature lift of 4.5 K in the evaporator, just as in the variable-volume case. However, it occurs that this hot flow has to be fixed in the case in which the HP is OFF and there exists user demand (cold flow). Thus, this circulation flow, appointed as MWevapOFF, has considered as an optimization variable, since it affects the energy recovered from the network and the performance of the system. Further information is provided in section 2.3.

The R744 heat pump has been modelled using IMST-ART software (Corberan et al. 2002), the base capacity of the heat pump has been 47 kW, the selected compressor has been extracted from catalogue data of a commercially available compressor. The gas cooler has been selected in order to maintain a temperature difference at the outlet of the gas-cooler of 3K. The gas cooler pressure working point has been selected in order to work in the optimum condition of the system. The water mass flow in the evaporator has been selected in order to maintain a water temperature lift of 4.5 K.

2.1.2 Subcritical propane system

The subcritical propane system consists of a variable-volume storage tank coupled with a booster HP and a heat recovery unit that corresponds with the HP installation developed and analysed in (Hervás-Blasco et al., 2019). The subcritical installation is illustrated in Figure 3.
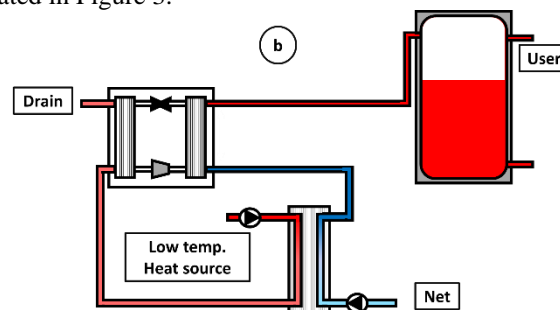

Figure 3. Illustration of the subcritical propane HP installation.

The variable-volume tank consists of a fully-mixed tank with one inlet and one outlet in which the internal volume varies depending on the user demand and the HP control. This fact causes the variable-volume case to be commanded by two different controls: temperature and volume. First, the volume control that consist of a minimum value of volume defined through the parameter Alpha (as a percentage of the total volume) that switches the system ON when reached. This parameter is considered as an optimization variable, as explained in section 2.3. Second, the temperature control that consist of a signal when the temperature is under 60 ℃ to switch the system and reach the set-point of 60 ℃. According to (Hervás-Blasco et al., 2019), the volume control always commands the system over the temperature control. Specially for the lowest values of HP and tank size, in which the temperature control never occurs.

The HP model consists of the Subcooled HP (SHP) developed under the frame of the EU project "Next Heat Pump Generation (NxtHPG)". The SHP model consists of a 47 kW heating nominal capacity working with R290 (Propane) as refrigerant and capable of working with a variable degree of subcooling. More details about the SHP can be found

in (Hervas-Blasco, Pitarch, Navarro-Peris, & Corberán, 2017). The SHP has been experimentally tested and fully characterised in the laboratory (Pitarch, Navarro-Peris, Gonzálvez-Maciá, & Corberán, 2017) and the model, developed with IMST-ART (Corberán, Gonzálvez, Montes, & Blasco, 2002), shows deviations lower than 4 %. In the model, a constant temperature lift of 4.5 K is maintained in the evaporator through a PID controller since it maximizes the COP of the SHP.

2.2. Model assumptions and optimization variables

The main modules used are the following: own type developed for both HPs, based on real experimental data from heat pumps, type 60c for the stratified tank and 39 for the variable-volume one, type 742 for the circulation pumps, type 709 for the pipes, type 5b for the heat recovery unit, type 23 for the PID controller and type 2b for the control.

The parameters implemented in the different types are gathered, when available, from commercial models. This is the case for the stratified tank regarding dimensional data, insulation and inlets/outlets location. For the heat recovery unit it is deeply explained in reference Hervás-Blasco, E. et al 2019. The own type for the HP takes as parameters the size, in percentage of the nominal power and the Cp of the fluid. The circulation pump has the efficiency chosen from a commercial model and the pressure drop is calculated according to the real model HP condenser and evaporator and also for the heat recovery unit designed.

