FIELD MEASUREMENTS

P.O. FAHLÉN
SP (The Swedish National Testing and Research Institute), Box 857
S-501 15 BORÅS, Sweden

SUMMARY
Field measurements are important in making decisions on energy efficiency issues. To facilitate the use of such measurements there are internationally recognized documents [2, 6, 8]. There are also methods[9-12] for specific evaluation of chillers and refrigerating equipment. Modelling of both the measured object and the measuring installation is recommended to make general use of specific results and to provide information on the quality of measurement. In the analysis of measuring quality and presentation of overall uncertainty, the ISO GUM[7] method provides a harmonized, systematic tool box.

1. INTRODUCTION

Measurements are tools for **decision making**. The more important the decision, the greater the requirements on measurements become and therefore means and methods must be chosen that are compatible with the **purpose** of the activity. In contrast to the situation in a laboratory, you generally cannot control your experimental conditions in **field measurements** . Furthermore, field measurements often go on for long periods of time with no or intermittent supervision, yield large quantities of data and may be very costly. This makes planning the **design of the experiment** all the more important. The importance of field measurements is underlined by experience[2] from energy efficiency programs which indicates that savings improve by 20-30 % in projects with strong measurement and verification programs. This paper will discuss some **general principles** regarding field measurements. It will also discuss **measuring methods** applicable to refrigeration equipment and provide references. Finally, there is a section dealing with methods of systematically evaluating and presenting the **uncertainties of the measurements**.

2. PURPOSE OF THE MEASUREMENTS

The first question to answer is: **Why**? A clear statement of the purpose is the basis for the ensuing activities but whatever the purpose, system boundaries must be clearly defined and the flows across these boundaries must be recognized. An object such as a supermarket is an open system and distinction must be made between heat transfer (*Q*), work (*W*), and mass transfer (*M*), c.f. figure 1.

Clarification of the purpose will lead on to questions on **what** to measure (depending on the system boundaries), **when**, **how often**, **how long** and with what **accuracy**. Important categories deal with **contract guarantees**, **retrofit evaluation**, and **modelling**. These categories of purpose require the following types of measurement:

- **Commissioning** (generally short-term measurements)
- **Auditing** (generally short to medium-term measurements)
- **Monitoring** (generally long-term measurements)

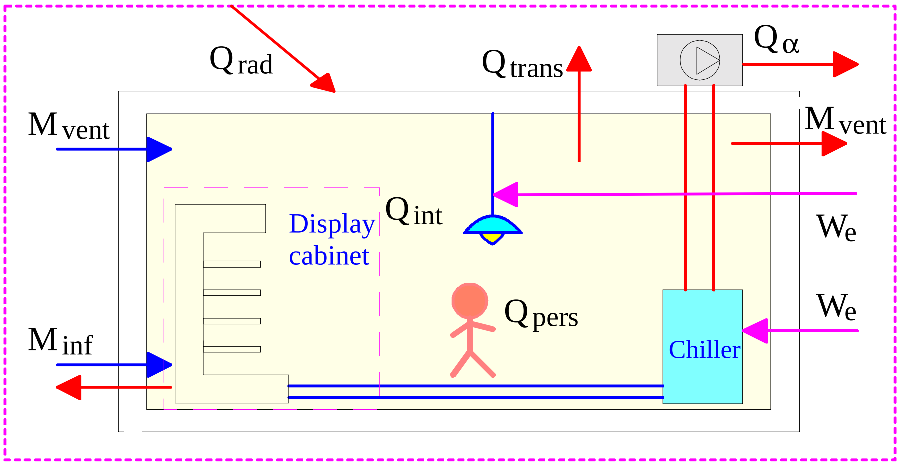


Figure 1. System boundaries and the different mass and energy flows.

Whatever the purpose, modelling of the measured object and the measuring installation is strongly advised. This facilitates generalization of specific results and transformation of reference values from theoretical operating conditions to those applicable for the actual measuring situation. It also helps in the analysis of the quality of measurement. Models can be analytic expressions, computer soft-ware such as CoolPack[8], and diagrams or tables describing the influence of varying operating conditions.

