Generalized effects of faults on normalized performance variables of air conditioners and heat pumps

Mehdi Mehrabi, University of Nebraska - Lincoln
David Yuill

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Mehdi Mehrabi*, David Yuill

University of Nebraska-Lincoln, Architectural Engineering, Omaha, NE 68182, USA

ABSTRACT

The effects of several types of faults on air conditioners and heat pumps have been studied in many laboratory experiments. All available data have been gathered, and the independent variable (fault intensity) and each of the dependent variables (fault impacts) are normalized to show the trends in a generalized fashion. Relationships are provided wherever there are sufficient results. Most of the significant fault types are included (except refrigerant charge variation, which was discussed in Mehrabi and Yuill (2017)): condenser heat transfer (CA), evaporator heat transfer (EA), liquid line restriction (LL), compressor leakage (VL), and non-condensables in the refrigerant (NC). Relationships are presented separately for fixed orifice and thermostatic expansion valve equipped systems. The variation level in the results indicates that in many cases, the generalized relationships provide reasonable predictors of fault effects on systems for which laboratory test results are unavailable. These relationships provide the first generalized fault effect models for air conditioners and heat pumps.

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Keywords:
Air conditioner
Heat pump
Fault
Generalized effect

1. Introduction

Several types of faults have the potential to significantly degrade the performance of air-cooled unitary air conditioning and heat pump systems, such as packaged units and split systems. To quantify the impact on performance, researchers have conducted controlled laboratory experiments on the effects of one or more faults on a given system. To generalize the effect of refrigerant charge faults, Mehrabi and Yuill (2017) gathered all of the known data, either from the researchers or from published literature, and non-dimensionalized the variables of interest, then conducted statistical analyses to provide simplified models of charge faults’ effects for the general case. In the current paper, this approach is taken to demonstrate the effect of several other fault types: condenser heat transfer....

* Corresponding author. University of Nebraska-Lincoln, Architectural Engineering, Omaha, NE 68182, USA.
E-mail address: mmehrabi@unomaha.edu (M. Mehrabi).
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reduction (CA); evaporator heat transfer reduction (EA); liquid line restrictions (LL); compressor leakage (VL); and non-condensable gas in the refrigerant (NC). Data have been gathered and analyzed to find generalized relationships between fault type, fault intensity, and normalized performance variables. The results presented here could be used to predict the effect of faults on systems that have not been tested in the laboratory, and to estimate the potential uncertainty for the estimates. Yuill and Mehrabi (2017) argue that these results could be used for administering utility and governmental programs, facilitating fault-enabled energy simulation, and as guidance for maintenance decisions. Although the relationships contain uncertainty and are not universally representative, they constitute the most reliable predictive model for fault effects on systems that have not been tested in a laboratory.

The test conditions in laboratory experiments are described in this paper in the format of "return air dry bulb temperature/return air wet bulb temperature/outdoor dry bulb temperature." These values for the A and B test conditions in cooling mode from AHRI Standard 210/410 (2008) are: 26.7/19.4/35 °C and 26.7/19.4/27.8 °C respectively. The values for the H1, H2 and H3 test conditions in heating mode are 21.1/15.6/8.33 °C, 21.1/15.6/1.67 °C and 21.1/15.6/–8.33 °C respectively.

The data for this analysis have been collected in experiments conducted over the past twenty years, and under a variety of operating conditions. These experiments are described below. Some faults affect performance with different severity depending on operating conditions, so we compare the experimental results under similar conditions wherever appropriate and practical. The conditions for all of the data analyzed in this paper will likely cause the evaporator to be condensing humidity ("wet coil" cases), so some of the results may not generalize well to dry coil conditions. In all cases, the faults are imposed singly, i.e. there are no simultaneously occurring faults in the data used in this paper. Also, all of the systems in the experiments have constant speed fans and compressors. Variable speed equipment is likely to have quite different responses.

Breuker and Braun (1998) studied a Rooftop Unit (RTU) equipped with a thermostatic expansion valve (TXV), reciprocating compressor, R22 refrigerant, and 10.6 kW of nominal cooling capacity. They imposed CA, EA, LL and VL faults under test conditions of 23.3/15.6/26 °C, and also varied outdoor temperatures to 23.3, 26.7, 30, and 32.2 °C. We use the results from the 23.3/15.6/26.7 °C test condition for this paper.