In order to compare the different system configurations proposed four indicators have been selected: the SPFuser, the SPF1, the total annual network energy consumed and the total annual energy consumption.

$$SPF_{user} = \frac{Q_{user}}{W_{HP\ compressor} + W_{auxiliaries}} \tag{1}$$

$$SPF_1 = \frac{Q_{HP\ condenser}}{W_{HP\ compressor}} \tag{1}$$

The SPFuser is defined, as shown in Equation (1), as the quotient between the Quser, which is the useful heat that the user receives, calculated as the energy contained in the water flow exiting the mixer valve to the user at 45ºC. The denominator of the formula corresponds with the energy consumption of the facility. In a similar way, the SPF1 shown in Equation (2) is defined as the quotient between the energy provided by the HP condenser and the energy consumed by the HP compressor. Finally, the annual network energy consumption has been calculated as the energy contained in the flow taken from the network at 20 ºC and considering as reference temperature the minimum of the system.

Several restrictions have been imposed to the model in order to guarantee the user comfort as well as the system reliability, referring the number of starts of the SHP and the overflow of the variable-volume tank. Regarding the comfort restrictions, a maximum annual discomfort of 0.05 % has been imposed and a maximum value of 30 minutes per year of discomfort for each different hour of the day that corresponds with a maximum value of 5 seconds of discomfort per day for each hour of the day. Regarding the system reliability, a maximum of 9 starts/hour has been imposed and a limit to the overflow of the variable-volume tank was also settled. Each of the above commented restrictions are implemented in the integrated TRNSYS model, in such a way that the simulated cases for the optimization are discarded if any of the restrictions are reached and neither included in the performance maps.

Parametric studies have been settled for the analysis of the cases. The variables studied are the minimum control volume (alpha) only for the variable-volume case, the size of the SHP (as a percentage from 5 to 100 % of the total nominal heating power), the tank volume and the circulation flow above commented (MWevapOFF) only for the stratified case. The values considered are shown in Table 2. Considering all the simulations, more than 3000 simulations have been performed for the study.

Table 2. Optimization variables considered for the study.

SUBCRITICAL PROPANE CASE			TRANSCRITICAL CO2 CASE		
ALPHA	**VOLUME**	**HP SIZE**	**MWevapOFF**	**VOLUME**	**HP SIZE**
%	**Litres**	**heating kW**	**kg/hr**	**litres**	**heating kW**
10%	80	2.35 kW (5 %)	50	80	2.6 kW (5 %)

20%	100	4.7 kW (10 %)	100	100	5.2 kW (10 %)
30%	200	9.4 kW (20 %)	200	200	10.4 kW (20 %)
40%	300	14.1 kW (30 %)	300	300	15.6 kW (30 %)
50%	400	18.8 kW (40 %)	400	400	20.8 kW (40 %)
60%	500	23.5 kW (50 %)	500	500	26 kW (50 %)
70%	600	28.2 kW (60 %)	600	600	31.2 kW (60 %)
80%	700	32.9 kW (70 %)	700	700	36.4 kW (70 %)
90%	800	37.6 kW (80 %)	800	800	41.6 kW (80 %)
-	900	42.3 kW (90 %)	900	900	46.8 kW (90 %)
-	1000	47 kW (100 %)	1000	1000	52 kW (100 %)

2. RESULTS AND DISCUSIÓN

This section includes the main results for this research work. The results of the parametric study conducted for each of the cases are first thoroughly presented. The objective of the parametric study consists of identifying the different trends as well as determine the optimal case for each system and its peculiarities. Finally, the last subsection compares the different cases using the above commented system performance indicators.

