Precision Monitoring of Automotive Compressor Capacity Values Determined From Calorimeter Measurements

J. D. Clark
Sanden International (USA)

Precision Monitoring of Automotive Compressor Capacity Values Determined from Calorimeter Measurements

***James D. Clark**, Lab Project Engineer, Compressor Engineering
Sanden International (USA) Inc., 601 S. Sanden Blvd., Wylie, TX 75098-4999
Ph: (972) 442-8758, Fx: (972) 442-8715, E-Mail: JimClark@sanden.com

ABSTRACT

In routine mobile A/C compressor testing, Secondary Refrigerant Calorimetry and the First Law of Thermodynamics are employed in the determination of calorimeter primary mass flow rate of volatile refrigerants. An energy balance is performed on the secondary refrigerant calorimeter (SRC) to yield the primary system mass flow rate. This term is the ratio of energy transferred as heat into the SRC to the change in specific refrigerant enthalpy across the SRC. It is important that the calculated flow rate be as close as possible to the actual value so that compressor capacity and volumetric efficiency are correctly calculated. The enthalpy terms are determined from thermodynamic property values recorded during system testing, typically several hundred test points. The average flow rate may be calculated by two methods discussed in this work: (1) at each test point (ratio of SRC heat transfer to enthalpy change) and then averaged over all test points or (2) from the SRC test-averaged heat rate divided by the test-averaged enthalpy change. The first method is the *average of ratios* approach (AOR) and the second method is the *ratio of averages* approach (ROA). The ROA calculation is straightforward while the AOR result is shown here to be the product of the ROA and a function that depends on the distribution of numerator and denominator values about their respective means. Identification of the averaging technique used in a given work is important because laboratories' reported values will depend on the technique employed. Also, analysts reporting AOR results will disagree with those reporting ROA results obtained from operations on the same set of data. It is suggested here that for a given set of data the amount of separation between mass flow rate calculated from ROA and AOR indicates the degree of precision of calorimeter measurements. Determination of flow rate ROA and AOR values' separation is of use (1) to those preparing to modify or specify a calculation procedure and (2) to those charged with monitoring the performance of an operational system. Guidelines for use of these calculations to monitor calorimeter precision are provided. The considerations cited here for mass flow calculations may be applied to any set of calculations employing ratios of measured values.

INTRODUCTION

This work was undertaken as a result of discussions between Sanden International (USA) Inc. and one of its suppliers of automotive compressor calorimeter equipment. The discussions concerned the method by which the average system mass flow rate should be calculated and how such a calculation may be used to indicate the state of validation of the calorimeter system. Each of the partners, user and supplier, properly employed thermodynamic First Law analysis in their study. Analysis of compressor calorimeter test data carried out on the respective computers of the partners consistently yielded similar results but not exact agreement of mass flow rate values. This led to internal investigations of calculation techniques by both companies.

Comparison of calculation routines from the two companies showed that (1) one party was carrying out the calculations by a Ratio Of Averages (ROA) procedure, in which parameter values were determined as averages taken over the complete test time and then used in a First Law analysis to give mass flow rate, and (2) the other party was performing the calculations as an Average Of Ratios (AOR) procedure, in which mass flow rate was calculated from the First Law at each test point and then averaged over the complete test time. Each company had assumed that the other was carrying out the calculations in the manner of their own work. Furthermore, each company implicitly assumed that their approach was the only one possible. When the discrepancy was noted, a review of standard statistical texts and of standards organizations' publications did not reveal treatment of the ROA or AOR question. Thus, there appear to be no reference articles or other publications regarding this matter. Initially it was assumed that the topic was of such an ordinary or mundane nature that it was not addressed by the above sources. However, following discussions with individuals within the A/C industry it became clear that the difference between the two techniques is not universally recognized. This determination precipitated the current work.