3. COMMISIONING AND AUDITING

Commissioning involves a comparison between actual performance of a component or system with **design** or **guarantee** values. This is common in new installations but can equally well occur in retrofit situations and often has economic implications in terms of bonuses and fines. Commissioning should always be requested if the client considers performance sufficiently important to warrant a contractual requirement. The verification method and operating conditions should also be specified together with the requirement.

Auditing is applied in situations where you are assessing the status of your system, either looking for potential upgrades or evaluating the result of a retrofit (Post Implementation Performance Analysis[8]). This also involves the comparison of measured results with different types of indicators, key numbers or other forms of **reference values**.

Commissioning and auditing are normally short-term or instantaneous investigations. Since measured variables will not be integrated over long periods it is important to find intervals when the system is close to **steady-state**. Otherwise large errors may result from energy storage within the audited system. Furthermore, variations in the operating conditions will introduce uncertainties in the comparison with reference values. Although there are a number of guides and standards covering the general aspects of commissioning and auditing, few deal specifically with refrigerating equipment.

3.1. Comparison of measured results and reference values

In the comparison of measured values with reference values one must be aware of the presumed **system boundaries** and know accurately the relevant **operating conditions**. All power inputs and outputs must refer to the same system boundary. This also implies that measuring equipment must be installed in positions related to this boundary. For this purpose, a system diagram is useful, e.g. according to NTVVS076[9] or NTVVS115[10] (see figure 2). NTVVS076 discusses in some detail the prerequisites for a comparison of measured and reference performance data regarding heat pumps but the principles are valid for refrigerating machinery in general.

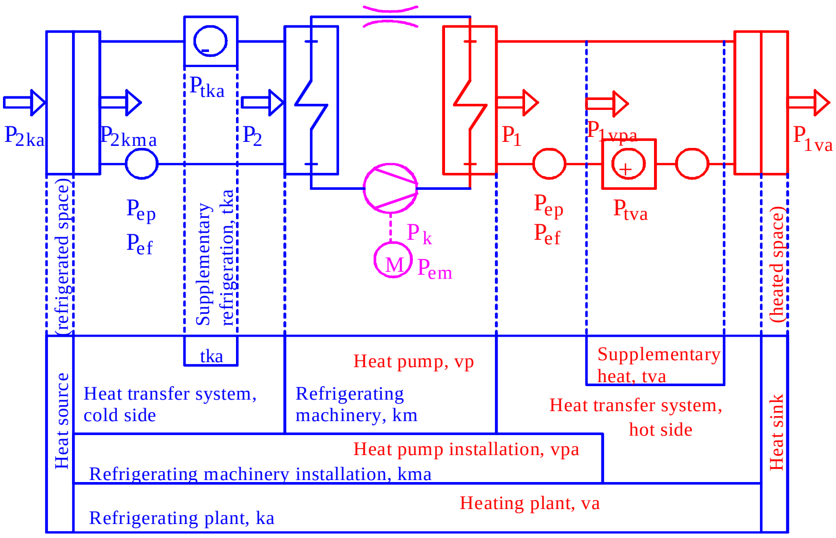


Figure 2. System diagram[10] of a refrigerating plant.

The lack of control of the operating conditions in most field situations generates a few complications. Firstly, the actual operating conditions will normally not coincide with the presumed reference conditions. The aforementioned modelling can provide the means to transform reference values to the actual test conditions.