Shen (2006) and Shen et al. (2009) studied three different systems by imposing CA and EA faults in each while in cooling mode. Unit A is a split system with reciprocating compressor, R410A refrigerant and 10.6 kW of nominal cooling capacity, which was studied using both fixed orifice expansion valve (FXO) and TXV. The FXO tests were performed in the A test condition. The TXV tests were conducted in 27.8/19.4/36.1 °C for CA faults, and in A test condition for EA faults. Unit B is an FXO-equipped RTU with a scroll compressor, R410A refrigerant and 10.6 kW of nominal cooling capacity. Unit C is an FXO-equipped RTU with a scroll compressor, R407C refrigerant, and 17.6 kW of nominal cooling capacity. The Unit B and Unit C measurements were conducted mostly in the B test condition. Shen (2006) also investigated a split system heat pump in heating mode (Unit D) with a reciprocating compressor, R22 refrigerant, and 10.6 kW nominal capacity. It was tested with both FXO and TXV metering devices with EA faults in the H1, H2, and H3 test conditions.

Kim et al. (2006, 2009), Domanski et al. (2014) and Cho et al. (2014) investigated a TXV-equipped split system with a scroll compressor, R410A refrigerant, and 8.8 kW of nominal cooling capacity, imposing CA, EA, LL, VL, and NC faults. These tests were conducted mostly in the B test condition. This system is referred to as Kim et al. (2006) in the current paper. Yoon et al. (2011) and Domanski et al. (2014) also investigated the system in heating mode, in the H1 and H3 test conditions, imposing CA, EA, LL and VL faults.

Kim et al. (2008) imposed EA faults on three different systems, mostly in the A and B test conditions. We used the results from the A test condition for this paper. Unit A is an FXO-equipped split system with a scroll compressor, R22 refrigerant and 10.6 kW of nominal cooling capacity. Unit B is a TXV-equipped system with a scroll compressor, R22 refrigerant and 10.6 kW of nominal cooling capacity. Unit C is a TXV-equipped split system with a scroll compressor, R410A refrigerant and 10.6 kW of nominal cooling capacity. Units B and C were also tested in the H1, H2, and H3 test conditions in heating mode while imposing EA faults.
SCE (2009) studied a TXV-equipped RTU with a scroll compressor by imposing CA and EA faults in the A test condition. The CA fault was imposed by using very light (1-ply), light (one 2-ply), medium (two 2-ply) and heavy (three 2-ply) tissue papers. The resulting condenser airflow was not measured.

SCE (2012) studied a TXV-equipped split system with R410A refrigerant and 10.6 kW of nominal cooling capacity, by imposing EA, CA, LL and NC faults. The resulting condenser airflow reduction was not measured in this study. SCE (2015) studied a TXV-equipped RTU with R410A refrigerant and 17.6 kW of nominal cooling capacity, by imposing CA and EA faults in the A test condition. The tests on SCE (2012) and SCE (2015) were conducted in the A test condition, and several other test conditions. In the current paper we consider results from the A test condition.

Davis and D’Albora (2001) studied an FXO-equipped air conditioner with R22 refrigerant and 10.6 kW of nominal cooling capacity, then they replaced the expansion valve with a TXV and tested the system again. They imposed EA faults in the A test condition.

Mowris et al. (2012) studied an FXO-equipped split system with R22 refrigerant and 10.55 kW of nominal cooling capacity. They imposed CA, EA and NC faults while simultaneously mimicking a hot attic test condition (26.7/19.4/47.8 °C), including allowing of stray heat transfer into the ductwork and air-handler.

Qureshi and Zubair (2014) studied a TXV-equipped split system with R22 refrigerant and 5.27 kW of nominal cooling capacity. They imposed CA faults in a 21/NA/31.6 °C test condition.

**Fig. 1** – T-s and P-h diagrams showing effect of $F_{\text{CA}}$ on a vapor compression cycle for systems equipped with FXO.

**Fig. 2** – T-s and P-h diagrams showing effect of $F_{\text{CA}}$ on a vapor compression cycle for systems equipped with TXV.
Fig. 3 – Effect of $F_{ICA}$ on normalized variables in cooling mode: a) FXO, b) TXV.
RMA (2016) studied the effect of imposing CA and EA faults on three systems (RTU2, RTU3, and RTU5). Also, they imposed LL and NC faults on RTU2 and RTU3. RTU2 is a TXV-equipped unit with R22 refrigerant and 26.4 kW of nominal cooling capacity. RTU3 is an FXO-equipped unit with R22 refrigerant and 26.4 kW of nominal cooling capacity. RTU5 is an FXO-equipped unit with R22 refrigerant and 10.6 kW of nominal cooling capacity.