BACKGROUND: COMPRESSOR MASS FLOW RATE

Laboratory calorimeter testing of mobile air conditioning compressors is an established method for determination of compressor capacity, volumetric and isentropic efficiency, and power requirement. References in this document to calorimeter measurements and testing are with regard to a secondary refrigerant calorimeter as depicted in Figure 1 and further described below. Compressor capacity and efficiency are directly proportional to the refrigerant mass flow rate resulting from compressor operation. Reporting mass flow rate as close as possible to its actual value is thus of great concern to laboratories delivering compressor performance findings. The importance of proper mass flow rate (or capacity) determination is evidenced by the existence of ASHRAE, JIS, and ISO specifications on the allowed difference between measured and calculated flow values. Calculated mass flow rate is determined from an energy balance on the secondary refrigerant calorimeter evaporator vessel. Measured mass flow rate is reported by a flowmeter positioned and operated in the liquid refrigerant stream between the system condenser and expansion valve. Good agreement between these flow values is an indication that the overall measurement capability of the calorimeter is high and helps to ensure that the proper mass flow rate value is reported. The percent difference between the two mass flow rate terms is often referred to as “heat-balance” but is actually a condition imposed on the mass flow rate and is thus also referred to as “mass-balance” or simply “balance”. It is expressly stated in each specification that measurements be made under calorimeter steady-state conditions which implies that all test parameters will have small deviation from their average values throughout the test.

For a compressor calorimeter test to be successful, it is required that suction pressure, discharge pressure, suction superheat degrees, and speed as well as the above noted balance term meet specifications set by the noted societies (ASHRAE, etc.). Employment of these specifications is at the discretion of each laboratory but should be adhered to once the laboratory policy is in place. A certification program such as QS-9000 may enforce the policy. If the test specifications are not met (1) the calorimeter engineer may examine the test compressor for defects or failure, (2) the engineer may investigate such obvious difficulties as failure or drift of the several instruments comprising the calorimeter, (3) or the engineer may simply rerun the test. Each of the three approaches requires the expenditure of test time that will be charged against the calorimeter laboratory schedule.

The first possible problem, compressor defect, is not a function of the test procedure. If a defect is found, it is corrected and the test rerun or if this is not possible the compressor is discarded or replaced.

The second problem, instrumentation, may be addressed by reviewing test parameter outputs and their variation during the test. The parameter values and their variation, perhaps expressed as standard deviation, may be compared to historical data. This approach requires access to a historical database or listing of typical results for the given test conditions.

The last approach, rerun, is often used: it is straightforward, can be carried out by the calorimeter operator, and requires known time expenditure. If, however, the rerun procedure does not yield a set of results within specification the retest time has not contributed to the problem resolution. In addition, parameter averaging techniques employed in the test analysis may yield poor results for the initial test and acceptable results for the second test while each set of data is flawed in the same fashion. For example, a sinusoidally varying parameter, which is undesirable, as noted above, may be averaged to an acceptable value depending on the sinusoidal variation period with respect to the length of the test. While the single-term indicator “balance” gives a warning of the presence of problems at several locations within the calorimeter system, it is possible to achieve a low or zero balance value from a set of data that is far from satisfactory within professional laboratory practice.

Another single-term indicator of the quality of recorded data is obtained from the difference between the two calculated mass flow rates ROA and AOR determined by separate analytical treatments of the test data. This indicator may be employed alone and is also helpful when used in conjunction with the balance term to identify data whose average is within specification but whose deviation about the average value is not acceptable by prudent laboratory standards. It may also be used to monitor the precision of test parameter measurements recorded during calorimeter operation.

The description, derivation and application of this second single-term indicator comprise the remainder of this report.

DETERMINATION OF COMPRESSOR MASS FLOW RATE FROM CALORIMETER TEST RESULTS

Figure 1 is a diagram of a secondary refrigerant calorimeter indicating the system components and direction of fluid flow. The four system components are: (1) compressor, (2) condenser, (3) expansion valve, and (4) evaporator vessel or secondary refrigerant calorimeter (SRC). The figure shows the parameters that are measured and recorded during a typical compressor test. Suction pressure (P_s), suction temperature [superheat degrees] (T_s), compressor speed (N_c), discharge pressure (P_d), and measured mass flow rate [balance] ($m\Re_{meas}$) must meet overall test specifications set by the societies (ASHRAE, etc.) referred to above. The parameters employed in the thermodynamic evaluation of the evaporator vessel are liquid temperature (T_l), energy input to evaporator by resistance heating (Q_h), calorimeter pressure (P_{cal}) [alternatively, the calorimeter temperature may be measured here, note that this is a saturation condition], evaporator ambient temperature (T_a), evaporator exit temperature (T_g), and evaporator exit pressure (P_g).

