MODELING AND VALIDATION OF THE EFFECTS OF SOFT FAULTS ON THE OPERATION OF AN AIR SOURCE HEAT PUMP IN COOLING MODE

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Abstract: *Some faults in heat pumps cannot be easily detected and diagnosed, as the system appears to function correctly, but it is working with lower efficiency. These soft faults occur either due to faults during installation or slowly over time, letting the heat pump operate without maintenance. It is relevant to acquire data from heat pumps operating with soft faults to develop techniques for detecting and diagnosing these faults. As this is a difficult task, we have modeled an air source heat pump in cooling mode, and performed simulations under different conditions of faults such as inadequate refrigerant charge, evaporator fouling, and compressor valve leakage. We validate them with available data from experimental tests fault-free and tests in which these faults have been imposed. Based on the model, we calculate the effects of soft faults when they appear at different levels and their impact on the Seasonal Energy Efficiency Ratio (SEER).*

Keywords: air source heat pump, refrigerant charge, improper air flow rate, fault impact, fault modeling

1. INTRODUCTION

In Europe, the heat pump market has been increasing every year, incrementing 7.4 % in 2020 [1]. According to a study conducted by IDAE [2], in Spain, there are 7.3 million homes and establishments with heat pumps (34 % of the total in Spain). This implies widespread use among households, commercial buildings, and industry. There are soft faults in heat pumps that cannot be easily detected since apparently, the system continues to operate normally. However, it is operating at a lower performance than it should under certain conditions. These faults occur slowly over time, and their detection and diagnosis are not easy. Some examples of these failures are undercharge or overcharge, evaporator fouling, or compressor valve leakage. Therefore, it is essential to develop fault detection and diagnosis techniques for heat pumps in order to be able to perform proper maintenance. It is difficult to have available data of heat pumps under fault conditions, as it is time- consuming to test these systems with imposed faults experimentally. Therefore, it is helpful to model and simulate these systems under different fault conditions and levels.

Previously, some studies were conducted to model these faults. Cheung and Braun [3] developed a vapor compression system model for predicting fault impacts. These have COP prediction with a maximum error of 21 %, and although they calculate similar trends to the experimental tests, some variables have significant differences under fault conditions. Zhang and Hong [4] developed a methodology for modeling and simulating faults in HVAC systems with EnergyPlus software. This study focuses on modeling faults and their impact on the whole building (such as dirty air filters and sensor faults) and not on faults of the heat pump components. Piacentino and Talamo [5] perform an analysis of thermo economic approaches for the diagnosis of heat pump faults using IMST-ART software [6]. They only simulate a single level of some faults and do not validate it with experimental tests. Instead, they check that the results follow the expected trend according to experimental campaigns presented in the literature.

This work explores how to model and simulate soft faults in heat pumps with IMST-ART software to have more data available from these systems under fault conditions and different levels of faults. Furthermore, we can quantify how much these faults affect the Seasonal Energy Efficiency Ratio (SEER) to justify the importance of developing techniques to detect and diagnose these faults.

2. METHODOLOGY

In this work, we have used experimental tests performed at the National Institute of Standards and Technology (NIST) in which soft faults were imposed on an air-source heat pump operating in cooling mode [7]. To model the heat pump, we utilized the IMST-ART software, which is used to model and simulate vapor compression cycles [6]. We have used this software to model the heat pump fault-free and under the conditions of each of the soft faults considered in this study.

Table 1. Soft faults considered in this study

Fault	Description	Fault levels (%)
Refrigerant undercharge and overcharge	% of undercharge or overcharge from the fault-free charge	-20, -10, +10, +20, +30
Evaporator fouling	% of air flow rate reduction	10, 20, 30
Compressor valve leakage	% of refrigerant mass flow rate leaked from discarge to suction	2.5, 4, 5, 5.5, 6.7, 9.5, 11.4, 27.2, 38.2

2.1. Fault-free modeling

We have modeled with IMST-ART software each of the heat pump components. We model the evaporator and the condenser with the geometrical data from the manufacturer's catalog of these heat exchangers. The compressor submodel uses the AHRI polynomials of mass flow rate and compressor power input. With the submodels of all the components defined, we have simulated the whole system under the same conditions in which the heat pump was tested, and we validate the model by comparing the performance obtained with the experimental one.

