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Normalized effect of condenser fouling and refrigerant charge on performance of vapor compression air conditioning systems

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ABSTRACT

Several laboratory experiments have studied the effect of faults on vapor compression cycle air-conditioning systems. There has been a particular focus on refrigerant charge variation, which is believed to be quite common in air conditioners, and a lesser focus on heat exchanger fouling. The majority of the published results evaluate the fault effects on particular system operating parameters in one unit. For example, the effect on capacity and efficiency are typically evaluated. The results differ from one study to the next. The current paper summarizes the effects for all of the results available in the literature for condenser fouling and refrigerant charge variation, and provides normalized relationships. The normalizations are provided for ANSI/AHRI 210/240 standard test conditions and are provided separately for fixed orifice and thermostatic expansion valve equipped systems. The level of variation found in the summary shows that for many applications, it is reasonable to the use normalized relationships to estimate the effect of faults on systems that have not been tested in a laboratory.

1. INTRODUCTION

Unitary air conditioners are prone to be affected by several types of fault, which can significantly degrade their performance and efficiency. Several laboratory experiments have been carried out to measure the fault effects on air conditioner performance. In the current paper, refrigerant charge and condenser faults have been studied in the existing literature, to find normalized relationships between fault type, fault intensity and several standardized performance variables. These relationships can be used to estimate the effect of the refrigerant charge and condenser faults on the other systems that will have not been tested under fault conditions in a laboratory. The remainder of this section provides a summary of the literature describing the experimental studies from which our results are derived.

O’Neal and Farzad (1990 and 1991) and Farzad and O’Neal (1993) studied an FXO-equipped split system, with R22 refrigerant, and 10.6 kW of cooling capacity. They imposed refrigerant charge faults under A and B test conditions, based on AHRI standard 210/410 (2008). The test conditions are described in format of “return air dry bulb temperature/return air wet bulb temperature/outdoor dry bulb temperature”. These values for A and B test conditions are 26.7/19.4/35 °C and 26.7/19.4/27.8°C respectively. Farzad and O’Neal (1993) also studied refrigerant charge faults on the same unit, but equipped with a TXV expansion valve. This unit is referred as Farzad and O’Neal (1993) in the current paper.

Breuker and Braun (1998a, and 1998b) studied a TXV-equipped RTU with reciprocating compressor, R22 refrigerant, and 10.6 kW of cooling capacity. They imposed both refrigerant charge and condenser faults under test conditions of 23.3/15.6/20, 23.3, 26.7, 30, 32.2°C. Gowsami et al. (2001) studied refrigerant charge faults on a TXV-equipped split system with reciprocating compressor, R410A refrigerant, and 10.6 kW of cooling capacity in the A test condition.
Shen (2006) studied three different units by imposing both refrigerant charge and condenser faults. Unit A is a split system with reciprocating compressor, R410A refrigerant and 10.6 kW of cooling capacity, which was studied using both FXO and TXV expansion valves. The FXO tests were performed in A and B test conditions for the refrigerant charge fault, and A test condition for the condenser fault. The TXV tests were performed under A test conditions for refrigerant charge faults, and 27.8/19.4/36.1°C for condenser faults. Unit B is an FXO-equipped RTU with scroll compressor, R410A refrigerant and 10.6 kW of cooling capacity. Unit C is an FXO-equipped RTU with scroll compressor, R407C refrigerant, and 17.6 kW of cooling capacity. Unit B and unit C measurements were conducted mostly on A and B test conditions for the refrigerant charge fault, and B test condition for the condenser fault.

Kim et al. (2006, 2009), Domanski et al. (2014) and Cho et al. (2014) investigated a TXV expansion valves. The tests were conducted mostly on B test condition. This unit is referred as Kim et al. (2006) in the current paper. Kim et al. (2008) imposed refrigerant charge faults on three different units, mostly in A and B test conditions. Unit A is an FXO-equipped split system with scroll compressor, R22 refrigerant and 10.6 kW of cooling capacity. Unit B is a TXV-equipped unit with the similar specifications, and Unit C is a similar unit, except using R410A as refrigerant.