2.1 Parametric studies results

3.1.1 Transcritical CO2 system
The results corresponding to the transcritical CO2 system are presented in Table 3 and Figure 4. The results included in Table 3 correspond to the 10 cases with the highest system global efficiency (SPFuser) and the lowest consumption. The table also includes the results for the energy used from the sewage or ULTDH network and the values for each optimization variable.

Table 3. Results of the performance indicators selected for the best 10 cases of the transcritical CO2 system.

	HP SIZE	VOLUME	MWEVOFF	SPF1	SPFUSER	ELEC_CONS	QSEW
	%	M3	kg/hr	-	-	kWh	kWh
1	0.40	0.30	1000.00	4.81	5.49	5709.68	65568.75
2	0.50	0.20	1000.00	4.80	5.48	5713.65	63501.16
3	0.40	0.30	800.00	4.81	5.48	5714.41	61697.41
4	0.50	0.20	900.00	4.80	5.48	5715.78	61491.40
5	0.40	0.30	700.00	4.81	5.48	5716.00	59749.04
6	0.50	0.20	800.00	4.80	5.48	5717.25	59457.48
7	0.40	0.30	600.00	4.81	5.48	5719.20	57828.51
8	0.50	0.20	700.00	4.80	5.48	5720.40	57477.66
9	0.40	0.30	500.00	4.81	5.48	5723.88	55905.20
10	0.50	0.20	600.00	4.80	5.47	5725.75	55511.10

In Figure 4 the results for the different values of the optimization variables: HP size and tank volume are illustrated in a map for the best value of the optimization variable MWevapOFF of 1000. The performance map for the annual energy consumption and the SPFuser are included in Figure 4. However, the rest of the maps for all the alpha values have been also considered for the conclusions here included.
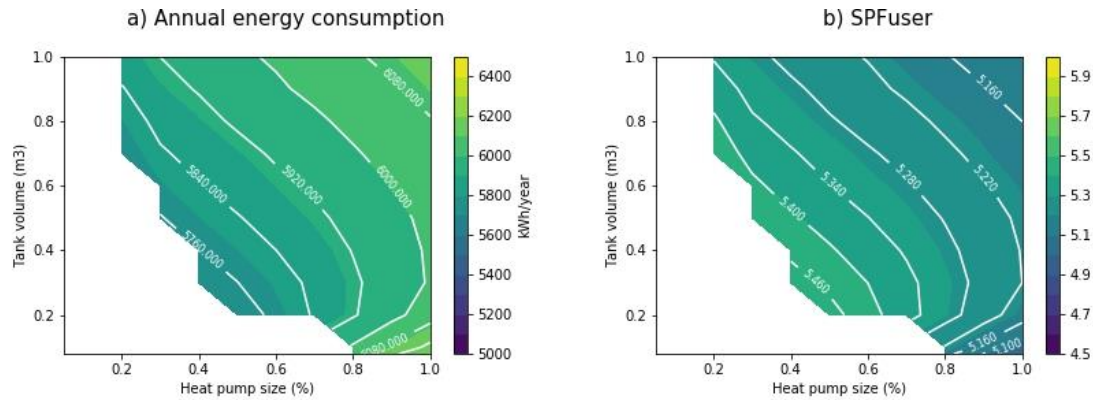
Figure 4. Performance maps of the annual energy consumption and SPFuser for the values of SHP and tank size and a MWevapOFF value of 1000 of the transcritical CO2 system.

The results show that there does not exist a best case but a flat map of best cases. There exists a maximum difference of 0.3 % between the 10 best cases shown in Table 3. The performance maps show the tendencies commented in the following:

- Volume: the maximum system performance is obtained for the minimum possible volumes. The volume shows to have more importance over the HP size.
- HP size: the maximum system performance is reached for the lowest HP sizes.
- For each heat pump there is an optimum tank volume. For small heat pump this tank will correspond with the minimum tank volume able to satisfy the demand.
- MWevapOFF: the energy recovered in the BPHE increases with the increase of this variable and thus the system performance. However, the energy used from the sewage or ULTDH network also highly increases and this could lead to a problem when the availability of the hot water from the network is limited.