Figure 1 shows the energy transfer terms to the calorimeter evaporator vessel or SRC. The energy transfer terms are the mass flow term, $m\Re$, multiplied by the entrance and exit specific enthalpy of refrigerant (R134a throughout this work), h_i and h_e respectively; energy added as heat by an electrical resistance device, Q_h; and convection exchange with the SRC surroundings, the overall heat transfer coefficient is UA, the SRC ambient temperature is T_a, and the internal SRC refrigerant saturation temperature is T_{sat}.

Two representations of flow rate

The First Law of Thermodynamics for steady-state applications without work terms and discarding changes in potential and kinetic energy of the refrigerant is

$$\Sigma \text{ Heat Terms } + m\Re\, h_i = m\Re\, h_e \qquad (1)$$

h_i and h_e are the entrance and exit enthalpy values of the refrigerant flowing through the evaporator. The SRC input enthalpy term is evaluated at the liquid saturation condition at the throttling valve temperature, $h_{sat}(T_l)$, and the exit enthalpy is evaluated at the superheated exit condition, $h_{sh}(P_g,T_g)$. The heat terms are given above as resistance input and convection input. The solution of Equation 1 for $m\Re$ is

$$m\Re = [Q_h + UA(T_a - T_{sat})] \;/\; [h_{sh}(P_g,T_g) - h_{sat}(T_l)] \qquad (2)$$

In order to evaluate Equation 2 for $m\Re$, the quantities Q_h, T_a, T_{sat}, P_g, T_g, and T_l are determined from calorimeter test data. Specifications generally call for at least four values to be recorded (separated by 10 to 15 minute intervals) during a steady-state calorimeter test. Unless otherwise stated, the specific testing reported here is composed of 180 points collected at 15 second intervals following an appropriate calorimeter warm-up time. Thus, steady-state testing is carried out for 45 minutes.

The $m\Re$ term may be evaluated by two different treatments of the experimental data: (1) the average of each of the six quantities listed above may be individually calculated over the 45 minute test and then used to evaluate the functional terms of Equation 2, yielding $m\Re$ or (2) the $m\Re$ term of Equation 2 may be evaluated at each of the 180 recorded test points and the average of those evaluations reported. In both cases the employment of Equation 2 requires evaluation of the ratio of quantities each determined from experimental data. The first treatment is the *ratio of averages* (ROA) method and the second treatment is the *average of ratios* (AOR) method.

Evaluation of $m\Re$ by the two methods above, ROA and AOR, yields unequal results. This is readily demonstrated by considering the average grade of a student who, in three tests, receives grades: 1 correct out of 4, 2 correct out of 5, and 3 correct out of 6. The ROA result is found by taking the average of the number of correct results, (1+2+3)/3 = 2, and the average of the number of possible correct results, (4+5+6)/3 = 5, and forming the ratio of the averages, 0.4. The AOR result is found by calculating the ratio of correct to possible correct results for each test (0.25, 0.40, 0.50) and forming their average, (0.25+0.40+0.50)/3 = 0.3833, not equal to the ROA result.

Results from a calorimeter test performed within a set of prescribed specifications on P_s, T_s, P_d, N_c, and balance are as follows:

PARAMETER	VALUE	STANDARD DEVIATION
Heater Power (W) [Q_h]	**1937.48**	**87.96**
Evaporator Exit Temperature (ºC) [T_g]	**5.23**	**0.06**
Liquid Temperature (ºC) [T_l]	**54.74**	**0.32**
SRC Ambient (ºC) [T_a]	**31.02**	**2.19**
Evaporator Exit Pressure (kPa) [P_g]	**191.06**	**1.79**
SRC Pressure (kPa) [P_{cal}]	**251.32**	**0.90**

The calorimeter test acquired 180 measured values of the six parameters required for evaluation of $m\Re$ by Equation 2. The ROA determination of $m\Re$ yields 2.17696 lb_m/min and the AOR determination yields 2.17706 lb_m/min. The percent difference

$$PD = 100 * [(m\Re_{AOR} / m\Re_{ROA}) - 1] \qquad (3)$$

between these values is 0.00459%. This calculation demonstrates a difference between ROA and AOR results. The importance of the percent difference magnitude is discussed below.

