Numerical study on the influence of internal heat exchanger in transcritical CO₂ heat pumps under optimal pressure conditions

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Abstract. This paper presents a numerical study on the influence of internal heat exchanger (IHX) exchanging surface in the performance of a transcritical CO₂ heat pump water heater at different operating conditions. Five different IHX geometries and four different evaporation temperatures have been studied with water temperature ranging from 10 °C to 60 °C at the gas cooler inlet. The results show a strong influence of IHX characteristics on system’s performance.

1. Introduction
The use of internal heat exchangers (IHX) in transcritical CO₂ heat pumps and refrigeration systems has been studied numerically [1], [2], experimentally [3], [4], [5] or both numerically and experimentally [6] by different researchers. Experimental studies usually only compare system performance with and without IHX at different evaporation temperatures or different gas cooler operating conditions [3], [4] and [5]. On the other hand, numerical studies typically assume different constant values for the IHX efficiency and study its influence on system’s performance. As far as the authors’ knowledge, only Cao et al. [6] have studied the influence that the exchange surface of the IHX has on the system’s performance. They studied the influence that the length of a spiral tube-in-tube IHX had in the performance of a transcritical CO₂ heat pump that operated with a flooded evaporator and a liquid separator placed after the evaporator.

This paper pretends to contribute to increase the understanding on the influence that IHX characteristics have on system’s performance for other type of IHX and other system’s configuration. Concretely, this paper focusses in the study of a brazed plate IHX employed in a transcritical CO₂ heat pump that operates with a dry expansion evaporator and a liquid receiver placed before the evaporator.

2. System studied
The system numerically studied in this work correspond to the experimental facility developed at Technical University of Cartagena for the study of transcritical CO₂ heat pump systems, schematically...
depicted in figure 1. It consists of a compressor, a gas cooler, an IHX, a back pressure valve (BPV), a liquid receiver an electronic expansion valve (EEV) and an evaporator.

Evaporator, gas cooler and IHX are brazed plate SWEP heat exchangers, the compressor is a reciprocating semi-hermetic DORIN compressor, the liquid receiver is a 10 liters capacity TECNAC vertical receiver and both, the BPV and the EEV are CAREL electronic valves. The BPV controls the pressure in the gas cooler, whereas the EEV controls the superheating degree at evaporator outlet.

![Figure 1. Sketch of the system studied.](image)

3. Numerical model
The system’s behavior has been studied using a numerical model developed in MATLAB® and validated against experimental results previously obtained [7]. For the evaporator, gas cooler and IHX, a one-dimensional cell-by-cell discretization of each heat exchanger has been posed that applies energy conservation equation to each control volume and solves iteratively until convergence is reached. Further details of the model can be found in [8]. Both, BPV and EEV has been modeled as isenthalpic expansion devices capable to exactly maintain the set point assigned. Liquid receiver has been treated as an adiabatic pipe that does not produce any effect (nor even pressure drop) in the system. Finally, compressor has been modeled through its ANSI/AHRI Standard 540-2015 behavioral curves, using the correlation coefficients provided by the manufacturer.

All these components have been connected in a MATLAB® model in order to analyze the influence that the size of the IHX has on system’s performance at different operating conditions during domestic hot water generation using a 100 liters capacity storage tank. The initial tank temperature was assumed to be 10 ºC and the system operates under transient operating conditions until the temperature in the tank reaches 60 ºC. The BPV maintains the optimal operating pressure according to the model developed by the authors [7] and the EEV maintains the superheating degree at 5 K. The water mass flow rate has been set at 1000 kg·h⁻¹ for the evaporator and 500 kg·h⁻¹ for the gas cooler. Four different water temperatures at the evaporator inlet has been studied (5, 10, 15 and 20 ºC) whereas the water temperature at the gas cooler inlet increases gradually as the test progresses.

Table 1 shows the geometrical characteristics of the IHX available in the experimental facility and used as comparison reference.

| Number of plates | Height (m) | Width (m) | Pitch (mm) | Pitch (mm) | Heat transfer area (m²) | Corrugation angle |
|------------------|-----------|-----------|------------|------------|------------------------|------------------|
| 4                | 0.377     | 0.1195    | 2          | 0.35       | 0.082                  | 120°             |
| Channels according to the fluid | 2 channels high pressure side/1 channel low pressure side |
In order to analyze the influence that IHX characteristics have on system’s performance, five different cases have been studied by increasing the number of plates to 8 and 16 and, since it is impossible to decrease the number of plates of the original IHX, by decreasing the height and the width of the plates in order to obtain half and a quarter of the original exchanging surface.

4. Results and discussion

Figure 2 shows the influence that the IHX size has on system’s performance and operating conditions.

Figure 2. Influence of IHX exchanging surface in system’s performance.

According to figures 2.a and 2.b, the system’s efficiency clearly improves as the exchanging surface increases, being the improvement in the COP proportional to the improvement obtained in the IHX effectiveness as the exchanging surface increases. This improvement in the IHX effectiveness produces two opposite effects. On the one hand, it produces a decrease in the enthalpy of the refrigerant at the evaporator inlet. Since the water inlet temperature and mass flow rate in this point are constant, the evaporation temperature decreases as shown in figure 2.c. This decrease yields an increase in the gas cooler optimal pressure and thus a decrease in the system’s efficiency. On the other hand, it produces an increase in the temperature of the refrigerant leaving the IHX low pressure side; this effect produces a decrease in the gas cooler optimal pressure and thus an increase in the system’s efficiency. Since this second effect dominates over the first, as figure 2.d shows, the gas cooler optimal pressure tends to decrease as the IHX effectiveness increases and thus system’s efficiency increases. Although the gas cooler optimal pressure clearly increases as the water temperature increases, when the compressor discharge temperature reaches 140 °C, the model reduces gas cooler pressure to avoid higher discharge temperatures. As figure 2.d shows, the higher the IHX effectiveness is the sooner this situation is reached.

Figure 3 shows the influence that the temperature of the water entering the evaporator has on IHX effectiveness and compressor discharge temperature for the base IHX (4 plates). According to figure 3.a, when the temperature difference in the IHX increases its effectiveness also increases. As figure 3 shows, the stronger variation in the IHX effectiveness takes place during the initial water heat up, when the optimal gas cooler pressure remains stable in 74 bar, the COP is almost constant and
the increase in water temperature is faster. Calculations begin at this pressure as this study is restricted only to transcritical cycles. When the pressure begins to increase, the COP decreases more quickly and the increase in water temperature is slower. This effect can be appreciated in the refrigerant inlet and outlet temperatures at both low and high pressure sides of the IHX (figure 3.b), as well as in the gas cooler optimal pressure (figure 2.d). While gas cooler pressure stays stable, the effectiveness increases; when it begins to increase, the effectiveness stays almost stable; finally, when it decreases due to the increase in compressor discharge temperature, the effectiveness increases again.

![Figure 3. Influence of water temperature at evaporator inlet on system’s behaviour (4 plates IHX).](image)

5. Conclusions
A numerical model for studying the influence of IHX size on the performance of a transcritical CO₂ heat pump water heater has been presented. The main conclusions obtained are:

- The efficiency of the system and the effectiveness of the IHX are directly related. An increase in IHX surface increases its effectiveness and thus the system’s COP.
- The IHX effectiveness also varies with the temperature difference between IHX ports, increasing as evaporation temperature decreases or heated water temperature increases.

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