3.1.2 Subcritical propane system
The results corresponding to the subcritical propane system are presented in Figure 5 and Table 4. The results included in Table 4 correspond to the 10 cases with the highest system global efficiency (SPFuser) and the lowest consumption. The table also includes the results for the energy used from the hot network (considering net water temperature as reference) and the values for each optimization variable.

Table 4. Results of the performance indicators selected for the best 10 cases of the subcritical propane system

	HP SIZE	VOLUME	ALPHA	SPF1	SPFUSER	ELEC_CONS	QSEW
	%	M3	%	-	-	kWh	kWh
1	0.20	0.20	0.80	5.07	5.75	5425.53	50535.83
2	0.30	0.20	0.40	5.07	5.74	5433.87	49246.56
3	0.20	0.30	0.50	5.07	5.74	5442.00	49644.06
4	0.30	0.20	0.50	5.07	5.74	5442.42	49368.12
5	0.20	0.20	0.90	5.07	5.74	5443.56	51816.69
6	0.20	0.30	0.60	5.07	5.74	5447.61	49802.93
7	0.40	0.20	0.20	5.06	5.73	5449.53	48649.77
8	0.30	0.20	0.60	5.06	5.74	5451.32	49512.36
9	0.20	0.30	0.70	5.07	5.73	5452.74	50032.98
10	0.30	0.30	0.30	5.07	5.72	5457.71	49362.34

In Figure 5 the results for the different values of the optimization variables: HP size and tank volume are illustrated in a map for the best value of the optimization variable alpha of 0.8. The performance map for the annual energy consumption and the SPFuser are included in Figure 5. However, the rest of the maps for all the alpha values have been also considered for the conclusions here included.
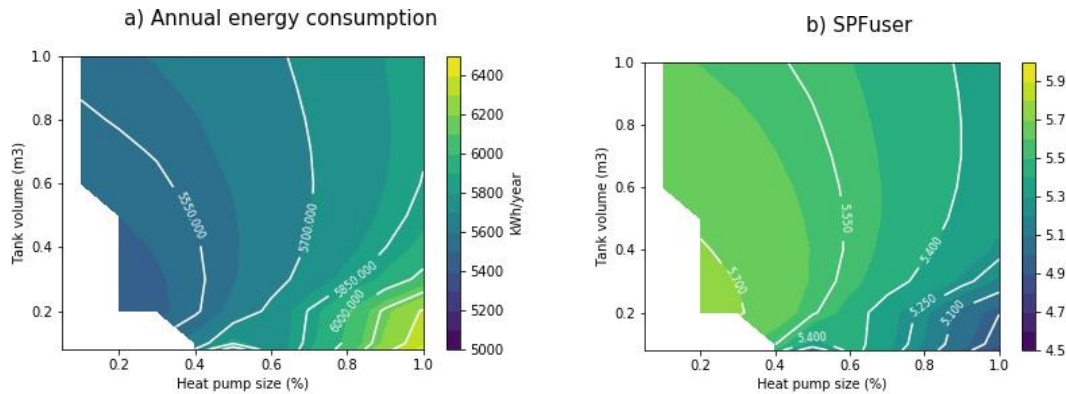
Figure 5. Performance maps of the annual energy consumption and SPFuser for the values of SHP and tank size and an alpha value of 0.8 of the subcritical propane system.

Similarly to the transcritical CO2 case, the results show that there does not exist a best case but a flat map of best cases. Maximum difference of 0.6 % between the 10 best cases shown in Table 4 is observed. The performance maps show similar tendencies to the previously commented for the transcritical CO2 system. The best results are obtained for the lowest values of HP and tank size and the volume variable dominates over the HP size variable. The alpha value takes a great importance regarding the comfort conditions and the system performance. The high the alpha value the lower is the system global efficiency, however the higher the alpha value more are the cases that comply with comfort restrictions. This makes that for higher alpha values more cases with low values of HP size and tank volume comply with the restrictions and in this manner better results are obtained. Also, is observed that lower values of HP and tank size are achieved with the subcritical propane system compared to those of the transcritical CO2 system. Also, better results are obtained with lower use of energy from the sewage water (5.000,00-15.000,00 kWh/year lower). The R744 heat pump has shown also a higher sensibility to the design conditions than the R290 heat pump which is demonstrated by its closer isolines in the figure 4 compared to figure 5.