<u>Derivation of relation between ROA and AOR calculations</u>

The determination under consideration in this work is the value of a quantity that is derived from the ratio of values obtained in laboratory testing. Those reporting results may tacitly refer to a value derived from test data as an average value without further comment. Thus the value being presented might be written as the ROA value

$$V_{ROA} = [\ (1/n)\ \Sigma\ A_i\ ]\ /\ [\ (1/n)\ \Sigma\ B_i\ ]\ = \Sigma\ A_i\ /\ \Sigma\ B_i = \alpha\ /\ \beta \qquad (4)$$

where n is the total number of measurements, the summations are over n, A_i and B_i are the individual laboratory measurements, and the averages of the datasets $\{A_i\}$ and $\{B_i\}$ are $(1/n)\sum A_i$ and $(1/n)\sum B_i$ which are given by α and β.

The average might also be presented as the AOR value

$$V_{AOR} = (1/n)\ \Sigma\ [\ A_i\ /\ B_i\ ] \qquad (5)$$

which may be rewritten as

$$V_{AOR} = (1/n)\ \Sigma\ [(\alpha + \delta_{Ai}) / (\beta + \delta_{Bi})] \qquad (6)$$

where all terms are defined above except for δ_{Ai} and δ_{Bi} which are the individual deviations from average for each A_i and B_i respectively. Straightforward algebraic operations on Equation 6 lead to the following:

$$V_{AOR} = (1/n)\ (\alpha / \beta)\ \Sigma\ [(1 + \delta_{Ai} / \alpha) / (1 + \delta_{Bi} / \beta)] \qquad (7)$$

and

$$V_{AOR} = (\alpha / \beta)\ [(1/n)\ \Sigma\ (1 + \delta_{Ai} / \alpha) / (1 + \delta_{Bi} / \beta)] \qquad (8)$$

then

$$V_{AOR} = V_{ROA}\,[(1/n)\,\Sigma\,(1 + \delta_{Ai} / \alpha) / (1 + \delta_{Bi} / \beta)]. \qquad (9)$$

The above demonstrates that the AOR calculation is given by the ROA result multiplied by a function of the involved datasets' averages and dispersions, $f(\alpha, \{\delta_{Ai}\}, \beta, \{\delta_{Bi}\})$, thus

$$V_{AOR} = V_{ROA}\, f(\alpha, \{\delta_{Ai}\}, \beta, \{\delta_{Bi}\}). \qquad (10)$$

Several observations may be made from Equation 9. First, if the B_i are constant and the A_i are not (all δ_{Bi} are zero but δ_{Ai} not zero) then the ROA and the AOR values are the same. Second, if the B_i vary and the A_i are constant (δ_{Bi} not zero but δ_{Ai} all zero) then the ROA and the AOR values are not the same. Third, if both δ_{Ai} and δ_{Bi} are not zero then the ROA and AOR values are not the same and are not equal to those in the second instance above. The third observation describes, by far, the most prevalent condition in laboratory practice.

CALORIMETER DEGREE OF VALIDATION AND COMPRESSOR TEST PRECISION

Investigation of the term $f = f(\alpha, \{\delta_{Ai}\}, \beta, \{\delta_{Bi}\})$ leads to useful applications.