Finally, Du et al. (2016) modeled the effect of the faults on the normalized values of cooling capacity, COP, and sensible heat ratio, using multivariable polynomial regression, for five split and rooftop systems.

2. Methodology

The systems that are described above have a range of characteristics, such as nominal capacity, airflow rate across the heat exchangers, etc. Therefore, the first step in generalizing the effects of faults is to non-dimensionalize the variables of interest. These variables, both dependent and independent, are referred to in this and other papers as “normalized”, which is appropriate for most, since their values are typically of order of magnitude unity. As a second step in this generalization, we must consider whether the sample is representative of the population. The systems in the literature can reasonably be assumed to represent existing field-deployed air conditioners, since the literature is mainly from tests of new systems published in the past ten years. However, it’s possible that it doesn’t accurately represent newer air conditioners with higher efficiencies, or those equipped with new features such as microchannel heat exchangers. The systems used in the analysis have capacities that range from 5.27 to 26.4 kW, rated efficiencies from 9.3 to 15.2 SEER, and contain R22, R407C and R410A as their working fluid.

2.1. Normalized variables

In the current paper, fault levels (i.e. the severity of the faults) are quantified using fault intensity (FI), defined by Yuill and Braun (2013) for Eqs. (1–4), and Mowris et al. (2012) for Eq. (5). For non-condensables faults (Eq. (5)), an alternate definition in Kim et al. (2009) uses the mass of N₂ gas that would occupy the system at standard atmospheric temperature and pressure (to represent a system that was open to the atmosphere prior to adding refrigerant), as the denominator. This definition is the most meaningful, but the dataset from Mowris et al. (2012) didn’t provide sufficient information to calculate FInc in this way, and there is a scarcity of data from non-condensables testing, so we adopted the definition from Mowris et al. (2012) to maximize the sample size.

\[ F_{CA} = \frac{V_{actual} - V_{nominal}}{V_{nominal}} \]  
\[ F_{EA} = \frac{V_{actual} - V_{nominal}}{V_{nominal}} \]
\( F_{\text{IC}} = \frac{\dot{m}_{\text{faulted}} - \dot{m}_{\text{unfaulted}}}{\dot{m}_{\text{unfaulted}}} \)  

\( F_{\text{IL}} = \frac{\Delta P_{\text{fault}}}{\Delta P_{\text{sys}}} \)

\( F_{\text{IR}} = \frac{m_{\text{nom, fault}}}{m_{\text{ref}}} \)

Δ\( P_{\text{LL, fault}} \) is the pressure drop caused by the restriction, and Δ\( P_{\text{sys}} \) is the pressure difference between system's high side and low side, prior to imposing the fault. \( m_{\text{ref}} \) is the nominal mass of refrigerant. For four of the dependent variables of interest—capacity (Q), coefficient of performance (COP), input power (PWR), and refrigerant mass flow rate (\( \dot{m} \))—the normalized values are calculated using fault impact ratio (FIR) (Yuill and Braun, 2013) as given in Eqs. (6–9). For suction superheat

\[
\text{Table 2 – Regression coefficients (Eq. (12)) for normalized variables in cooling mode.}
\]

