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PROCEDURE FOR THE ERROR ANALYSIS OF A SECONDARY REFRIGERANT COMPRESSOR CALORIMETER

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ABSTRACT

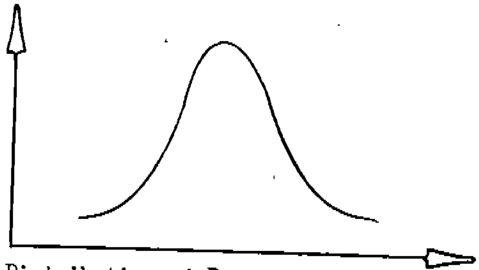
A method is presented for tabulating the components of error that each test and control parameter contributes to the overall uncertainty of a secondary refrigerant type compressor calorimeter. The contributing components are combined by a root-sum-square procedure to yield the overall uncertainty of the test results. Each component of error includes both the uncertainty of each measurement or control parameter and the sensitivity of the test compressor to that parameter.

INTRODUCTION

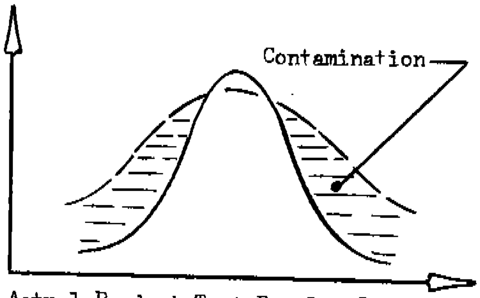
Instrumentation and test methods are rapidly changing today due to the influx of new higher precision and accurate instrumentation. The costs, performance and adaptability vary widely and to choose the highest performance and most flexible instrumentation system proves to be very expensive. Even then, occasionally the results are disappointing.

Reviewed here is a method of tabulating the components of measurement uncertainty and combining the components into an estimate of the overall test result uncertainty. Some components are found to be very small and relatively inexpensive instruments can be used. To the other extreme, special in-house instruments may have to be developed for large components in order to meet an overall accuracy goal.

The overall measurement uncertainty needed to establish a goal are determined with product and test engineers according to their needs. The product engineer needs test results that are indicative of his product only. What he gets from a test result is the product variability plus contamination due to instrumentation uncertainty and technician error. To filter out the contamination as well as understand the product variability, several samples are tested and classical statistical analysis is done. Testing of large sample sizes can be an expensive way of filtering out instrument errors. Therefore, the overall cost of testing depends on the trade off made between the cost of testing numbers of product to establish a certain confidence in the result versus the cost of the instrumentation system that minimizes the desired uncertainty in the test method.



Distribution of Performance Results Due to Product Varibility Alone.



Actual Product Test Results Including Product Variability Plus Instrument Uncertainty.

ACCURACY AND PRECISION

With every measurement there is a variability or uncertainty. This is due to inherit inaccuracies and everpresent lack of precision to some degree. Inaccuracies appear as systematic or fixed errors yielding results containing a bias. Common sources of inaccuracy are insufficient traceable calibration source or procedure, inaccuracy in instrumentation when operating off calibration points, and inherit loading one instrument will induce in a second. For example, a volt meter used to monitor power to a compressor requires power that an upstream watt meter measures in addition to the compressor power yielding a wattage result biased high. (1) Correction factors can be used to minimize errors of this type but extreme care must be exercised to ensure that random errors don't creep into the correction factor. Random errors can be removed with digital filtering (2).

Precision is a term used to characterize random errors and can be quantified by the use of the standard deviation statistic. (3) Contributions to the deviation occur due to changes with time (day-to-day), space (variations due to location of transducers and instruments), instrumentation (one from another similar instrument) as well as operator inconsistencies. (4)

The following analysis applies to the manipulation of random errors and assumes that bias errors are accounted for by other means.

GENERAL FORMULATIONS

A root-sum-square formulation is used to combine the measure of each parameter uncertainty, sensitivity of the test result to each parameter and the effects of all parameters on the overall result. (5,6)

$$\delta W^{*}=\left[\Sigma\left(\frac{\partial W}{\partial X_i}\cdot\delta X_i\right)^2\right]^{\frac{1}{2}}$$

Or explicitly for the example in Table I:

$$\delta W_c=\left[\left(\frac{\partial W_c}{\partial T_1}\cdot\delta T_1\right)^2+\left(\frac{\partial W_c}{\partial P_s}\cdot\delta P_s\right)^2+\dots+\left(\frac{\partial W_c}{\partial M_c}\cdot\delta M_c\right)^2\right]^{\frac{1}{2}}$$

The partial derivatives are the slopes of sensitivities of W_c to the individual measured parameters (see Appendix B). δX_i is the uncertainty interval for each measured parameter (see Appendix C).

