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Comparison of Multiple Fault Impacts on a Heat Pump and an Air Conditioner in Cooling Mode

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ABSTRACT

Operating faults that degrade performance of residential air-conditioning systems can be caused by problems during installation, and are believed to be quite common. When a problem occurs during installation, potentially from a lack of training or care by a technician, difficult work conditions, etc., it is likely that several faults can occur simultaneously. Many studies have investigated single-fault impacts on system performance during the past three decades. However, few of them studied simultaneous fault impacts, especially for more than two simultaneous faults. Therefore, the current study investigated four common installation fault impacts, both singly and in combination (up to 4 at a time), on the performance of a high-efficiency split heat pump system equipped with a thermostatic expansion valve and a standard-efficiency air conditioner equipped with a fixed orifice expansion device in cooling mode. These four faults are: improper evaporator airflow, improper refrigerant charge, liquid line restrictions, and the presence of non-condensable gas in the refrigerant. The fault intensities for each fault are varied, with limits selected based on practical considerations, and are imposed similarly on each system. The results are compared according to fault type and fault intensity imposed. For single faults, the air conditioner performs better than the heat pump when refrigerant overcharge (OC) or low evaporator faults are present. When simultaneous faults are present, the heat pump performs better for almost all fault combinations except for combinations that include OC.

1. INTRODUCTION

According to the residential energy consumption survey (EIA, 2015), more than half (51% in 2015) of energy consumption is for space heating and air conditioning in the United States. Air conditioning in residential buildings is usually provided by split system air source heat pumps or unitary cooling air conditioners. Common installation faults, such as refrigerant undercharge or low evaporator airflow, can degrade system performance and lead to energy consumption increase. Therefore, research evaluating fault impacts on performance and developing fault detection and diagnosis (FDD) methods has been conducted over the past three decades.

Numerous studies (e.g. Farzad, 1990; O'Neal and Farzad, 1990; Farzad and O'Neal, 1991, 1993; Neal and O'Neal, 1992; Goswami et al., 2001; Harms et al., 2003; Dooley, 2004; Kim et al., 2006, 2009; Payne et al., 2009; Shen et al., 2006, 2009; Raj and Lal, 2010; Kim and Braun, 2012; Cho et al., 2014; Domanski et al., 2014; Du et al., 2016; Qureshi and Zubair, 2014; Hu et al,.2021a; Hu and Yuill, 2022a) have investigated fault impacts on split residential air conditioning systems. However, few (Shen et al., 2011; Palmiter et al., 2011; Hu et al,.2021b, c, d, e; Hu and Yuill, 2021; Hu, 2021; Hu and Yuill, 2022b, c) examined multiple simultaneous faults. Shen et al. (2011) and Palmiter et al. (2011) each investigated improper indoor airflow and improper refrigerant charge (CH) on a 3-ton split heat pump. Hu et al. (2021a, b, c, d, e), Hu and Yuill (2021), and Hu (2021) studied four common installation faults – CH, improper evaporator air flow (EA), liquid line restriction (LL), and the presence of non-condensable gas (NC) in the refrigerant – on a 4-ton split high-efficiency heat pump equipped with a thermostatic expansion valve (TXV) in cooling mode. The faults were imposed both singly and in combination (up to 4). The fault impacts on cooling capacity and coefficient of performance (COP), and also characteristic fault detection features, such as refrigerant superheat and subcooling, were investigated as a function of fault type, intensity, and number of faults that are present. Hu and Yuill (2021a, b) subsequently investigated these faults in the same fashion on a 3-ton standard efficiency split air conditioner equipped with a fixed orifice expansion device (FXO).

Most previous studies examined the fault impacts on system performance for one expansion device type (either TXV or FXO). Few of them (Shen et al., 2011) compared fault impacts between these two different expansion devices with comparable operating conditions and fault intensities, especially for multiple simultaneous faults. In the current paper, the fault intensity for each fault type is imposed at comparable magnitude while the systems are operating with the same indoor and outdoor conditions. The faults' impacts on system performance are normalized against the same fault-free condition so that comparisons can be made between a 4-ton high-efficiency split system heat pump and 3-ton standard efficiency air condition.