2.2. Refrigerant undercharge and overcharge model

IMST-ART can estimate the amount of refrigerant charge in the system. When introducing the subcooling as an input, it determines the charge using void fraction correlations. Following the procedure explained by Corberán et al. [8], we first calculated the heat pump's performance using the measured subcooling from the fault-free experimental tests as input. Then, we have evaluated the difference between the real charge and the one calculated by IMST-ART, which is usually lower. We have used the difference to introduce a correction in all the simulations where the refrigerant charge is used as input. In order to simulate a fault of undercharge or overcharge of refrigerant in the system and evaluate its performance, we have increased or decreased the corrected refrigerant charge used as input by the same proportion as it was modified in the experimental tests. Table 1 shows the different refrigerant charge levels considered to emulate the experimental tests' results.

2.3. Evaporator fouling model

To model the evaporator fouling fault, we have considered that it mainly affects the pressure drop in the coil. This reduces the air flow rate and increases fan consumption. We have not included in this work the increase of fan consumption. However, we have simulated this fault by imposing as input to the model the evaporator air flow rate reduced in the same proportion as it has been done in the experimental tests. The different levels of air flow reduction in the evaporator that we have studied are presented in Table 2.

2.4. Compressor valve leakage model

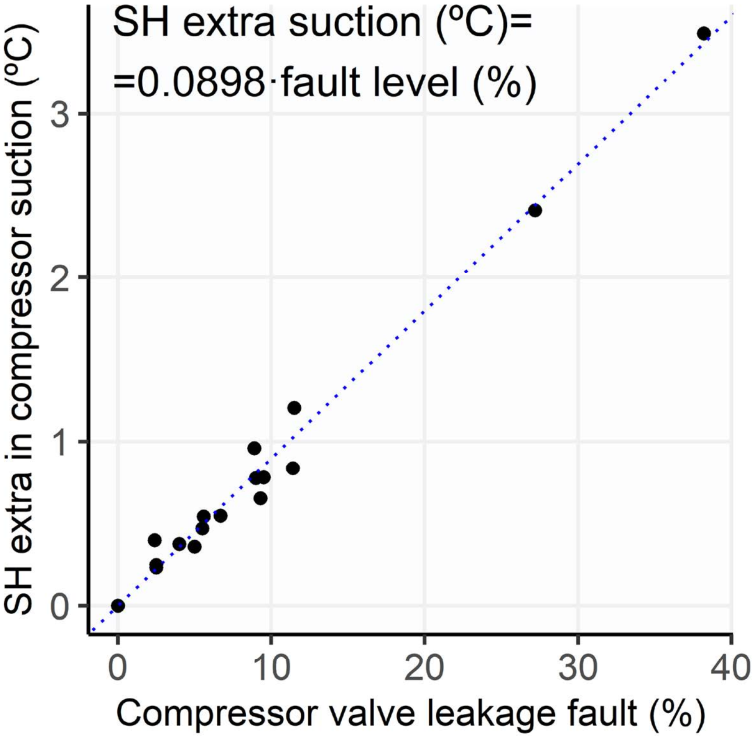

Figure 1. Additional superheat in suction conditions under compressor valve leakage fault.

This fault occurs when the compressor suction or discharge valve is not closed correctly, and an internal leakage occurs, resulting in a mixing of the discharge flow with the suction flow. This fault can also happen if an internal leak occurs in the 4-way reversible valve. In the experimental tests, this fault was tested with a hot gas bypass between the discharge and suction lines of the compressor. The level of this fault is the fraction of mass flow rate that is bypassed with respect to the mass flow rate under the same conditions but fault-free.

To simulate this fault in the IMST-ART model, we have modified the coefficients of the AHRI polynomials of the mass flow rate in the compressor submodel to reduce the resulting mass flow rate in the same way at which the experimental tests were performed. The different fault levels are explained in Table 3.

In addition, as part of the compressor discharge mixes with the suction, a change in the compressor suction conditions occurs, generating an extra superheat (SH). To impose this change in suction, we have studied how much extra SH there is in the compressor suction compared to the same conditions fault-free with each fault level. It results approximately that for every 10 % of bypassed mass flow rate, it increases 0.9 °C the suction temperature (see Figure 2). Therefore, to simulate this fault, the changes we impose in the model are the mass flow rate penalty in the compressor submodel and the increase in suction temperature.