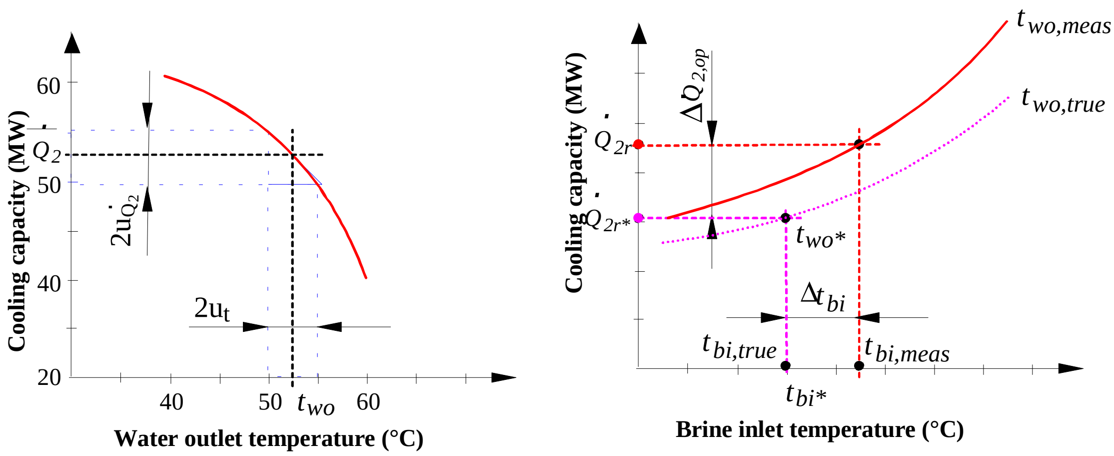


Figure 3. Illustration[3] of the uncertainty and error of a comparison induced by variations and incorrect measurement of the operating conditions.

Secondly, temporal fluctuations cause enlarged uncertainties regarding the mean values of both the performance variable, e.g. *COP*, and the variables defining the operating conditions such as flowrate and temperature. For instance, the *COP* of chillers changes by 2-3 % per K change in evaporating or condensing temperature. This will introduce an extra uncertainty in the comparison of reference value and measured result, which figure 3 tries to illustrate. For instance, uncertainties in the measurement of brine temperature will affect both directly the calculated capacity and indirectly the reference value.

NTVVS115[10] deals with the general conditions of field testing of refrigeration and heat pump equipment. Irrespective of the purpose of a chiller or heat pump test, there are two principally different field methods, **direct** testing or **indirect** testing.

3.2. Direct testing

Direct testing is well established and relies on the measurement of flowrate and temperature difference of the heat transfer medium, assuming that the thermophysical properties are known. Capacity is calculated as

$$\dot{Q} = \dot{M} \cdot \left(h_o - h_i\right) = \dot{V} \cdot \rho \cdot c_p \cdot \left(t_o - t_i\right) \qquad (1)$$

This equation also forms a model for the uncertainty analysis (c.f. 5.4). Direct testing is well known, its accuracy can be analyzed in a straight-forward manner and there is a well-established standard for this purpose[9]. The obvious disadvantage is the necessity of flow measurement, normally invasive, and the associated cost of installation and wet-calibration. For large flowrates and for brines, calibration facilities are scarce. NTVVS076[9] includes two accuracy classes, one with a total uncertainty less than ±5 % and one with ±10 %. Experience[5] shows that in large installations with first class measuring equipment, it is often possible to reach uncertainties lower than ±2 %.

In complex systems, especially retrofitted or upgraded installations, the boundaries may not be easy to identify. If you can find drawings of the system, these all too often do not agree with reality. Therefore the person responsible for a measuring project should always identify measuring positions on site, preferably together with the operational staff. Figure 4 indicates that, depending on whether you wish to determine the cooling capacity of the unit or the cooling load of your refrigerated space, sensors will have to be located in different positions. Of course temperature sensors and flowmeter must always relate to the same flow, i.e. be on the same side of any mixing valves!