2. EXPERIMENTAL SETUP

2.1 Description of the Tested Systems

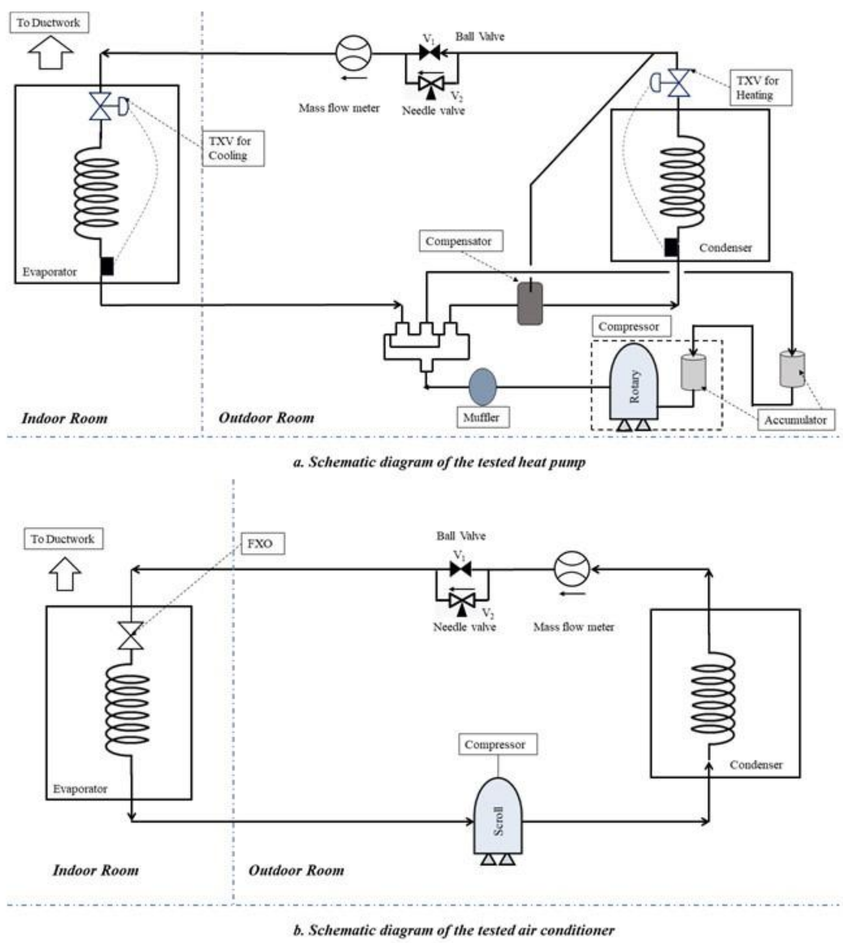

Figure 1: Schematic diagram of the tested systems (Hu and Yuill, 2021, 2022a)

Table 1 provides the general descriptions of two tested systems. System I is a split residential heat pump, rated as 18 seasonal energy efficiency ratio (SEER) that uses an inverter compressor. However, to provide a uniform operation for the testing, the controller of the inverter is deactivated. This system has two accumulators, to prevent liquid refrigerant entering the compressor; a compensator for storing extra refrigerant during heating operation; a muffler to attenuate compressor noise, a reversing valve for heating and cooling mode control, two TXVs (one is for cooling and the other is for heating), and two finned tube heat exchangers. System II is a split residential air conditioner, rated as

13 SEER. It has a microtube finned tube condenser, a traditional finned tube evaporator, and an FXO. Figure 1 shows a schematic diagram of the two tested systems.