2.5. Seasonal Energy Efficiency Ratio (SEER) calculation

Table 2. Partial load conditions for SEER calculation [9]

Point	Outside air dry bulb temperature (ºC)	Inside air dry bulb (wet bulb) temperature (ºC)
A	35	27 (19)
B	30	27 (19)
C	25	27 (19)
D	20	27 (19)

We use the Seasonal Energy Efficiency Ratio (SEER) according to the standard UNE-EN 14825 [9] to measure the heat pump's performance. Using SEER instead of EER at a single point gives us more information about its performance over an entire season. We have not considered the consumption of the fans in this work. Therefore, the EER of each partial load condition has been calculated as the cooling capacity divided by the compressor power input. So, once we have modeled the system and imposed the faults described above, we simulate it at the partial load conditions indicated by the standard (see Table 2), and we can analyze how much the SEER is affected by each fault level.

3. RESULTS

3.1. Fault-free

After simulating the model without faults, we obtain that the cooling capacity has a maximum relative error of 5.6 % and an RMSE of 0.306 kW when comparing the simulated and experimental results. With the EER, we obtain a maximum relative error of 7.3 % and an RMSE of 0.257 (see Figure 2).

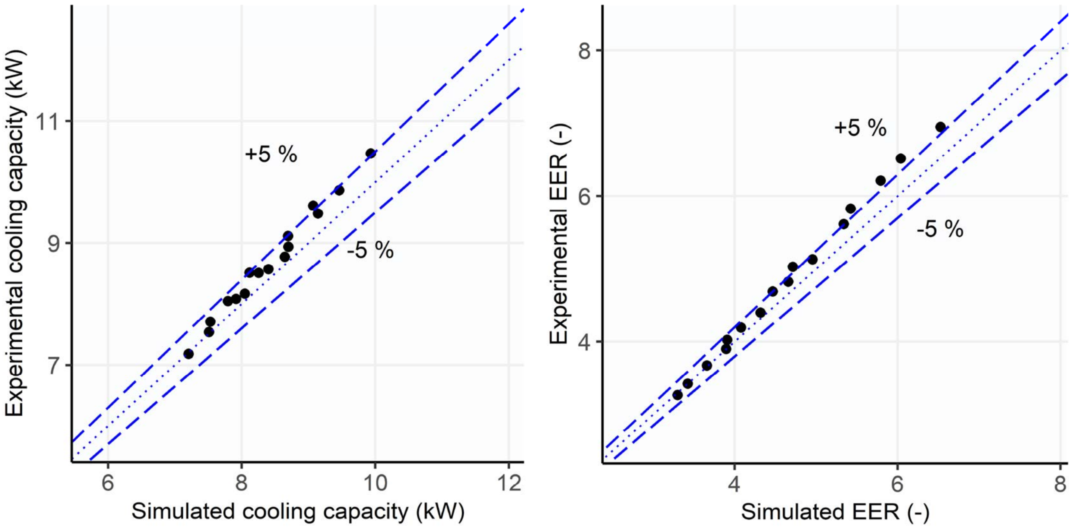

Figure 2. Comparison of the simulated and experimental results in cooling capacity (left) and EER (right).

3.2. Refrigerant undercharge and overcharge

Figure 3 shows the cooling capacity and EER results under different undercharge and overcharge fault levels. We compare the results of the experimental tests and the model simulations for various indoor and outdoor air temperature conditions.