Mass flow rate calculation percent difference and AOR standard deviation

Combining Equations 3 and 10 gives the percent difference between $m\Re_{AOR}$ and $m\Re_{ROA}$

$$PD = 100*(m\Re_{AOR} - m\Re_{ROA}) / m\Re_{ROA} = 100*(m\Re_{AOR} / m\Re_{ROA} - 1) = 100*(f - 1) \qquad (11)$$

For a given calorimeter test the two mass flow rates considered here and their percent difference may be readily calculated. Absolute percent difference (all values reported positive) for 1800 calorimeter tests employing various compressor models is shown in Figure 2. In this series of tests the calorimeter PID controllers were adjusted at test number 737 and the whole calorimeter system was validated following test number 900. Consideration of this plot gives the first signal that the size of the percent difference between mass flow calculation types indicates the status of the calorimeter instrumentation: when the system is properly validated the mass flow calculation percent difference term is small compared to results under conditions of poor validation.

Figure 3 shows the standard deviation of the individual mass flow rate terms comprising the AOR calculation for the data displayed in Figure 2. This figure again indicates a drop in dispersion of measured values following controller adjustment and validation of the calorimeter system. This plot shows an increase in precision of reported $m\Re_{AOR}$ following validation.

The dispersion indicated in the above plots is attributed to variation or dispersion of parameter measurements associated with the SRC: Q_h, T_a, T_{sat}, P_g, T_g, and T_l. The variation or dispersion is an indication of the precision associated with these measurements. This result indicates that monitoring $m\Re_{AOR}$ and $m\Re_{ROA}$ and their percent difference gives useful information regarding the precision of several calorimeter parameter measurements and, thus, the state of validation of the calorimeter.

Analytical study

Results of an analytical study of the difference between $m\Re_{AOR}$ and $m\Re_{ROA}$ calculations are shown in Figure 4. The construction of this plot was carried out by employing a successful "within specification calorimeter data set" adjusted as follows: a mass flow analysis was carried out employing typical (from the successful test) *constant* values of each of the parameters noted in Figure 1 followed by additional analyses in which an individual parameter, such as evaporator pressure, was given an artificial variation (only 20 points were considered in the analysis rather than the usual 180). In each of the artificial analyses, variation of the single parameter yielded a standard deviation of that parameter and a percent difference between $m\Re_{AOR}$ and $m\Re_{ROA}$. Results of several analyses are shown in the figure for each of three SRC measurement parameters (the three parameters considered are those that appear in the denominator of Equation 2). The percent differences between mass flow calculations are shown as functions of the dispersion, or standard deviation, of the varied parameter. While it is not expected that real test data will be collected in which only one parameter has a dispersion, the present result demonstrates that a relation exists between parameter dispersion and the percent difference of calculated values of $m\Re_{AOR}$ and $m\Re_{ROA}$. The results shown in Figure 4 are for a single parameter variation within a given test, similar plots may be obtained for simultaneous variation of two or more parameters—a situation that more closely represents actual calorimeter testing. The horizontal axis units of Figure 4 are ºC for temperature values and kPa/10 for pressure values.

Application

The above shows that there is a straightforward relation between SRC parameter dispersion and $m\Re_{AOR}$ and $m\Re_{ROA}$ percent difference . Thus, alternatively, by monitoring the percent difference, indication of failure or drift of the SRC measuring equipment may be observed.

In actual testing one expects to see variations in all SRC parameters simultaneously. Attempts to model such a situation by including several ranges of variation in the several mass flow parameters are not feasible. Rather, a database of percent differences for successful testing may be compiled so that each mass flow result may be compared to historically "good" tests. The range of "good" tests is to be determined individually by each laboratory for its particular set of measurement equipment. Questionable tests' percent difference values will appear outside the database range of acceptable ("good") tests.

The terms "good" and "acceptable" here are with respect to precision of the SRC parameters (Q_h, T_a, T_{sat}, P_g, T_g, and T_l). It is up to each laboratory to decide on the percent difference values beyond which further investigation of SRC measurement precision is required. A "within specification" or "successful" test is one that meets the accuracy requirements set by one of the above noted societies (ASHRAE, JIS, ISO) for compressor parameters (P_s, T_s, P_d, N_c, and balance).