SCE (2009) studied a TXV-equipped RTU with scroll compressor, by imposing both refrigerant charge and condenser faults in the A test condition. The tests on the condenser fault are based on very light (1-ply), light (one 2-ply), medium (two 2-ply) and heavy (three 2-ply) tissue papers. Raj and Lal (2010) investigated the effect of charge fault on a window system with reciprocating compressor, FXO unit and 5.23 kW of cooling capacity, using two types of refrigerants alternately. The first refrigerant was R22, and the other one, which was named M20, was combination of 80% of R407C and 20% of hydrocarbon refrigerants. The tests were conducted in A test condition, as well as couple of other test conditions.

Kim and Braun (2012) studied the effect of charge faults on six air conditioning units. The measurements for A, B, C and D units were collected from a manufacturer company, and E and F units were studied and measured by the authors. Unit A is a split system with tandem compressors, R22 refrigerant, EEV (electronic expansion valve) and 14.5 kW of cooling capacity. Unit B is an FXO-equipped split system with rotary compressor, R22 refrigerant, and 15.2 kW of cooling capacity. Unit C is an FXO-equipped split system with reciprocating compressor, R22 refrigerant, and 14.5 kW cooling capacity. Both B and C units were studied with and without accumulators. They are named in the current paper as B1, C1 and B2, C2 for without and with accumulator respectively. Unit D is an FXO-equipped split system with tandem compressor, R22 refrigerant, and 14.5 KW of cooling capacity. The measurements for A, B, C and D units were conducted in A test condition. Unit E is a TXV-equipped split system with scroll compressor, R22 refrigerant, and 10.5 kW of cooling capacity. The measurements on this unit were conducted at 20/16/10, 35, 45°C. Unit F is a TXV-equipped split system with scroll compressor, R410A refrigerant, and 10.5 kW of cooling capacity, imposing the faults at 21/17/4, 35, 51°C, 27/19/4 °C and 32/21/4°C.

Mowris et al. (2012) studied an FXO-equipped split system with R22 refrigerant, and 10.55 kW of cooling capacity. They imposed both refrigerant charge and condenser faults on hot attic test condition (26.7/19.4/27.8°C). Qureshi and Zubair (2014) studied a TXV-equipped split system with R22 refrigerant and 5.27 kW of cooling capacity. They imposed the condenser fault at 21/NA/31.6°C.

2. METHODOLOGY

In the current paper, the relationships between the fault intensities and the normalized values are analyzed for refrigerant charge and condenser faults, based on the above mentioned laboratory experiments. The charge fault measurements are analyzed focusing on a test condition. Since the measurements are limited on the condenser fault, all the test conditions are considered, except for Breuker and Braun (1998 a, b) data, for which just the 23.3/15.6/26.7°C test condition is analyzed.

2.1 Normalized Values

Normalized values are used in the current paper to standardize the fault quantification and the system effect variables for each study. Fault intensity (FI) defined by Yuill and Braun (2013), is applied to quantify fault severity based on Equations 1 and 2.
The normalized values for the system effect variables are defined with fault impact ratio (FIR) for Q and COP, which are defined in Equation 3 and 4 based on Yuill and Braun (2013), and a Residual for suction superheat (SH), which is defined in Equation 5.

\[ FIR_Q = \frac{Q_{faulted}}{Q_{nominal}} \]  
\[ FIR_{COP} = \frac{COP_{faulted}}{COP_{nominal}} \]  
\[ \text{Residual}_{SH} = SH_{faulted} - SH_{nominal} \]

The relationship between FI and normalized values in the studied literature are presented in Figure 2 for the refrigerant charge fault, and Figure 4 for the condenser fault.

2.2 Normalized Relationships

To provide normalized relationships, we applied 2\textsuperscript{nd} order polynomial regressions using the ordinary least squares method to relate FI values to the normalized variables. The process described below was executed for each combination of: normalized variable; fault type; and expansion valve (e.g. a regression model was generated for FIR\textsubscript{Q} versus FI\textsubscript{CH} in TXV-equipped units).