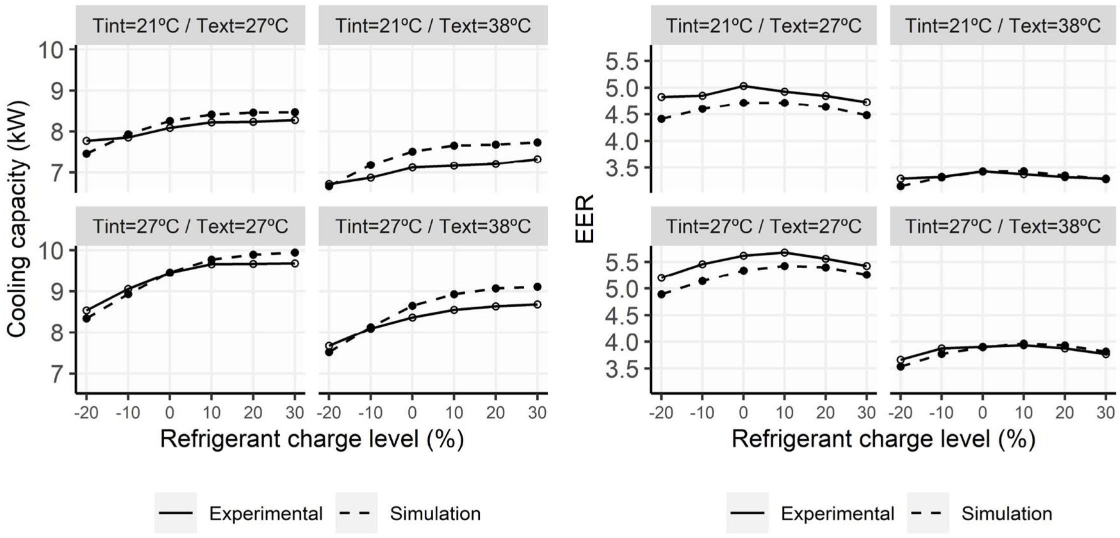

Figure 3. Cooling capacity (left) and EER (right) results for different levels of undercharge and overcharge (simulated and experimental) at various indoor and outdoor air temperature conditions.

3.3. Evaporator fouling

Figure 4 illustrates the cooling capacity and EER for various evaporator fouling fault levels. We compare the results of experimental tests and the model simulations for different indoor and outdoor air temperature and relative humidity conditions.

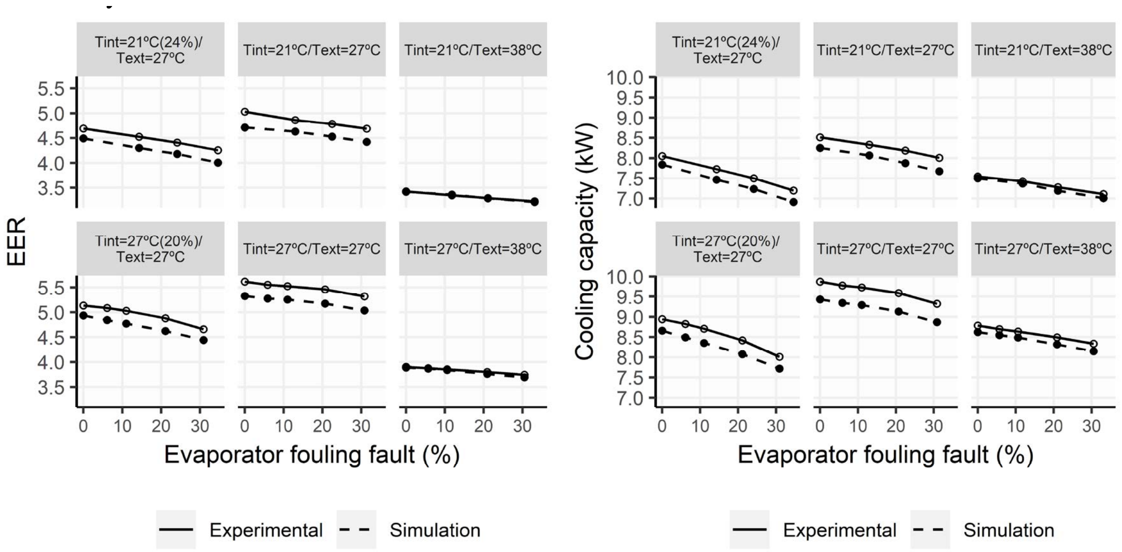

Figure 4. Cooling capacity (left) and EER (right) results for different levels of evaporator fouling (simulated and experimental) at various indoor and outdoor air temperature and relative humidity conditions.

3.4. Compressor valve leakage

Figure 5 shows the cooling capacity and EER results for different levels of compressor valve leakage and several indoor and outdoor air temperature conditions.