Table 1: Description of tested systems (Hu and Yuill, 2022b)

System	Nominal size (tons)	Compressor	Refrigerant	Expansion device	Accumulator	SEER
I	4	Rotary	R410A	TXV	Yes	18
II	3	Scroll	R410A	FXO	No	13

2.2 Test Conditions and Matrix

The test conditions in cooling mode are described in Table 2. Condition D was not imposed on System II. Two of four test conditions are from the rating conditions specified in AHRI Standard 210/240 (2017). Conditions A to C are wet evaporator coil tests, in which only outdoor dry-bulb temperature varies, while the last condition is a dry evaporator coil test. The test matrix of intensities of each fault for both systems is presented in **Error! Reference source not found.**.

Table 2: Operating conditions in cooling mode

Test condition	Indoor room temperature (°C)		Outdoor room temperature (°C)
	Dry-bulb	Wet-bulb	Dry-bulb
A*	26.7	19.4	35.0
B*		19.4	27.8
C		19.4	40.5
D		<13.3	35.0

* correspond to rating conditions used in AHRI Standard 210/240 (2017).

Table 3: Test matrix for selected faults

Fault	Abbreviation	Definition of intensity	Intensity (%)
Improper evaporator airflow	EA	% of the nominal evaporator airflow	60*, 80, 100,120
Improper refrigerant charge	CH	% of the nominal refrigerant charge	70, 80, 100,120
Liquid line restriction	LL	ratio of liquid line pressure drop to compressor pressure lift at rating A condition	0, 22 [20], 32 [30]
Non-condensable gas	NC	ratio of injected nitrogen pressure at 35 °C to atmospheric pressure	0, 49, 105 [99]

"*" Not tested for System II

"[ ]" Values in the square brackets indicate a different fault intensity for System II.

Only single faults were tested in all operating conditions shown in **Table 2**. To further decrease the test matrix, simultaneous faults were only tested at the rating "A" operating condition, which is 35 °C/26.7°C/19.4 °C (outdoor dry-bulb, indoor dry-bulb and wet-bulb).

Table 4 describes the fault intensities for each of the four fault types, and includes the fault-free condition (100% for EA and CH; 0% for LL and NC). For the heat pump, there are 133 possible combinations of fault condition from this set: 37 double; 60 triple; and 36 quadruple; while for the air conditioner, there are 98 possible combinations of fault condition from this set: 30 double; 44 triple; and 24 quadruple. Some of these combinations could not be tested, because they exceed the safe operating bounds for the system. For example, the combination CH70, NC49, and LL32 (LL30 for air conditioner) caused the discharge temperature to exceed the manufacturer's limit of 105 °C. The remaining number of test conditions for heat pump and air conditioner is 117 and 77, respectively. Each of these tests was conducted after the system reached steady state. Measurements were made over a period of at least 10 minutes, and the measurements (taken on one second interval) were averaged to provide the results in this study. **Table 4** gives a count of each fault combination of fault types within the 117 results for heat pump and within the 77 results for air conditioner. The figures in the results use a combination of the abbreviation and fault intensity to represent the fault. For instance, EA80 represents the evaporator airflow rate at 80% of the nominal level.

Table 4: Fault notation, intensity, and simultaneous combinations

Fault categories		
Fault	**Intensities (%)**	**Notation**
EA	60*, 80, 100, 120	EA60*, EA80, EA100, EA120
CH	70, 80,100,120	CH70, CH80, CH100, CH120
LL	0, 22 [20], 32 [30]	LL0, LL22 [LL20], LL32 [LL30]
NC	0, 49, 105 [99]	NC0, NC49, NC105 [NC99]
Double-fault combinations		
Combination	**Example**	**Counts (37 [29])**
EA, CH	EA80 + CH120	9 [6]
EA, LL	EA80 + LL22 [LL20]	6 [4]
EA, NC	EA120 + NC49	6 [4]
CH, LL	CH120 + LL32 [LL32]	6 [5]
CH, NC	CH80 + NC49	6
LL, NC	LL22 [LL20] + NC49	4
Triple-fault combinations		
Combination	**Example**	**Counts (56 [36])**
EA, CH, LL	EA80 + CH120 + LL32 [LL30]	18 [10]
EA, CH, NC	EA80 + CH80 + NC49	18 [12]
EA, LL, NC	EA120 + LL22 [LL20] + NC49	12 [8]
CH, LL, NC	CH80 + LL22 [LL20] + NC49	8 [6]
Quadruple-fault combinations		
Combination	**Example**	**Total counts**
EA, CH, LL, NC	EA80 + CH80 + LL22 [LL20] + NC49	24 [12]

"*" Not tested for System II
"[]" Values in the square brackets indicate a different fault intensity for System II.