1- For each experiment, a regression is fitted to generate a model
2- The regression model is applied to input values of FI in increments of 0.01 throughout the model’s range to calculate normalized values (e.g. FIR\textsubscript{Q} etc.)
3- At each FI increment, the model values from each system within a set are averaged, creating a new series
4- A final 2\textsuperscript{nd} order polynomial regression model is generated from the new series of mean values

The reason for using this procedure instead of simply using the entire data set for a regression model is that the number of measurements and the range of FI values vary from one experiment to the next. The method above ensures that each air-conditioning unit measured in a given range has equal weighting within the final regression model.

The resulting regression model curves are shown on Figures 2 and 4 with a thick transparent line. The regression model coefficients are tabulated in Tables 1 and 3, based on Equation 6. This form of normalized results is continuous, and suitable for inclusion in an energy simulation model, for example.

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

We have also used a different statistical approach to generate a table of values for fault-induced degradation at discrete FI levels in increments of 0.1. This approach can answer the question: how much degradation can be expected at a given FI, and how much variation will in this degradation quantity for a large set of air-conditioning units? Mean values and standard deviations of normalized variables for FI from -0.4 to 0.2 are presented in Tables 2 and 4. In calculating these values, we conducted linear interpolations between each measured point in the data sets to get a value for a discrete FI value (unless there happened to be a measurement made at that exact point).
3. RESULTS AND DISCUSSION

3.1 Charge Faults

Undercharge and overcharge are treated together as a continuous variable, so that $FI_{CH} = 0$ is the unfaulted condition. Figure 1 demonstrates the effect of $FI_{CH}$ on a temperature entropy (T-s) diagram, for both FXO and TXV-equipped units, based on data from Kim et al. (2008) unit A and unit B, respectively. A comparison of these plots shows how effective a TXV can be at accommodating charge variation.

Figure 1: Effect of $FI_{CH}$ on a vapor compression cycle for FXO and TXV systems

The charts in Figure 2 show the effect of $FI_{CH}$ on $FIR_Q$, $FIR_{COP}$, and $Resid_{SH}$, both in FXO and TXV-equipped units. The thicker transparent curve in each graph demonstrates the calculated quadratic regression, which was discussed earlier.
As demonstrated in Figure 2, in FXO-equipped units, the FIR₀ decreases sharply when the FIₐ is less than 0. In TXV-equipped units, the effect of FIₐ on FIR₀ is negligible for FIₐ values of more than -0.2. In this range, the TXV regulates the refrigerant flow rate to the evaporator to maintain superheat, which keeps the evaporator’s heat transfer quite steady. For FIₐ values less than -0.2, as FIₐ decreases, FIR₀ decreases, since in this range the TXV is totally opened and cannot further regulate the refrigerant flow rate to the evaporator.

In the FXO-equipped units, FIR_COP is at a maximum when FIₐ is 0. It decreases more steeply for undercharge. The effect is similar, but much smaller for TXV-equipped units.

**Figure 2:** Effect of FIₐ on FIR₀, FIR_COP and Residuals for a) FXO and b) TXV-equipped units
In the FXO-equipped units, as Fl\textsubscript{CH} increases, Residual\textsubscript{SH} decreases. In some experiments, for high Fl\textsubscript{CH} values, the curve becomes flat, since the SH cannot be less than zero, so the Residual\textsubscript{SH} has a lower limit. In TXV-equipped units, the effect is negligible except for Fl\textsubscript{charge} values less than -0.2, which has a small increasing effect, since as mentioned before, the TXV in this range cannot regulate the refrigerant flow rate to regulate the SH.

Table 1 demonstrates the coefficients of the quadratic regression of normalized variables versus Fl\textsubscript{CH}, based on Equation 6. Table 2 demonstrates the mean value and standard deviation of normalized variables, for a range of discrete values of Fl\textsubscript{CH}. For example at 20% undercharge (Fl\textsubscript{CH} = -0.2) the FXO systems produce 81.4% of their nominal cooling capacity with a standard deviation of 2.6%. For the systems studied, use of the mean values would typically result in standard deviation of up to 8% when used to predict FIR\textsubscript{Q} and FIR\textsubscript{COP}.