Figure 5 shows a fourteen-test database, tests 1 through 14, whose only parameter is mass flow percent difference as defined in this work. These tests are "within specification" and "acceptable". The percent difference values for tests 1 through 14 in the figure are typical of many "good" (precise) tests investigated. The figure also shows two tests with quite different values of mass flow percent difference. Tests 15 and 16 indicate a large dispersion of some parameter—instrumentation is malfunctioning in some fashion, perhaps failing or losing calibration. All 16 test results meet accuracy standards for compressor parameter measurements and thus were passed out of the laboratory as successful calorimeter tests. Investigation of the variation of the SRC mass flow parameters of these fourteen tests shows that the resistance heater input for tests 15 and 16 has large variation while that for tests 1 through 14 does not: the ratio of standard deviation to the average of the 180 points for tests 15 and 16 is 17.0 and 26.9 respectively while the average value of this term for tests 1 through 14 is 3.7. This suggests that investigation of all equipment associated with resistance heating of the SRC liquid is in order. These results indicate that while the accuracy of the mass flow parameters is acceptable the precision of these measurements is questionable. Thus, the precision of the reported mass flow value is also questionable.

CONCLUSIONS

There are two sets of conclusions associated with this work. Both are concerned with the method of calculation of calorimeter average mass flow rate: the Ratio Of Averages (ROA) approach and the Average Of Ratios (AOR) approach.

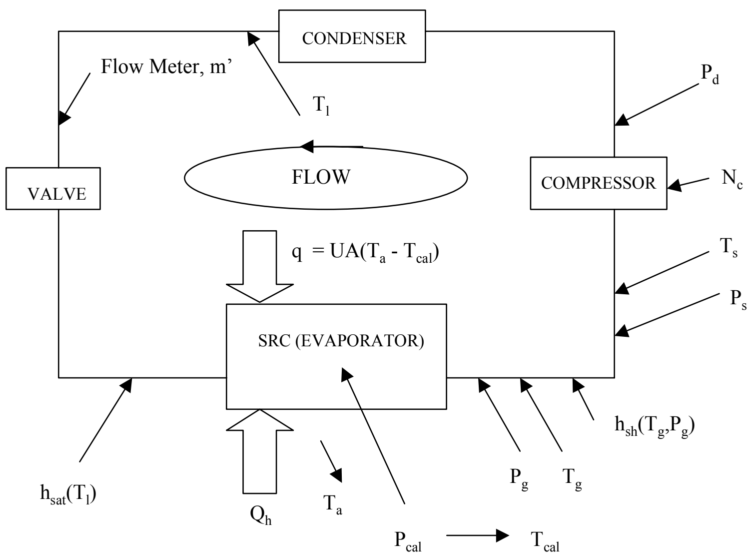
First, the method by which the average value of derived results, calorimeter mass flow rate in this instance, are calculated should be stated as part of a calorimeter laboratory report (or any report that delivers derived results):

- The reported value depends on whether the ROA or AOR method is employed.
- Designation of the method used will avoid disagreement among laboratories and among analysts.
- The ROA approach should be the default method of calculation—this method is not a function of the dispersion of the test measurements and it incorporates average values from a complete test. Such average terms are usually envisioned by laboratory engineers and technicians.

The second set of conclusions regards the employment of a function of AOR and ROA mass flow values to identify secondary refrigerant calorimeter measurement precision problems in calorimeter mass flow calculations:

- The size of the percent difference between calorimeter mass flow rate determined from AOR and ROA calculations can be related to the precision of individual parameter measurements.
- Lack of precision of individual parameter measurements is related to lack of precision of reported mass flow value.
- Calorimeter test results that are within mass flow balance specifications may be determined and reported based on imprecise SRC parameter measurements—this can be avoided by monitoring the percent difference between AOR and ROA mass flow determinations and taking action to reduce this percentage when it is outside some predetermined range.