2.3 Comparison Method

The normalized impact on a performance variable, R, of a faulted system compared to the fault-free system is provided in Eq. 1. This impact is characterized using ρ, where *i* refers to the number of faults, so 0 implies the fault-free condition. In the current study, the performance variables are cooling capacity and COP.

$$\rho_i = \frac{R_i - R_0}{R_0} \times 100\% \qquad i = 1,2,3,4 \tag{1}$$

The fault types and intensities imposed for each system are very similar. Therefore, comparing fault impacts of these two systems with different configuration and similar fault intensity is valuable, because it gives a clear comparison between these two types of system. Since the EA60 was not tested on the air conditioner, the number of fault tests for the air conditioner is smaller. Therefore, the intensities of faults imposed on the air conditioner were selected as the comparison baseline for presentation in the results section. The results are reduced by showing the difference between the two systems, Δ:

$$\Delta = \rho_{i,AC} - \rho_{i,HP} \qquad i = 1,2,3,4 \tag{2}$$

where Δ is the fault impact difference between the air conditioner and heat pump at the same or similar fault intensity; $\rho_{j,AC}$ and $\rho_{j,HP}$ are degradation or improvement of system performance for the air conditioner and heat pump under fault conditions. Table 5 summarizes the interpretation of the sign of Δ.

Table 5: Sign convention for difference, Δ

Sign of Δ	Fault impact difference
Δ > 0	AC fault impact less than HP fault impact
Δ = 0	AC fault impact equal to HP fault impact
Δ < 0	AC fault impact larger than HP fault impact

