Normalization of Test Data for Refrigerant Compressors

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ABSTRACT

In a refrigerant compressor test, we always encounter a small discrepancy between the required setting condition of a calorimeter and its actual condition. This paper presents the methodology of applying Taylor series expansion to test data normalization. Using this normalization, we can adjust calorimeter test data to compensate for errors due to this discrepancy and provide consistency of test results for compressor capacity and performance.

INTRODUCTION

To determine positive displacement refrigerant compressor capacity and performance, ASHRAE standard 23-78 [1] has specified the required data and has established conditions and methods of testing. However, it is up to each individual test facility to determine how to normalize or adjust the data to compensate for errors of various measurement and control devices of calorimeters.

Basically, two types of errors are associated with calorimeter tests. One is due to the accuracy range of measurement devices, and another is due to the limited capability of control devices to maintain the calorimeter cycle under a required test condition. This paper deals with the latter type of error and presents the methodology for normalizing compressor capacity and performance test data.

The basis of our test data normalization is Taylor's theorem [2]. In this application, since the first order terms of Taylor series expansion become dominant, we are going to use Taylor series expansion in the linearized form as

\[
y(x_1, x_2, ..., x_n) = y(a_1, a_2, ..., a_n) + \sum_{i=1}^{n} \frac{\partial y(a_1, a_2, ..., a_n)}{\partial x_i} (x_i - a_i)
\]

where \( x_i \) is close to \( a_i \), the function \( y \) depends on \( n \) variables \( x_1, x_2, ..., x_n \), and \( y \) is differentiable to the first order around the point \( (x_1 = a_1, x_2 = a_2, ..., x_n = a_n) \).

REFRIGERATION CYCLE IN CALORIMETER TEST

In a refrigerant compressor performance test, the compressor becomes an element in the refrigeration system. To demonstrate the normalization of capacity, power and energy efficiency ratio (EER), let's use the ideal refrigeration system, as an example, to derive their expressions. These expressions can then be applied in our normalization using Equation (1).

A schematic diagram of the refrigeration system is shown in Figure 1 and its P-h diagram is shown in Figure 2. In this system we choose test control variables as: refrigeration mass flow rate \( (m_r) \), evaporator pressure or compressor suction pressure \( (P_s) \), compressor suction superheated vapor temperature \( (T_s) \), condenser pressure \( (P_d) \), and sub-cooled liquid temperature at the condenser exit.
(T_c). Let's further assume the compression process to be isentropic so that the state at point (d) in the
cycle is determined. As a result, the system can be fully defined by the five control variables above.

Figure 1. Schematic Diagram for Refrigeration System

By definition [3], compressor capacity (q) is the product of the refrigerant mass flow rate (m_s) and the
difference between the specific enthalpy of refrigerant vapor entering the compressor (point s) and
that of sub-cooled refrigerant liquid at condenser pressure (point c), and can be expressed by

\[ q = m_s (h_s - h_c) \]  

(2)

where specific enthalpy \( h_s \) is a function of \( T_s \) and \( P_s \), and specific enthalpy \( h_c \) is a function of \( P_d \) and
\( T_c \). Suppose the compressor volumetric displacement rate and volumetric efficiency near a set
condition are constant, then the rate of the refrigerant vapor flow entering the compressor varies
inversely as the specific volume of the refrigeration vapor. In other words, the vapor mass flow rate
(m_s) becomes also a function of \( T_s \) and \( P_s \). As a result, the capacity becomes a function of control
variables \( T_s, P_s, P_d, T_c \).

\[ q = f_q(T_s, P_s, P_d, T_c) \]  

(3)
Similarly, to compress the vapor refrigerant from the suction state (point s) to the discharge state (point d), the required power for isentropic compression is a function of $T_s$, $P_s$, and $P_d$

$$w = f_w(T_s, P_s, P_d)$$ \hspace{1cm} (4)

The compressor performance, EER, by definition, is the ratio of capacity to power

$$EER = \frac{q}{w}$$ \hspace{1cm} (5)

Equations (3), (4), and (5) show capacity, power and EER as functions of selected control variables. With these expressions and variables, we can then apply Equation (1) for test data normalization.