Figure 1. Secondary Refrigerant Calorimeter



T_l = Liquid Temperature
Q_h = Resistance Heat Input
T_a = SRC Ambient Temperature
P_{cal} = SRC Saturation Pressure
T_{cal} = SRC Saturation Temperature
T_g = SRC Exit Temperature
P_g = SRC Exit Pressure

$h_{sat}(T_l)$ = SRC Input Enthalpy
$h_{sh}(T_g, P_g)$ = SRC Exit Enthalpy
UA = SRC Convection Coefficient
q = SRC Convection Exchange

P_s = Compressor Suction Pressure
T_s = Compressor Suction Temperature
P_d = Compressor Discharge Pressure
N_c = Compressor Speed
m’ = Measured Mass Flow Rate

SRC = Secondary Refrigerant Calorimeter

Figure 2. Absolute Percent Difference Between Mass Flow Rate Calculation Methods

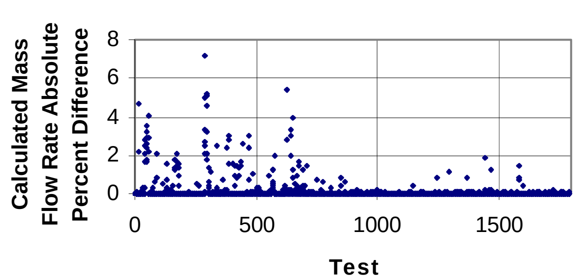


Figure 3. Standard Deviation Of Average Of Ratio (AOR) Mass Flow Calculations

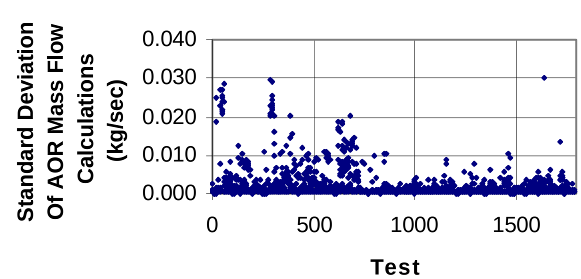


Figure 4. Percent Difference as Function of Parameter Dispersion

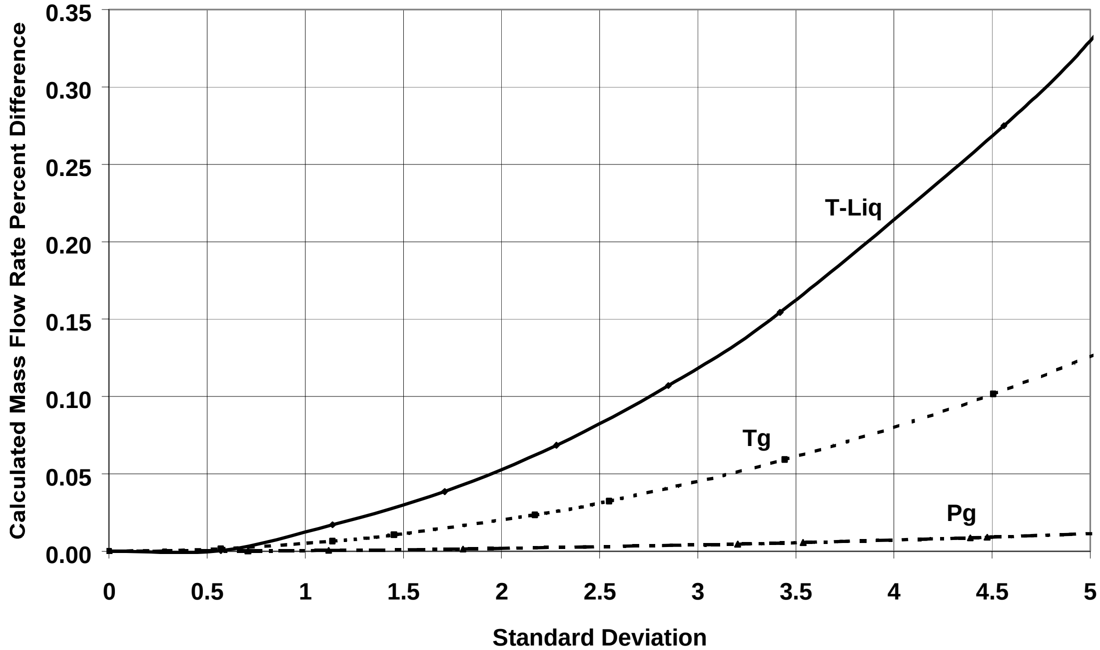


Figure 5. Percent Difference Between Mass Flow Rate Calculation Methods