3. RESULTS AND DISCUSSION

3.1 Single Faults

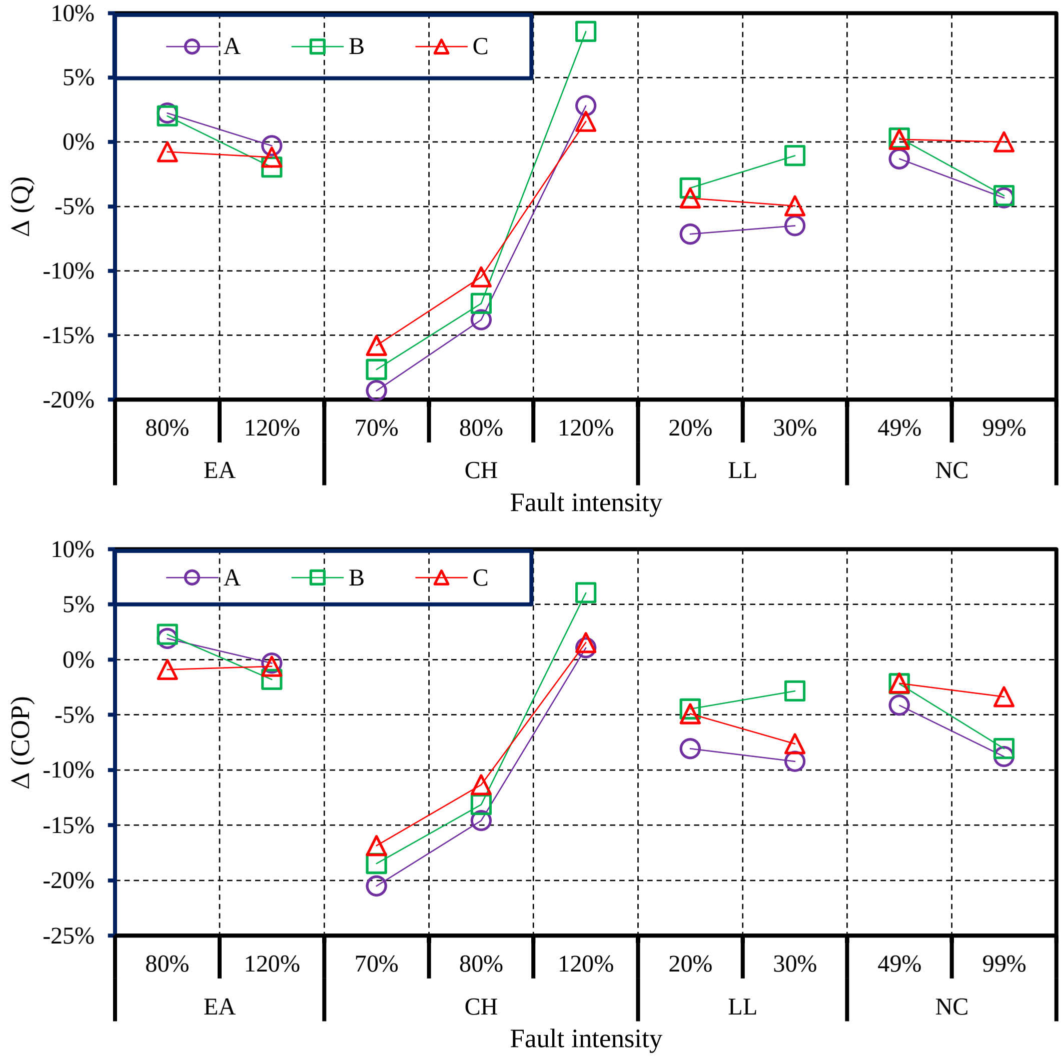

Figure 2: Single fault impacts on cooling capacity and COP between two systems

Figure 2 presents single fault differences in impact on cooling capacity and COP, comparing the heat pump and air conditioner for different fault types and intensities, using Eq.2. The trend for cooling capacity and COP is similar. For low evaporator airflow, there are small differences in the fault impact on performance between the two systems. The only times that the air conditioner has less fault impact than the heat pump are for some of the cases when low evaporator air (EA80) or refrigerant overcharge (OC) faults are present. In many cases the air conditioner's fault impacts are smaller for lower ambient temperature. For example, at test condition B (27.8 °C ambient) with 20% OC, the air conditioner performs 9% and 6% better in capacity and COP than the heat pump, respectively. For refrigerant undercharge (UC), the heat pump is much less sensitive to the fault. For example, with 30% UC, cooling capacity and COP for the air conditioner are degraded 18-19% more than for the heat pump. Although the fault intensity for LL and NC faults imposed on the heat pump is slightly higher than that on the air conditioner, the heat pump is impacted less by these faults. TXVs can compensate for many of the detrimental effects caused by LL, CH, and NC faults, which is believed to be the primary explanation for the differences.