<table>
<thead>
<tr>
<th>Normalized Variable</th>
<th>Expansion Valve Type</th>
<th>( a_0 )</th>
<th>( a_1 )</th>
<th>( a_2 )</th>
<th>Applicable Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIR(_Q)</td>
<td>FXO</td>
<td>0.99631</td>
<td>0.01003</td>
<td>-0.39578</td>
<td>(-0.55 \leq F_{\text{IC}} \leq 0)</td>
</tr>
<tr>
<td></td>
<td>TXV</td>
<td>1.00483</td>
<td>0.35150</td>
<td>0.29643</td>
<td>(-0.55 \leq F_{\text{IC}} \leq 0)</td>
</tr>
<tr>
<td>FIR(_{COP})</td>
<td>FXO</td>
<td>1.00000</td>
<td>0.31372</td>
<td>-0.36470</td>
<td>(-0.55 \leq F_{\text{IC}} \leq 0)</td>
</tr>
<tr>
<td></td>
<td>TXV</td>
<td>1.0093</td>
<td>0.79837</td>
<td>0.54101</td>
<td>(-0.55 \leq F_{\text{IC}} \leq 0)</td>
</tr>
<tr>
<td>FIR(_{PWR})</td>
<td>FXO</td>
<td>0.99815</td>
<td>-0.25471</td>
<td>0.26357</td>
<td>(-0.55 \leq F_{\text{IC}} \leq 0)</td>
</tr>
<tr>
<td></td>
<td>TXV</td>
<td>0.99270</td>
<td>-0.53782</td>
<td>-0.17427</td>
<td>(-0.55 \leq F_{\text{IC}} \leq 0)</td>
</tr>
<tr>
<td>FIR(_m)</td>
<td>FXO</td>
<td>0.99641</td>
<td>-0.18368</td>
<td>-0.20009</td>
<td>(-0.33 \leq F_{\text{IC}} \leq 0)</td>
</tr>
<tr>
<td>Residual(_{\text{SH}}) [( ^\circ \text{C} )]</td>
<td>FXO</td>
<td>0.29042</td>
<td>22.988</td>
<td>26.381</td>
<td>(-0.55 \leq F_{\text{IC}} \leq 0)</td>
</tr>
<tr>
<td></td>
<td>TXV</td>
<td>-0.06964</td>
<td>-10.650</td>
<td>-17.208</td>
<td>(-0.29 \leq F_{\text{IC}} \leq 0)</td>
</tr>
<tr>
<td>Residual(_{\text{SC}}) [( ^\circ \text{C} )]</td>
<td>FXO</td>
<td>0.10093</td>
<td>-0.85744</td>
<td>-2.5302</td>
<td>(-0.45 \leq F_{\text{IC}} \leq 0)</td>
</tr>
<tr>
<td></td>
<td>TXV</td>
<td>0.04912</td>
<td>-0.72591</td>
<td>47.351</td>
<td>(-0.29 \leq F_{\text{IC}} \leq 0)</td>
</tr>
</tbody>
</table>

**Fig. 4 – Effect of \( F_{\text{IC}} \) on normalized variables in heating mode for an FXO-equipped system.**
Fig. 5 – Effect of $F_{CA}$ on normalized variables in heating mode for TXV-equipped systems in a) H1, b) H2 and c) H3 test conditions.
amount (SH) and subcooling amount (SC), the normalized variables are defined with a dimensional residual value, as shown in Eqs. (10) and (11). This residual value is used because it is more easily interpreted than a non-dimensional value would be, and is consistent with other literature (Kim et al., 2008, 2009; Mehrabi and Yuill, 2017; Yoon et al., 2011).

Most of the researchers provide results based on measurements of total power, which include parasitic power (e.g. from controls) and fan power, and also include fan heat in their calculations of system capacity, Q. The exceptions, in which compressor power and coil capacity are used to calculate Q and COP, are Breuker and Braun (1998) and Qureshi and Zubair (2014) for cooling mode; and Kim et al. (2008) in heating mode. Since fan power, parasitic power, and fan heat are each relatively constant, regardless of whether a fault is imposed, and are smaller than compressor power, the non-dimensionalized values are not significantly affected by their inclusion, so the results group quite well despite the two approaches to calculate Q, COP, and power.

\[ \text{FIR}_Q = \frac{Q_{\text{faulted}}}{Q_{\text{nominal}}} \]  
\[ \text{FIR}_{\text{COP}} = \frac{\text{COP}_{\text{faulted}}}{\text{COP}_{\text{nominal}}} \]  