Notice that in reality, there are various losses in the refrigeration cycle, such as over- or under-compression losses, pressure drops in the lines, etc. In addition, there are cycles which have economizer processes or other multi-stage compression processes. Control variables may also be selected differently from one calorimeter setting to another. Equations (3), (4) and (5) will differ accordingly. Nevertheless, the general approach to normalization acquired data presented in this paper should remain the same.

**TEST DATA NORMALIZATION**

Given capacity, power, and EER expressions and their control variables, we can process the test data normalization using linearized Taylor series expansion (Equation 1). In the following equations, the superscript $n$ stands for the normalized condition and $a$ for the actual test condition.

Applying Equation (1) to Equation (3), normalized capacity condition becomes

$$q^n \bigg|_{T_s^n, P_s^n, P_d^n, T_c^n} = q^a \bigg|_{T_s^a, P_s^a, P_d^a, T_c^a} + \frac{\partial f_q}{\partial T_s} \bigg|_{T_s^n, P_s^n, P_d^n, T_c^n} (T_s^n - T_s^a)$$

$$+ \frac{\partial f_q}{\partial P_s} \bigg|_{T_s^n, P_s^n, P_d^n, T_c^n} (P_s^n - P_s^a) + \frac{\partial f_q}{\partial P_d} \bigg|_{T_s^n, P_s^n, P_d^n, T_c^n} (P_d^n - P_d^a)$$

$$+ \frac{\partial f_q}{\partial T_c} \bigg|_{T_s^n, P_s^n, P_d^n, T_c^n} (T_c^n - T_c^a)$$ \hspace{1cm} (6)

where values of partial derivative terms on the right hand side of the equation represent sensitivities of capacity with respect to control variables $T_s$, $T_c$, $P_s$, and $P_d$, respectively, and these partial derivatives can be numerically calculated.

Understanding sensitivities to each control variable will help us to set more reasonable tolerances for control devices and to eliminate the time spent on unnecessary adjustments. The normalization process can be used to compensate for errors and provide consistency of results.

Let's introduce a normalization factor for the capacity ($NF_q$), which can be defined by

$$q^n = (1 + NF_q) q^a$$ \hspace{1cm} (7)

or
The normalization factor represents a correction magnitude of the normalization process. It can be used to determine if the test condition is close enough to the specified condition therefore assessing the quality of test results.

Similarly, when Equation (1) is applied to Equation (4), normalized power becomes

\[
N_{F_w} = \frac{\frac{q^n - q^a}{q^a}}{q^n} = \frac{\Delta q}{q^a}
\]  

(8)

Again, values of partial derivative terms on the right hand side of the equation represent sensitivities of compression power with respect to control variables \(T_s\), \(P_s\), and \(P_d\), respectively, and they can be numerically calculated.

The normalization factor for power \((N_{F_w})\) is defined by

\[
\frac{w^n}{T_s^a, P_s^a, P_d^a} = \frac{w^a}{T_s^a, P_s^a, P_d^a} + \frac{\partial f_w}{\partial T_s}\bigg|_{T_s^a, P_s^a, P_d^a} (T_s^n - T_s^a) + \frac{\partial f_w}{\partial P_s}\bigg|_{T_s^a, P_s^a, P_d^a} (P_s^n - P_s^a) + \frac{\partial f_w}{\partial P_d}\bigg|_{T_s^a, P_s^a, P_d^a} (P_d^n - P_d^a)
\]  

(9)

Using the following approximate relationship

\[
\Delta EER = \frac{w^n \Delta q - q^a \Delta w}{(w^a)^2}
\]  

(14)

with Equations (8), (11) and (5), the expression for \(N_{F_{EER}}\) can be reduced to

\[
N_{F_{EER}} = N_{F_q} - N_{F_w}
\]  

(15)