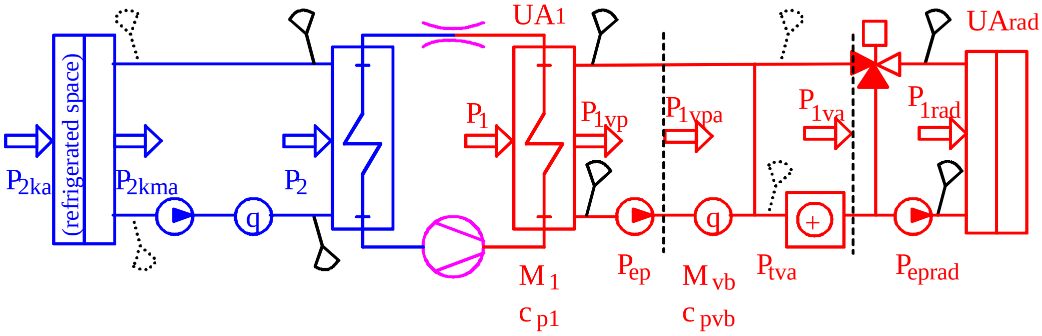
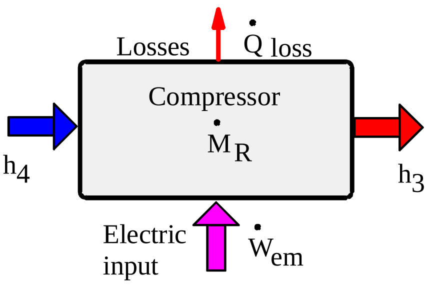


Figure 4. Illustration of sensors positioned at different system boundaries.

3.3. Indirect testing

Indirect testing relies on a heat balance of the compressor. Figure 5 illustrates the principle which presumes that you can measure the inlet and outlet temperatures and pressures of the compressor plus the sub-cooled condensate temperature after the condenser. Assuming that all but a small fraction *f* of the power input to the compressor raises the enthalpy of the refrigerant, a heat balance provides the expression (2) for COP_1 (this is also seen directly from the h-p diagram and an analogous expression for COP_2 can easily be derived). Knowing the power input, you can also derive heating or cooling capacity.

NTVVS116[11] describes this method, which has a long history of practical experience. Accuracy[4] is normally better than ±15 %. The main advantages with this type of measurement are that you do not need a flowmeter and since you actually map the process in the refrigerant h-p diagram you will automatically receive information on how the unit works and why it works as it does. This is the only established method which is generally cost-effective for small and medium-sized installations.



$$COP_1 = \frac{(h_3 - h_5)}{(h_3 - h_4)} \cdot (1 - f) \quad (2)$$

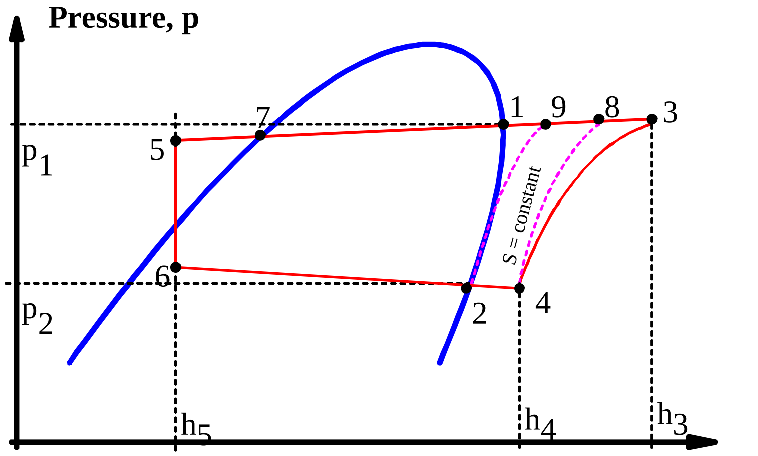


Figure 5. Heat balance of the compressor and the refrigerant pressure-enthalpy diagram.

4. MONITORING AND MODELLING

Monitoring and modelling are symbiotic; a model is needed to **generalize** monitored data and monitored data are required to **validate** models. It is obvious that in modelling you must recognize which parameters are important and which can be neglected. If, for instance, you wish to monitor the performance of a display cabinet, then the performance will mainly depend on the immediate surroundings (ambient temperature and humidity, lighting, product turn-over etc.) but only indirectly on outdoor climate. Hence there will be fewer direct influence factors in this case (c.f. figure 1) than if you want to model the entire supermarket. It is also obvious that if you monitor one object and want to draw general conclusions, your model must be better and your measurements more detailed than if you monitor a large number of objects.