<table>
<thead>
<tr>
<th>Normalized Variable</th>
<th>Test Condition</th>
<th>( F_{\text{COP}} )</th>
<th>( a_0 )</th>
<th>( a_1 )</th>
<th>( a_2 )</th>
<th>Applicable Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{FIR}_Q )</td>
<td>H1</td>
<td>0.99910</td>
<td>0.21199</td>
<td>0.01026</td>
<td>(-0.27 \leq F \leq 0.18)</td>
<td></td>
</tr>
<tr>
<td>H2</td>
<td>1.0063</td>
<td>0.19869</td>
<td>0.00256</td>
<td>(-0.27 \leq F \leq 0.18)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H3</td>
<td>1.00461</td>
<td>0.21544</td>
<td>0.05943</td>
<td>(-0.27 \leq F \leq 0.18)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{FIR}_{\text{COP}} )</td>
<td>H1</td>
<td>1.00001</td>
<td>0.24508</td>
<td>(-0.15008 \leq F \leq 0.27091)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H2</td>
<td>1.00160</td>
<td>0.17266</td>
<td>0.02799</td>
<td>(-0.27 \leq F \leq 0.18)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H3</td>
<td>1.00404</td>
<td>0.14369</td>
<td>0.26916</td>
<td>(-0.27 \leq F \leq 0.18)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{FIR}_{\text{FIR}} )</td>
<td>H1</td>
<td>0.99932</td>
<td>0.06822</td>
<td>0.17928</td>
<td>(-0.27 \leq F \leq 0.18)</td>
<td></td>
</tr>
<tr>
<td>H2</td>
<td>1.00102</td>
<td>0.02283</td>
<td>0.35219</td>
<td>(-0.27 \leq F \leq 0.18)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H3</td>
<td>1.00107</td>
<td>0.04579</td>
<td>0.35219</td>
<td>(-0.27 \leq F \leq 0.18)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{Residual}_{\text{SH}} \ [\degree \text{C}] )</td>
<td>H1</td>
<td>0.13136</td>
<td>0.51192</td>
<td>(-1.70776 \leq F \leq 0.27091)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H2</td>
<td>0.21772</td>
<td>0.43652</td>
<td>(-0.17184 \leq F \leq 0.27091)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H3</td>
<td>0.2855</td>
<td>0.02154</td>
<td>(-0.18662 \leq F \leq 0.27091)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{Residual}_{\text{SC}} \ [\degree \text{C}] )</td>
<td>H1</td>
<td>0.12709</td>
<td>1.31069</td>
<td>4.58706</td>
<td>(-0.27 \leq F \leq 0.18)</td>
<td></td>
</tr>
<tr>
<td>H2</td>
<td>0.6803</td>
<td>2.35812</td>
<td>3.18673</td>
<td>(-0.27 \leq F \leq 0.18)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H3</td>
<td>0.05178</td>
<td>1.79280</td>
<td>3.18673</td>
<td>(-0.27 \leq F \leq 0.18)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.2. Generalized relationships

Two statistical treatments are deployed to provide generalized relationships between FI and the normalized dependent variables. These treatments give slightly different results, and are intended to provide tools for two different deployments of the results. In the first treatment, second order polynomial regression analysis is applied using the ordinary least squares method for each individual system and each normalized variable, to provide a continuous function relating FI to the normalized variables. A continuous function is convenient for use in simulation software, for example. Second-order polynomials were found to be adequate, as can be seen in Figs. 3, 5 and 8. Using higher-order polynomials would cause overfitting in many cases, and although linear approximation may be more appropriate in some cases, for consistency, the second order polynomial is applied in all cases. The polynomial is the first step in a four-step process, shown below, that is conducted for each combination of normalized variable and expansion valve (e.g. a regression model was generated for FIRCop versus FI_EA in FXO-equipped systems).

1- Regression analysis is conducted to generate a model for each experiment.

2- For FI in increments of 0.01 throughout the model’s domain, the regression model is applied to calculate normalized variable values (e.g. FIR).

3- The normalized variable values from all systems are averaged at each FI increment, if more than two datasets are available (applicable range in Tables 2, 4 and 6), creating a new series.

4- From the new series in step 3, a final second order polynomial regression model is generated.

This method equally weights each effects of a fault on each system at any given FI, as long as the FI value is within the range of the tests for that system. The resulting regression models are shown in Figs. 3, 5 and 8 with a thick transparent line. The regression coefficients are tabulated in Tables 2, 4 and 6, based on Eq. (12).

\[ \text{Normalized Variable} = a_0 + a_1 \cdot \text{FI} + a_2 \cdot \text{FI}^2 \]  

(12)

The regressions were not forced through one (or zero for residuals) at the FI = 0 point, since this would unrealistically skew the results at all other FI values. Therefore, the regressions give non-zero results at FI = 0. However, the variation from zero is very small; an inspection of the a0 values shows less than 1% variation in the non-dimensional FIR outputs in all cases. Users that cannot tolerate this error at FI = 0 could implement the model only for cases with a non-zero FI value.

The second statistical treatment provides estimates of fault effects on the dependent variables for several discrete values of FI, and unlike the regression treatment, it also characterizes the variation in the fault’s effect for the air conditioning systems in our sample. In this method, mean values and standard deviations of normalized variables were calculated at discrete FI levels in increments of 0.1 for any cases where three or more datasets were available. Since tests were generally not
conducted at these discrete FI values, linear interpolations between measured points are conducted for each series to generate the necessary values. This is repeated for each normalized variable to generate the full set of results, which are presented in Tables 1, 3 and 5.