In other words, to calculate \(EER^n\), we don't have to calculate the partial derivatives as we do for \(q^n\) and \(w^n\). We can first calculate \(N_{F_{EER}}\) and then use Equation (12) to determine \(EER^n\).
To demonstrate the effect of normalization, we begin by applying typical test condition variation to an ideal cycle. Table 1 shows differences of reduced test data with and without normalization. In these calculations, system condition for the ideal refrigeration cycle is 45/130/20/15 (ARI condition), where 45 stands for the evaporator saturation temperature; 130 for condenser saturation temperature; 20 for degrees of vapor superheated at the compressor suction inlet; and 15 for degrees of liquid sub-cooling at condenser exit. A constant volumetric displacement rate is assumed. HFC-134a chlorine-free refrigerant is used for property calculations. Actual test deviations from ARI condition are: 1.0 F additional superheated, 1.0 F additional sub-cooling, and both evaporator and condenser pressure shifted 0.5 PSIA higher.

Table 1: Data Normalization at ARI Condition

<table>
<thead>
<tr>
<th>Setting (ARI)</th>
<th>q (BTU/HR)</th>
<th>w (Watts)</th>
<th>EER (BTU/HR-W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Data</td>
<td>3795.83</td>
<td>226.93</td>
<td>16.73</td>
</tr>
<tr>
<td>Normalized Data</td>
<td>3795.67</td>
<td>226.94</td>
<td>16.73</td>
</tr>
<tr>
<td>% Error, Actual Data</td>
<td>1.51912</td>
<td>0.38804</td>
<td>1.12671</td>
</tr>
<tr>
<td>% Error, Normalized Data</td>
<td>-0.00406</td>
<td>0.00167</td>
<td>-0.00575</td>
</tr>
<tr>
<td>% Normalized Factor</td>
<td>-1.50039</td>
<td>-0.38486</td>
<td>-1.11553</td>
</tr>
</tbody>
</table>

Notice that data normalization reduces the errors for capacity and EER from about 1.5 % and 1.1 % to 0.004 % and 0.006 %, respectively, which practically eliminates the errors.

Normalization factors are also listed in this table. To provide a better understanding of these normalization factors, $NF_q$ and $NF_{EER}$ with respect to each individual control variable $T_s$, $T_c$, $P_s$, and $P_d$ were also calculated and are shown in Figure 3. When the change of a control variable is equal to 1.0, the value of NF shows the sensitivity of test data with respect to that variable. Figure 3 illustrates that capacity and EER are more sensitive to $P_d$ and $T_c$ than $T_s$ and $P_s$, which means their allowable variation should be set lower in a calorimeter test.

Figure 3. Normalization Factors with Respect to Control Variables
For an actual test case, compressor power will be elevated by a factor corresponding to the inverse to the overall isentropic efficiency. This will appear as a constant in the power expression (Equation 4). As we did for the volumetric efficiency, we assume the isentropic efficiency is also constant near the set point. The result for normalization factors in Figure 3 will remain the same for the given test condition. It is up to the individual test engineer to determine the actual variation of the isentropic efficiency of a given compressor design with the operating condition near the set point and to set reasonable limits on the normalization factor.

SUMMARY OF NORMALIZATION PROCEDURE

Data normalization of calorimeter test data for a refrigerant compressor can be performed by applying a linearized Taylor series expansion. The procedure for normalizing data is:

- Understand the calorimeter system and select its control variables
- Derive capacity and power expressions as functions of the selected control variables (Equations 3 and 4)
- Acquire test data at the actual condition (approximately the required condition)
- Calculate corresponding partial derivative terms as in Equations (6) and (9) using appropriate numerical schemes and refrigerant property routines
- Calculate \( q^o, q^a, NF_q \) and \( w^o, w^a, NF_w \) using Equations (6) through (11)
- Calculate \( EER^o, NF_{EER}, EER^a \) using Equations (5), (15) and (12)

CONCLUSION

Test data normalization can be a useful tool to help us understand the calorimeter test and provide consistency of results. Knowing the sensitivities to each control variable ensures that testing is accomplished efficiently. Calculating normalization factors will show the correction magnitude, and therefore help us assess the quality for test results. Hopefully, the simple procedures provided in this paper will help us apply data normalization more effectively.

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REFERENCES