3.2 Simultaneous Faults

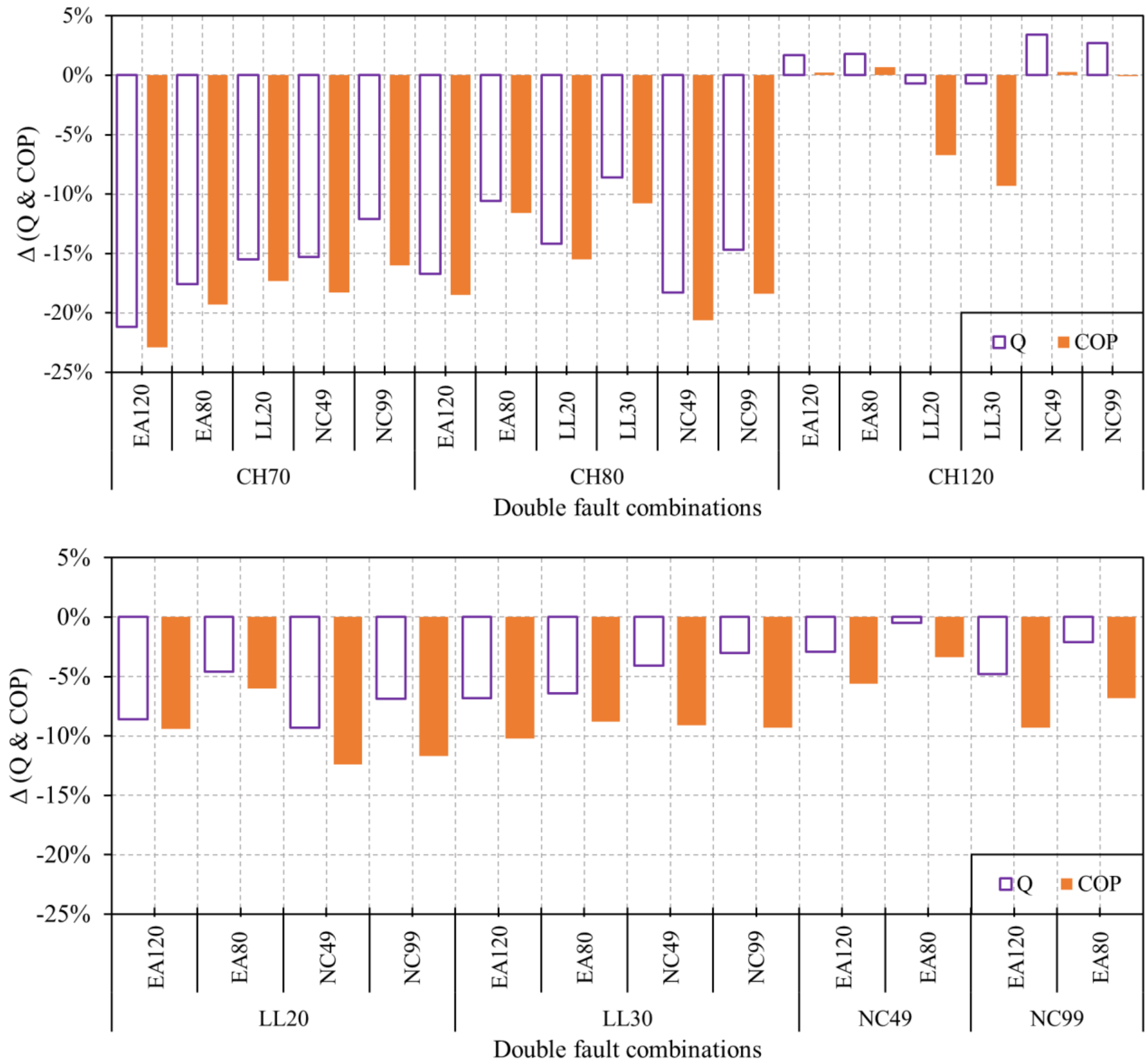

Figure 3: Double fault impacts on cooling capacity and COP between two systems

Figure 3, Figure 4, and Figure 5 present comparisons between the heat pump and air conditioner of double, triple, and quadruple fault impacts on cooling capacity and COP for different fault types and intensities, respectively. Unlike Figure 1 and Figure 2, these figures provide data only at the A operating condition, which is why they are presented as bar charts instead of scatter plots. They also combine capacity and COP comparisons onto a single chart. For double faults, the heat pump was less sensitive to faults for almost all the fault combinations, except for some that include OC. The combinations of CH120 + EA/NC resulted in positive values of Δ, indicating that the degradation for the air conditioner was less than for heat pump. In fact, the OC tends to increase capacity for FXO-equipped systems, so that in some cases the positive value of Δ reflects that the capacity increased more for the air conditioner than for the heat pump. However, the impacts on COP for these four fault combinations is roughly the same for both systems. We can conclude that OC can compensate more for EA or NC faults in the air conditioner than the heat pump in capacity degradation, but not for COP. In contrast, when LL faults are present in the air conditioner, OC cannot compensate for the detrimental effects. However, TXV can compensate for LL faults. Therefore, the heat pump's performance is always less impacted with fault combinations that include LL.