3. Results and discussion

3.1. CA fault

There are several potential causes of a condenser heat transfer reduction fault (CA). Airside fouling is believed to be common, and its effects can be effectively simulated by reducing airflow across the condenser, assuming the condenser fan to operate at a single speed, since the airflow reduction affects heat transfer far more than changes to the overall thermal conductance (Yang et al., 2007; Yuill and Braun, 2013). This is the typical method for imposing this fault in laboratory tests, and has the benefit of being repeatable and replicable. Therefore, this fault is quantified using airflow rates, as shown in Eq. (1). Many of the studies, including Breuker and Braun (1998), Mowris et al. (2012), RMA (2016), Kim et al. (2006) and Qureshi and Zubair (2014), imposed the condenser fault by blocking a portion of the face area of the condenser, and did not measure the reduction in airflow. In the current paper, we have three options: discard these data; assume flow to be proportional to unobstructed face area; or assume flow is proportional to the square root of the open area fraction of the coil (e.g. 49% open area equates to 70% airflow rate). We chose the latter, for three reasons: (1) it’s important to include all tests, to improve the sample size; (2) because this approach approximately matches the expectation for turbulent flow and a typical condenser fan; (3) because the results seem to cluster well using this approach.

3.1.1. Cooling mode

From the data in Shen (2006) Unit B and Kim et al. (2006), the effect of \( \text{FIC}_{\text{A}} \) in system performance is plotted on T-s and P-h diagrams, in Figs. 1 and 2. These graphs generally illustrate the effects on other studied systems. In Fig. 1, the condenser airflow reduction retards the heat exchanger’s ability to reject heat, causing the condensing temperature and pressure to increase, which causes the refrigerant to enter the evaporator at a slightly higher pressure and quality, reducing capacity. The increased compressor lift increases power input, which combines with the reduced capacity to reduce efficiency. Fig. 2 shows that similar effects are found in TXV-equipped systems, but the high side is more affected and the low side is less affected than for FXO systems.

Fig. 3 shows graphically the effect of \( \text{FIC}_{\text{A}} \) on normalized variables in FXO- and TXV-equipped systems. The qualitative effects of the fault described with Figs. 1 and 2 are apparent in Fig. 3. Numerical results are given in Table 1, showing the mean value and standard deviation of each normalized variable at each of several discrete values of \( \text{FIC}_{\text{A}} \). For example, at 70% of nominal condenser airflow rate (\( \text{FIC}_{\text{A}} = -0.3 \)), FXO systems attain an average of 92.9% of their nominal COP, with a standard deviation of 2.2%. Table 2 provides coefficients for second
order regression models of each normalized variable as a function of FIEA, based on Eq. (12). In Fig. 3, some subplots, such as the plot for FIRm in Fig. 3(b), do not show a regression curve. This is because there were not enough data present for a meaningful regression analysis. Similarly, numerical results are not provided for these cases in Tables 1 and 2; Table 1 shows dashes, and Table 2 simply omits the case, where appropriate.

In Fig. 3 and Table 2, which describe the effects of FIEA on normalized variables in the cooling mode, we observe the following:

- For FXO-equipped systems, CA faults cause the condenser temperature and pressure to increase. The low-side pressure is also increased slightly, as evident in Fig. 1. This reduces suction superheat (ResidualSH), and increases suction density.
- Mass flow rate (FIRm) is not significantly affected by CA faults for FXO-equipped units. There are competing effects, such as an increase in suction density, which tends to increase mass flow, and increase in discharge pressure, which tends to decrease mass flow.
- Capacity (FIRQ) is reduced by the decreased enthalpy difference across the evaporator, while COP (FIRCOP) is slightly more reduced because of the simultaneous increase in compressor power (FIRPWR).
- For TXV-equipped systems, the effects are similar. However, there aren’t enough datasets (and some variation between the sets that are available) to draw conclusions about FIRm, ResidualSH and ResidualSC, or to conclude that this modeling approach is valid for this case.

### 3.1.2. Heating mode

In heating mode the indoor heat exchanger acts as the condenser. In this case, filter fouling or excessive air distribution system resistance could cause the CA fault. Fig. 4 shows the effect of FIEA on normalized variables in an FXO-equipped system in heating mode (Shen, 2006 Unit D). Fig. 4 shows results from three different operating conditions on a single heat pump.
Fig. 8 – Effect of \( F_{\text{EA}} \) on normalized variables in cooling mode: a) FXO, b) TXV.
in contrast to Fig. 3, which showed multiple systems at a single condition.