2.2 Optimal case results and comparison

In Table 5 the best of both cases considered have been included. The best case with a similar annual energy use from the network for the transcritical CO2 cycle has also been included.

Table 5. Results of the performance indicators selected for the best 10 cases of the subcritical propane system

CASE	CONSIDERATION	SCALE	VOLUME	ALPHA/ MWevapOFF	SPF1	SPFUSER	ANNUAL EN. CONSUMPTION	DIFFERENCE	ANNUAL EN. FROM NETWORK
-	-	%	m3	%/kg/hr	-	-	kWh	%	kWh
R290 VAR-VOL	-	0.2	0.2	0.8/-	5.1	5.8	5425.5	0.0%	50535.8
CO2 STRATIFIED	-	0.4	0.3	-/1000	4.8	5.5	5709.7	5.2%	65568.8
CO2 STRATIFIED	SIMILAR kWh FROM NETWORK	0.4	0.3	-/200	4.8	5.4	5765.6	6.3%	50603.7

The results show a better system performance from the subcooled propane case, with a higher system global efficiency (SPFuser) and a lower annual energy consumption (5.2 %) with a higher energy use from the network at 20 ºC (15.000,00 kWh/year more, which is 30 % higher energy use). The results also show that the transcritical system needs higher HP and tank sizes compared to the ones of the subcooled propane system. The best subcooled system accounts for a total power of 9.4 kW and 200 litres whereas the best case of the transcritical system accounts for 20.8 kW and 300 litres. The tendencies shown with the optimization variables are similar for both cases, the best cases are obtained for the lowest values of HP and tank size. Considering the transcritical CO2 cycle with a similar energy use from the network at 20 ºC and included in Table 5. The results show a 6.3 % higher energy consumption compared with the subcooled propane system. The cases that show a similar energy use from the network are those obtained for values of MWevapOFF lower than 200 kg/hr, whereas the best cases are obtained with the highest MWevapOFF values.

The subcooled propane system achieves better results due on one hand to a better performance of the WtWHP unit, as shown in Table 5, and on the other hand due to a better efficiency in the in the heat recovery process. The subcooled propane system with the variable-volume tank needs less energy from the hot network for the same conditions regarding the transcritical CO2 cycle.

3. CONCLUSIONS

This research work focuses on the comparison of a commercially available transcritical CO2 system for DHW production with the innovative subcritical propane system considering a heat recovery application with a hot network at 20 ºC.

The comparison results show:
- A better energy performance of the subcritical system, with an energy consumption 5.2 % lower and 6.3 / lower when compared under the same energy use from the hot network.
- The better result of the subcooled system responds to a better energy performance of the subcritical propane WtWHP and a additionally a higher efficiency in the heat recovery since the best cases of the trasncritical system consume between 5k-15k kW more from the hot network.
- Furthermore, the transcritical CO2 cycle needs higher values of WtWHP size and tank volume than the subcritical system. The best results for the transcritical system are obtained for 20.8 kW and 300 litres whereas the subcritical system are obtained for 9.4 kW and 200 litres.

Finally, it should be pointed out that R744 heat pump performance is more affected by the increase of the water gas cooler inlet temperature than subcooled heat pump nevertheless for heat recovery applications, the introduction of the heat exchanger improves the performance of both systems. Therefore it is expected that the obtained differences obtained in this work will increase significantly in cases where the heat source could be at higher temperatures (30ºC-40ºC) showing that heat pumps based on R744 would not be the best alternative for these kind of application.

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