For triple faults, the analysis shows very similar trends to those shown in the double-fault combinations, and all of the same conclusions can be applied. OC can still compensate for the performance degradation to the air conditioner's cooling capacity with fault combinations of EA + NC. In the analysis of results for quadruple faults, heat pump had a better performance than the air conditioner because every fault combination necessarily includes LL faults.

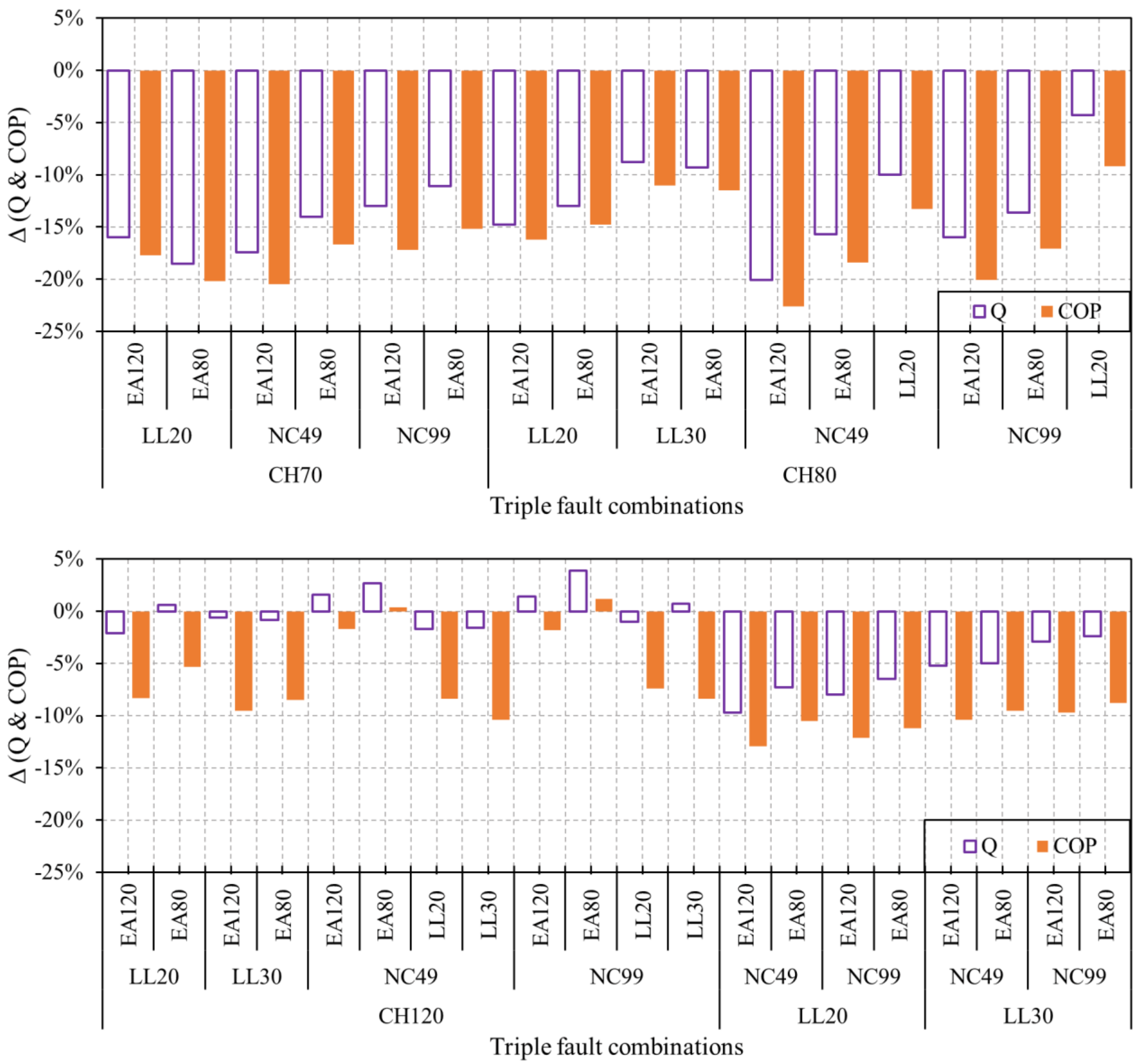

Figure 4: Triple fault impacts on cooling capacity and COP between two systems

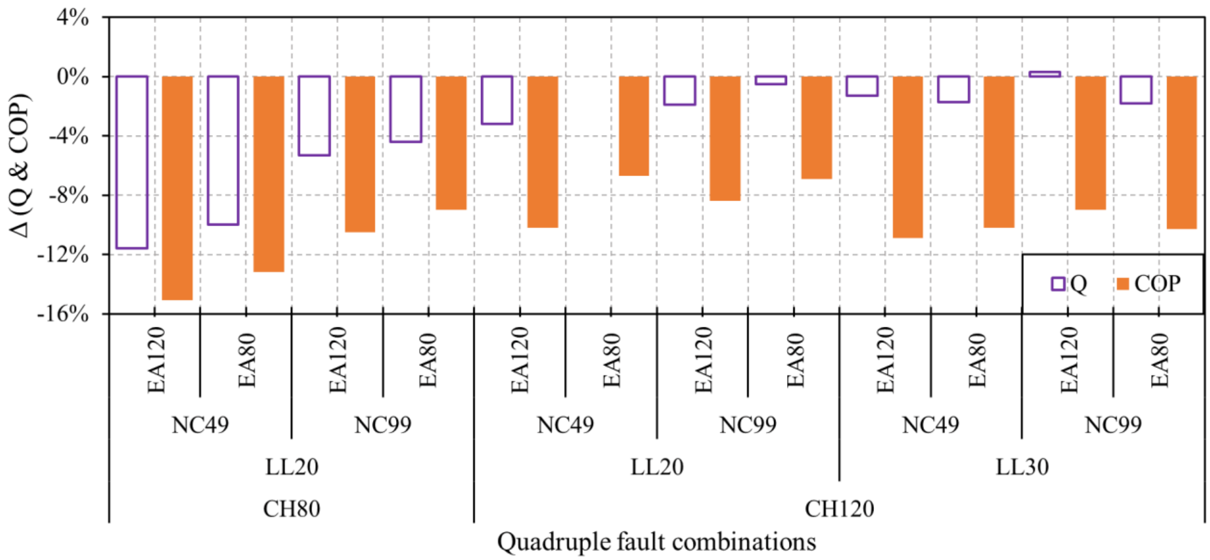

Figure 5: Quadruple fault impacts on cooling capacity and COP between two systems

4. CONCLUSIONS

Heat pump and air conditioner split systems were tested with faults systematically imposed at the same or similar fault intensities, both singly and in combination. The fault impacts on cooling capacity and COP were normalized to its fault-free condition for each fault test. Then the two systems were compared based on fault types and fault number that are present. The following conclusions can be drawn:

1. For single faults, the air conditioner had less performance degradation than the heat pump when low EA or OC are present; whereas the heat pump was less impacted by the faults UC, LL, and NC.
2. For simultaneous faults, the combinations for the air conditioner that had less degradation than for the heat pump each include OC, especially when combined with EA or NC, but not for LL.
3. Heat pump COP was less impacted by faults for almost all simultaneous fault combinations than the air conditioner, demonstrating that an air conditioning system equipped with a TXV is more tolerant for simultaneous faults than that one equipped with an FXO.

NOMENCLATURE

AC	air conditioner	HP	heat pump
ASHP	air source heat pump	LL	liquid line restriction
CH	refrigerant charge	NC	non-condensable gas
COP	coefficient of performance	OC	refrigerant overcharge
Δ	difference in performance impacts	Q	cooling capacity
EA	evaporator airflow	SEER	seasonal energy efficiency ratio
FDD	fault detection and diagnosis	TXV	thermostatic expansion valve
FXO	fixed orifice expansion device	UC	refrigerant undercharge

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