Fig. 5 shows the effect of FICA on normalized variables in TXV-equipped systems in heating mode. Table 3 gives the mean value and standard deviation of the normalized variables for discrete values of FICA. Table 4 provides the coefficients of the regression models for the normalized variables as a function of FICA in heating mode, based on Eq. (12). Some of the

![Fig. 9 - Effect of FICA on normalized variables in heating mode for a TXV-equipped system.](image)

![Fig. 10 - T-s and P-h diagrams showing the effect of FLL on a vapor compression cycle for systems equipped with FXO.](image)
experiments included airflow rates higher than the nominal value ($F_{I_{CA}} > 0$), which is possible with the indoor coil serving as the condenser in heating mode. The models fit the data quite well. Most are not very sensitive to $F_{I_{CA}}$, with the exception of $F_{I_{RQ}}$ and $F_{I_{RCOP}}$, which increase quite steadily with airflow rate.

3.2. **EA fault**

As with condenser faults, reduction in airflow is used to simulate evaporator faults in the laboratory experiments. This fault could simulate airside fouling of the coil or filter, or excessive flow resistance in the air distribution system.

3.2.1. **Cooling mode**

From the data in Breuker and Braun (1998) and Kim et al. (2006), the effect of $F_{I_{EA}}$ in cooling mode is plotted on T-s and P-h diagrams in Figs. 6 and 7. The figures show that the EA fault decreases the evaporating temperature very slightly, which decreases the condensing temperature, but has no visible impact on the enthalpy at the liquid line and evaporator inlet.

Fig. 8 shows the effect of $F_{I_{EA}}$ on normalized variables for FXO- and TXV-equipped systems. Table 5 gives the mean value and standard deviation of normalized variables for several discrete values of $F_{I_{EA}}$. Table 6 provides the coefficients of the regression model of normalized variables as a function of $F_{I_{EA}}$, based on Eq. (12). For FXO-equipped systems, a reduced evaporator airflow rate is expected to cause reduced heat transfer in the evaporator (decrease in $F_{I_{RQ}}$ and $Residual_{SH}$), hence decreased suction pressure, hence reduced suction density and mass flow rate (decrease in $F_{I_{Rm}}$), and hence decreased power consumption (decrease in $F_{I_{R}}$). The decrease in suction pressure shown in Fig. 7 is quite small—around 200 kPa—but it does follow the expected trend. The effects on most variables in Fig. 8 are not particularly severe. For TXV-equipped systems, the effects are similar except that the TXV regulates the superheat.

The effects on capacity and COP in Fig. 8 show quite a lot of variation. This suggests that potentially there are explanatory variables that are not considered in the model (i.e. true variation in performance from one system to the next), measurement error, or analysis errors. Therefore, the models of $F_{I_{RQ}}$ and $F_{I_{RCOP}}$, in particular, are less certain than others.

3.2.2. **Heating mode**

Fig. 9 shows the effect of $F_{I_{EA}}$ on normalized variables in a TXV-equipped system (Domanski et al., 2014) under two operating conditions in heating mode. The evaporator in heating mode is the outdoor coil. Regression coefficients and mean values are not provided for $F_{I_{EA}}$ in heating mode because there are not enough systems that have been studied.

3.3. **LL fault**

A liquid line restriction could be caused by, for example, a crimp in the liquid line or debris in a filter/drier. It is simulated in a laboratory by installing an adjustable valve in the liquid distribution system.

3.3.1. **Cooling mode**

From the data for an FXO-equipped system in Breuker and Braun (1998) and a TXV-equipped system in Kim et al. (2006), the effect of $F_{I_{LL}}$ on system performance is plotted on T-s and P-h diagrams in cooling mode in Figs. 10 and 11. The evaporator in heating mode is the outdoor coil. Regression coefficients and mean values are not provided for $F_{I_{LL}}$ because there are not enough systems that have been studied.

3.3.2. **Heating mode**

Fig. 12 shows the effect of $F_{I_{LL}}$ on normalized variables in a TXV-equipped system (Domanski et al., 2014) under two operating conditions in heating mode. The evaporator in heating mode is the outdoor coil. Regression coefficients and mean values are not provided for $F_{I_{LL}}$ because there are not enough systems that have been studied.

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**Fig. 11** – T-s and P-h diagrams showing the effect of $F_{I_{LL}}$ on a vapor compression cycle for systems equipped with a TXV.
Fig. 12 – Effect of \( F_{IL} \) on normalized variables in cooling mode: a) FXO, b) TXV.
Fig. 13 – Effect of Fl_{LL} on normalized variables in heating mode for a TXV-equipped system.