**Table 1**: Coefficients of quadratic regression of normalized variables versus Fl\textsubscript{CH}, based on Equation 6

<table>
<thead>
<tr>
<th>Normalized Variable</th>
<th>Expansion Valve Type</th>
<th>a\textsubscript{0}</th>
<th>a\textsubscript{1}</th>
<th>a\textsubscript{2}</th>
<th>Applicable Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIR\textsubscript{Q}</td>
<td>FXO</td>
<td>0.9708</td>
<td>0.4306</td>
<td>-1.4246</td>
<td>-0.5 ≤ Fl\textsubscript{CH} ≤ 0.3</td>
</tr>
<tr>
<td></td>
<td>TXV</td>
<td>0.99532</td>
<td>0.07739</td>
<td>-0.43953</td>
<td>-0.4 ≤ Fl\textsubscript{CH} ≤ 0.3</td>
</tr>
<tr>
<td>FIR\textsubscript{COP}</td>
<td>FXO</td>
<td>0.9722</td>
<td>0.2434</td>
<td>-1.3731</td>
<td>-0.47 ≤ Fl\textsubscript{CH} ≤ 0.3</td>
</tr>
<tr>
<td></td>
<td>TXV</td>
<td>0.98807</td>
<td>-0.05897</td>
<td>-0.54048</td>
<td>-0.4 ≤ Fl\textsubscript{CH} ≤ 0.3</td>
</tr>
<tr>
<td>Residual\textsubscript{SH} [\degree C]</td>
<td>FXO</td>
<td>0.3916</td>
<td>-41.0831</td>
<td>20.0159</td>
<td>-0.47 ≤ Fl\textsubscript{CH} ≤ 0.3</td>
</tr>
<tr>
<td></td>
<td>TXV</td>
<td>0.08068</td>
<td>-0.48767</td>
<td>7.55179</td>
<td>-0.4 ≤ Fl\textsubscript{CH} ≤ 0.25</td>
</tr>
</tbody>
</table>

**Table 2**: Mean value and standard deviation for normalized variables at discrete values of Fl\textsubscript{CH}, using linear interpolation

<table>
<thead>
<tr>
<th>Normalized Variable</th>
<th>Expansion Valve Type</th>
<th>Fl\textsubscript{CH}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.4</td>
<td>-0.3</td>
</tr>
<tr>
<td>FIR\textsubscript{Q}</td>
<td>FXO</td>
<td>0.564</td>
</tr>
<tr>
<td></td>
<td>TXV</td>
<td>-</td>
</tr>
<tr>
<td>FIR\textsubscript{COP}</td>
<td>FXO</td>
<td>0.660</td>
</tr>
<tr>
<td></td>
<td>TXV</td>
<td>-</td>
</tr>
<tr>
<td>Residual\textsubscript{SH} [\degree C]</td>
<td>FXO</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>TXV</td>
<td>-</td>
</tr>
</tbody>
</table>

### 3.1 Condenser Faults

The charts in Figure 3 demonstrate the effect of Fl\textsubscript{CA} on a T-s diagram, for both FXO and TXV-equipped units, based on data from Shen (2006) unit B and Kim et al. (2006) respectively. Figure 4 shows the effect of Fl\textsubscript{CA} on FIR\textsubscript{Q} and FIR\textsubscript{COP}, both in FXO and TXV-equipped units. The thicker transparent curve in each graph demonstrates the quadratic regression, which was discussed earlier.
Figure 3: Effect of $F_{IC_A}$ on a vapor compression cycle for FXO and TXV systems

Figure 4: Effect of $F_{IC_A}$ on $F_{IRQ}$ and $F_{IRCOP}$ for a) FXO and b) TXV-equipped units

Figure 4 demonstrates that as $F_{IC_A}$ decreases, $F_{IRQ}$ and $F_{IRCOP}$ also decrease for both FXO and TXV-equipped systems, but the slope in TXV-equipped units is slightly sharper. Table 3 gives the coefficients of the quadratic
regression of normalized variables versus $\text{Fl}_{\text{CH}}$, based on Equation 6. Table 4 gives the mean value and standard deviation of normalized variables, for a range of discrete values of $\text{Fl}_{\text{CA}}$. For example at 30% condenser fault ($\text{Fl}_{\text{CA}}$ = -0.3) the TXV systems produce 91.2% of their COP with a standard deviation of 1.5%. For the systems studied, use of the mean values would typically result in standard deviation of up to 6% when used to predict $\text{FIR}_Q$ and $\text{FIR}_{\text{COP}}$.