The above formulation can be set up in table form that permits ease of calculation and presents an overall picture of how each measurement or control parameter affects the uncertainty in the overall result.

ERROR ANALYSIS OF CALORIMETER

The performance testing of a compressor on a secondary refrigerant calorimeter requires making two primary measurements -- the wattage to a heater indicating cooling capacity or pumping rate and the wattage draw of the motor. (7)

The calorimeter heater watt-hour measurement, W_c, is a function of many parameters depending on the particular design and construction of the calorimeter.

$$W_c = g\ (T_1, P_s, T_s, T_p, T_r, T_i, P_d, M)$$

Table I shows a listing of the above parameters, the value used (in this case the test point industry frequently uses for R-12, low back pressure compressors), the sensitivity the calorimeter heater has to the parameter, the precision in which the parameter can be controlled (independent parameters) or measured (dependent parameters), and the square of the product of the sensitivity and precision. The numerical values used are not for any specific compressor or instrumentation and are presented here for illustrative purposes only.

In this particular illustrative example, the watt-hour meter is the greatest contributor to the error of the calorimeter heater measurement followed by the discharge pressure. Thus, for this calorimeter greater precision in the watt-hour measurement and better control and measurement of the discharge pressure yields the greatest improvement in system uncertainty.

The compressor motor watt-hour measurement, W_m, can be expressed as:

$$W_m = F\ (P_d, P_s, T_s, T_d, T_i, M_m, V)$$

Table II shows a listing similar to Table I. Again, the numerical values are for illustrative purposes only. The example indicates that the watt-hour meter is the prime contributor to system uncertainty followed by the voltage regulation and the discharge pressure control.

EER UNCERTAINTY

The Energy Efficiency Ratio uncertainty can be established as follows:

$$\text{EER} = W_c/W_m$$

by definition. Using the chain rule of differentiation the uncertainty is:

$$\delta\text{EER} = \left[\left(\frac{\partial\,\text{EER}}{\partial W_c}\cdot\delta W_c\right)^2 + \left(\frac{\partial\,\text{EER}}{\partial W_m}\cdot\delta W_m\right)^2\right]^{\frac{1}{2}}$$

or explicity

$$\delta\text{EER} = \left[\left(\frac{\delta W_c}{W_m}\right)^2 + \left(\frac{-W_c}{W_m^2}\cdot\delta W_m\right)^2\right]^{\frac{1}{2}}$$

Using values from Tables I and II yields

EER = ± 0.013 W/W,

the uncertainty in the energy efficiency ratio.

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* See Appendix A for definition of symbols used.

TABLE I:

ESTIMATION OF THE UNCERTAINTY OF THE CALORIMETER HEATER WATT-HOUR MEASUREMENT

PARAMETER X_i	PARAMETER VALUE	SENSITIVITY $\frac{\partial W_c}{\partial X_i}$	UNCERTAINTY $\pm \delta X_i$	$[\frac{\partial W_c}{\partial X_i} \cdot \delta X_i]^2$
Liquid Temp., T_l	32.2°C	1.1W/°C	± 0.10°C	0.012
Suction Press., P_s	31 kPa	0.6 W/kPa	± 0.40 kPa	0.058
Suction Gas Temp., T_s	32.2°C	0.7 W/°C	± 0.10°C	0.005
R-114 Temp., T_p	32.2°C	0.5 W/°C	± 0.10°C	0.003
Room Ambient, T_r	32.2°C	0.1 W/°C	± 0.10°C	0.000
Time of Test, T_i	60 min	0.1 W/sec.	± 1.0 sec.	0.010
Discharge Press., P_d	1250 kPa	0.0 W/kPa	± 7 kPa	0.490
Watt-hour Meter, M_c	150 W	1.0 W/W	± 1.0 W	1.000
				1.578

$$(\delta W_c)^2 = \Sigma\left[\frac{\partial W_c}{\partial X_i} \cdot \delta X_i\right]^2 = 1.58$$

$$\delta W_c = \pm 1.25 \text{ watt-hour}$$

Thus the overall uncertainty in the 150 watt-hour reading is ± 1.3 watt-hours.