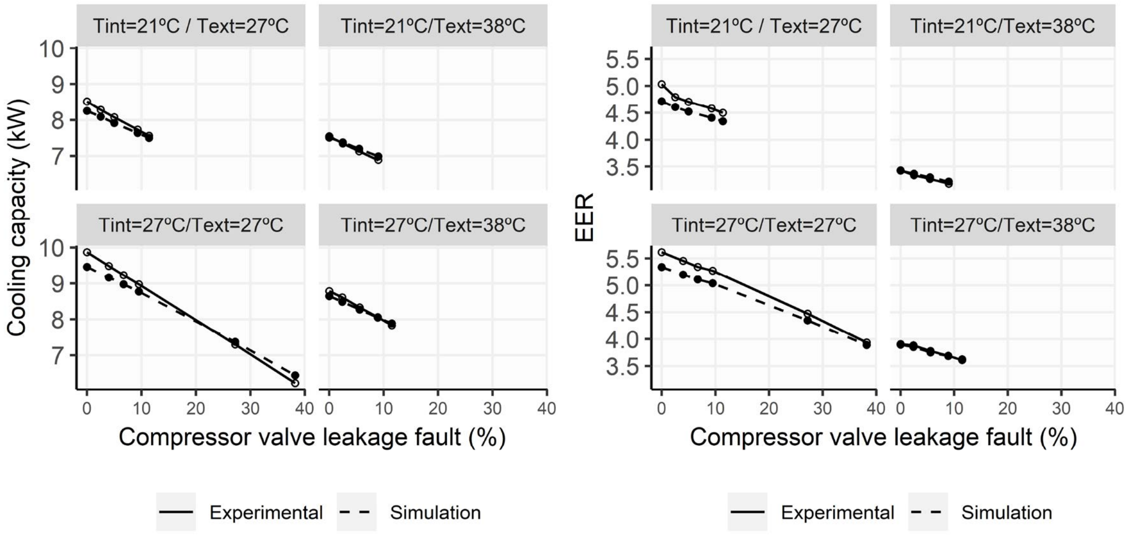

Figure 5. Cooling capacity (left) and EER (right) results for different levels of compressor valve leakage (simulated and experimental) at various indoor and outdoor air temperature conditions.

3.5. SEER

The SEER results with different levels of faults are shown in Figure 6. This Figure illustrates the normalized SEER (SEER divided by the SEER of the heat pump fault-free) for the different faults we have considered in this work. Fault level refers to the one defined for each fault.

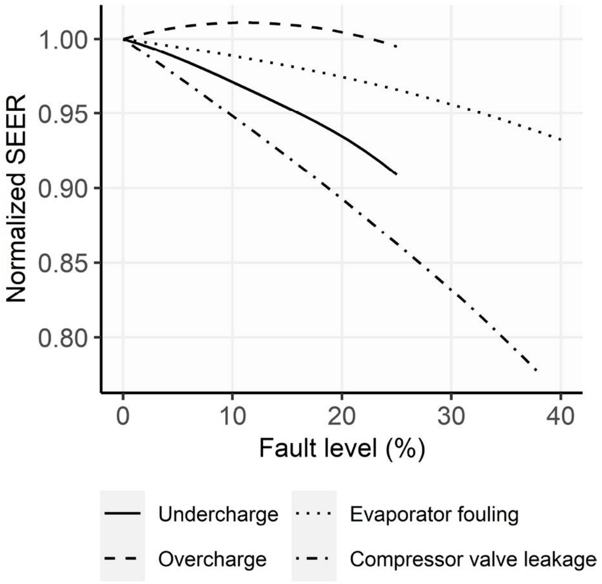

Figure 6. Normalized SEER under soft faults imposed in the model at different fault levels.

4. DISCUSSION

In Figures 3, 4, and 5, we show how our models with the imposed faults can reproduce the behavior of the heat pump under the fault conditions we have studied. The same trends are observed with the fault levels considered in the cooling capacity and EER results.

Figure 6 shows how each fault affects the SEER and in what proportion. Thus, the SEER is not affected until it exceeds 20 % and even improves slightly under overcharge. In the case of undercharge, it does affect the SEER, as we can see that 20 % undercharge decreases the

SEER by 7 %. For evaporator fouling, the tendency to decrease SEER is less than undercharge, since up to 30 % reduction of evaporator air flow penalizes SEER by 5 %. Finally, the compressor valve leakage fault is the one that affects SEER the most as the fault level increases, since with a 10 % fault level, the SEER is penalized by 10 %.

5. CONCLUSIONS AND FUTURE WORK

In this work, we have modeled and simulated faults in a heat pump, and we have calculated how different levels of these faults affect the SEER. With this, we can see the potential that IMST-ART has to model and simulate heat pump faults, which will later allow us to develop techniques to detect and diagnose these faults. Future work will be based on extending the available information by expanding these models to impose other soft faults that may occur in heat pumps and studying and modeling the cross effects of the combination of several of these faults.

6. ACKNOWLEDGMENTS

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