**Table 3**: Coefficients of quadratic regression of normalized variables versus $\text{Fl}_{\text{CA}}$, based on Equation 6

<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>$\text{FIR}_Q$</td>
<td>FXO</td>
<td>1.01159</td>
<td>0.04234</td>
<td>-0.20512</td>
<td>$-0.8 \leq \text{Fl} \leq 0$</td>
</tr>
<tr>
<td></td>
<td>TXV</td>
<td>1.00298</td>
<td>0.04958</td>
<td>-0.38096</td>
<td>$-0.9 \leq \text{Fl} \leq 0$</td>
</tr>
<tr>
<td>$\text{FIR}_{\text{COP}}$</td>
<td>FXO</td>
<td>1.0077</td>
<td>0.1296</td>
<td>-0.3526</td>
<td>$-0.8 \leq \text{Fl} \leq 0$</td>
</tr>
<tr>
<td></td>
<td>TXV</td>
<td>1.0128</td>
<td>0.2061</td>
<td>-0.5561</td>
<td>$-0.9 \leq \text{Fl} \leq 0$</td>
</tr>
</tbody>
</table>

**Table 4**: Mean value and standard deviation of normalized variables in discrete values of $\text{Fl}_{\text{CA}}$, using linear interpolation

<table>
<thead>
<tr>
<th>Normalized Variable</th>
<th>Expansion Valve Type</th>
<th>$\text{Fl}_{\text{CA}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.5</td>
<td>-0.4</td>
</tr>
<tr>
<td>$\text{FIR}_Q$</td>
<td>FXO</td>
<td>0.937</td>
</tr>
<tr>
<td></td>
<td>TXV</td>
<td>0.879</td>
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<tr>
<td>$\text{FIR}_{\text{COP}}$</td>
<td>FXO</td>
<td>0.865</td>
</tr>
<tr>
<td></td>
<td>TXV</td>
<td>0.767</td>
</tr>
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### 4. CONCLUSIONS

The effects of refrigerant charge and condenser faults on unitary air conditioners have been studied with laboratory measurements. Normalized effects of the faults on normalized variables are presented in this paper based upon an analysis of all available existing data. Polynomial regression models have been created from these data, and demonstrated on the related graph, and the coefficients of the regression functions, as well as the average and standard deviation values in several discrete points, were presented in the separated tables. Based on the average regression curves on the graphs, it can be detected that:

- In the TXV-equipped units, $\text{FIR}_Q$ and $\text{Residual}_{\text{SH}}$ are insensitive to charge variation in the range of $\text{Fl}_{\text{CH}} > -0.2$, because in this range, the TXV regulates the refrigerant flow rate to the evaporator. Also, the effect on $\text{FIR}_{\text{COP}}$ is not very significant. FXO-equipped units, conversely, are very sensitive to $\text{Fl}_{\text{CH}}$. As $\text{Fl}_{\text{charge}}$ increases, $\text{Residual}_{\text{SH}}$ decreases. Also $\text{FIR}_{\text{COP}}$ and $\text{FIR}_Q$ decrease where the $\text{Fl}_{\text{charge}}$ deviates up or down from zero.

- For condenser fault, as $\text{Fl}_{\text{CA}}$ decreases, $\text{FIR}_Q$ and $\text{FIR}_{\text{COP}}$ decrease in both FXO and TXV-equipped units, however the rate in TXV-equipped units is slightly sharper.

These results can serve as a means of predicting fault effects for systems that have not been tested, such as in a building energy simulation.
NOMENCLATURE

CA: condenser fault
CH: refrigerant charge fault
COP: coefficient of Performance
FI: fault Intensity
FIR: fault impact ratio
FXO: fixed orifice expansion valve
m: refrigerant mass
Q: cooling capacity of air conditioner
RTU: rooftop unit
SH: superheat value
TXV: thermostatic expansion valve
\( \dot{V} \): condenser air flow rate

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