Fig. 14 – T-s and P-h diagrams showing effect of Fl_{VL} on a vapor compression cycle for systems equipped with FXO.
Fig. 15 – T-s and P-h diagrams showing effect of $F_{IVL}$ on a vapor compression cycle for systems equipped with TXV.

Fig. 16 – Effect of $F_{IVL}$ on normalized variables in cooling mode for an FXO- and a TXV-equipped system.
3.3.2. Heating mode
Fig. 13 shows the effect of FILL on normalized variables in a TXV-equipped system (Domanski et al., 2014) operating at two conditions in heating mode. In both operating conditions, there is no significant error on any of the normalized variables. It might be attributed to the effect of TXV that can compensate the effect of liquid line restriction.

3.4. VL fault
Compressor leakage allows hot gas from the high pressure side to leak back to the low pressure side, such as by valve leakage in a reciprocating compressor, or radial and tangential leakage in a scroll compressor, for example (Ishii et al., 2016). It is simulated in laboratory experiments by piping a path from discharge to suction, with an adjustable valve in the path.

3.4.1. Cooling mode
From the data for an FXO-equipped system in Breuker and Braun (1998), and a TXV-equipped system in Kim et al. (2006), the effect of FIVL on system performance is plotted on T-s and P-h diagrams, in cooling mode in Figs. 14 and 15.

Fig. 16 shows the effect of FIVL on normalized variables for an FXO- and a TXV-equipped system. For FXO-equipped systems, compressor valve leakage causes reduced discharge pressure and increased suction pressure, hence reduced suction superheat (decrease in ResidualSH). For TXV-equipped systems, the TXV regulates superheat, decreasing the mass flow rate (decrease in FIRm) slightly more than for the FXO-equipped system.

3.4.2. Heating mode
Fig. 17 shows the effect of FIVL on normalized variables for the TXV-equipped system in heating mode measured by Domanski et al. (2014). In heating mode, the system is fairly insensitive to valve leakage, particularly at the H1 test condition.

Fig. 17 – Effect of FIVL on normalized variables in heating mode for a TXV-equipped system.
3.5. NC fault

Non-condensable gas faults can occur if air or nitrogen is not properly purged from a system prior to charging, for example. They are typically simulated by adding nitrogen gas to the system. From the data in RMA (2016) the effect of FINC on system performance in cooling mode is plotted on T-s and P-h diagrams in Figs. 18 and 19.

Fig. 20 shows the NC fault causes increased discharge pressure and power consumption (increase in FIRPWR).

Although there are not enough data for LL, VL and NC faults to do the statistical treatments described in the methodology section, a set of least squares regressions was conducted for these faults in cooling mode. The regression coefficients are presented in Table 7. Users should consider the small sample size associated with these regression models, which makes their accuracy and representativeness uncertain, before deploying them.

4. Summary and conclusions

The effects of CA, EA, LL, VL, and NC faults on the performance of air conditioners and heat pumps have been studied using existing experimental results in the literature. The dependent and independent variables have been normalized to enable comparisons between systems. Generalized relationships between fault intensity and normalized variables were
developed using two different statistical treatments. The coefficients of regression models relating FI to normalized values, as well as the average and standard deviation values at several discrete points, are presented in tables.

It would be advantageous to have larger datasets. There is some variation in the relationships, which translates to less certainty in the models. Larger datasets would clarify whether the variation is due to outliers or actual differences in the

Fig. 20 – Effect of $F_{\text{NC}}$ on normalized variables in cooling mode: a) FXO, b) TXV.
relationships from one system to another. Particularly for systems in heating mode and systems with LL, VL, and NC faults there are too few datasets to conduct the statistical analyses developed for this paper.

The similarity of results in many cases is remarkable considering that they come from different systems, both split and packaged, from different manufacturers, employing different refrigerants and compressor types. An informal examination has shown no clear trends with respect to rated efficiency of the systems, so it seems reasonable to use these models for new systems. However, it is likely that newer systems with microchannel condensers will respond differently to many faults.

The models presented in this paper predict the effect of faults on several performance variables. The models are directional; they do not inherently have the capability to predict the fault type or fault level given a set of effects on performance variables, such as what might be done in a fault detection and diagnosis algorithm.

Among the faults presented in this paper, several can cause very significant reductions in performance. Typically, the cost associated with faults is larger for equipment wear than it is for increased energy consumption (particularly in the US), so these large impacts are quite serious. However, an important piece of information that is not currently well understood is how common faults are in field-deployed systems, as a function of FL.

<table>
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<th>Normalized Variable</th>
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<th>Parameter</th>
<th>Applicable Range</th>
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**REFERENCES**


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