TABLE II: ESTIMATION OF THE UNCERTAINTY OF THE COMPRESSOR MOTOR WATT-HOUR MEASUREMENT

PARAMETER X_i	PARAMETER VALUE	SENSITIVITY $\frac{\partial W_m}{\partial X_i}$	UNCERTAINTY $\pm \delta X_i$	$[\frac{\partial W_m}{\partial X_i} \cdot \delta X_i]^2$
Discharge Pressure, P_d	1250 kPa	0.1 W/kPa	± 7 kPa	0.490
Suction Press, P_s	31 kPa	0.6 W/kPa	± 0.3 kPa	0.032
Suction Temp., T_s	32.2°C	3.0 W/°C	± 0.1°C	0.090
Shell Temp., T_d	65°C	0.4 W/°C	± 0.1°C	0.002
Time of Test, T_i	60 min	0.1 W/sec.	± 1.0 sec.	0.010
Voltage, V	115	3.5 W/volt	± 0.2 Volt	0.490
Watt-hour Meter, M_m	150 W	1.0 W/W	± 1.0 W	1.000
				2.11

$$(\delta W_m)^2 = \Sigma \left[\frac{\partial W_m}{\partial X_i} \cdot \delta X_i\right]^2 = 2.11$$

$$\delta W_m = \pm 1.5 \text{ watt-hours}$$

Thus the overall uncertainty in the 150 watt-hour reading is ± 1.5 watt-hours.

CONCLUSIONS

An effective method is illustrated that permits tabulating individual sources of error in a secondary refrigerant calorimeter. The sources are also combined to give an overall calorimeter uncertainty level for use in establishing confidence in test results. The individual tabulated sources of error can be used to show where the greatest errors are so that as improvements in accuracy are sought, for a particular calorimeter, the most effective plan can be implemented. For example, the illustrations indicated the watt-hour meter, voltage and discharge pressure were prime contributors to the overall error. New instrumentation costs can be developed for these three parameters and compared to the improved precision each would give (benefit) from which a cost-benefit ratio can be estimated for use in planning improved test systems.

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APPENDIX A

NOMENCLATURE

EER	Energy Efficiency Ratio or Performance Factor -- Watt/watt
δ EER	Uncertainty in the value of E.E.R.
M_c	Calorimeter heater watt-hour meter -- watt-hour
δM_c	Uncertainty of M_c -- watt-hour
M_m	Compressor motor watt hour meter -- watt hour
δM_m	Uncertainty of M_m -- watt hour
P_d	Compressor discharge -- Pascal pressure
P_s	Compressor suction -- Pascal pressure
T_i	Time of Test -- Seconds
T_d	Temperature of Compressor Shell-- Centigrade.
T_l	Temperature of liquid refrigerant entering expansion valve -- Centigrade
T_p	Temperature of secondary refrigerant in calorimeter -- Centigrade
T_r	Temperature of room in which calorimeter is located -- Centigrade
T_s	Temperature of suction gas -- Centigrade
V	Voltage at the compressor -- Volts
W_c	Calorimeter heater wattage measurement -- Watt-hour
δW_c	Uncertainty of W_c -- Watt-hour
W_m	Compressor motor wattage measurement -- Watt-hour
δW_m	Uncertainty of W_m -- Watt-hour
X_i	Generalized parameter
δX_i	Uncertainty of X_i

APPENDIX B

Determination Of The Sensitivities - $\frac{\partial W_i}{\partial X_i}$

The partial derivative can be estimated as the slope of a curve at the test point conditions being used. (6) For example; the sensitivity to suction pressure, P_s, is the slope of the capacity - vs - suction pressure performance curve for the compressor tested. Another example in Table I is the sensitivity of calorimeter heater to liquid temperature. This is the enthalpy change of the liquid per degree centigrade times the mass flow rate.

APPENDIX C

Parameter Uncertainty Interval -- δX_i

Uncertainty may be defined as the possible value a parameter error may have. (5) Determination of the uncertainty is the most difficult and time consuming aspect of this procedure. An experienced technician frequently knows a reasonable value but with today's high resolution digital meters (8) values for each parameter can be monitored on an existing test system and a standard deviation calculated. Once the standard deviation for each and every parameter is determined they should be adjusted to the same confidence level. (5) Use of the "t" statistic is one possible method. (3) A confidence level of 95% (20 to 1 odds) is used frequently. There are also sampling methods that can be used to obtain uncertainty bands for desired probability levels. (9)