In general terms, energy input may be described along the lines of expression (3):

$$E = E(B, W, I, L, P, O(B, W, I, A)) \qquad (3)$$

where E = energy, B = building, W = weather, I = indoor climate, L = lighting, P = processes (e.g. display cabinets), O = occupancy. Each symbol may involve several components, e.g. W may include temperature, humidity, insolation, wind speed etc.

In this model, B is a parameter such as the U-value of walls, windows etc., which may be estimated by calculation or one-off measurement. The other symbols designate variables which normally need to be monitored. Occupancy will to some extent depend on the other variables. The difference between external (W) and internal (I) climate decide the weather dependency. This should be understood in a general sense, e.g. a display case has its own internal and external climates ($W_{display\ case} = I_{supermarket}$).

An often employed, simple approach is to use a linear two-parameter model such as:

$$E = a + b \cdot (I - W) = a + b \cdot (T_i - T_o) \qquad (4)$$

The parameter a accounts for non-weather dependent effects such as occupancy, internal loads etc. whereas b provides the weather dependent effect. Either you determine both a and b from fitted measured data or b is calculated and a fitted. When the resulting model is used for **predictive** purposes it is known as a **degree-day model** and when used for **descriptive** purposes as an **energy signature**. Degree-day models are often used to normalize measured data regarding indoor and outdoor temperature.

Another application of simple models[13] is to identify an expression for $COP = COP(\dot{V}_w, \dot{V}_b, t_w, t_b)$. By changing some or all of the variables, sufficient data sets can be obtained to identify the respective coefficients and create a predictive model of the chiller. This can be useful in the situation described in 3.1 regarding the comparison with a reference value.

To assess the effect of retrofits and upgrades a combination of model and experiment is necessary. There are three basic types of experimental strategy in such monitoring projects:

- **Test - Reference**. Monitor *two* nearly identical objects, one retrofitted and the other unchanged. Measurements are parallel in time. *Case in point*: retrofit one of two supermarkets with capacity controlled compressors.
- **Before - After**. Monitor *one* object, before and after a retrofit. Measurements are successive in time. *Case in point*: monitor energy input before and after retrofitting display cabinets with night curtains.
- **On - Off**. Monitor one object with the retrofit in or out of operation. This is equivalent to successively repeating the before-after experiment. *Case in point*: monitor energy input with installed night covers in use one week and not in use the next week.

A plan for such an experiment should include descriptions of the type of object, the aim and design of the experiment, the measures taken, required measurements and model parameters, the course of investigation, data analysis and comments.

5. ANALYSIS OF MEASURING UNCERTAINTIES

Analysis of uncertainties is an important phase of any measuring project, field measurements included. This work should always be carried out at the **planning** stage, not after the measurements have been completed. It is during the analysis that you find which variables are important and where the main problems are likely to appear. At the planning stage you have a possibility to take **corrective action**, in hind-sight all you can do is to state the resulting uncertainty, which may not be what you required. Furthermore, in a commissioning situation, with fines and bonuses involved, uncertainties have the same economic impact as actual deviations.

The stated uncertainty is the quality label of a measurement and should always accompany a reported result. This can be done in different ways but I strongly recommend the approach by GUM[7]. This document has been endorsed by ISO, OIML etc., it is a requirement in certified calibration laboratories but not yet so well-known in applied measurement and testing. GUM categorizes uncertainties as **type A**, which can be assessed by repeating an experiment (statistics), and **type B** which have to be estimated by other means (calculation, experience etc.). Both types are characterized by a standard deviation (my designations: ***s* for type A** and ***w* for type B**). For type A uncertainties, a normal distribution is often assumed but in this case the real distribution may be assessed by repeating the experiment (if your system is in statistical balance). If type B uncertainties are based on expected maximum deviations from the expectancy, then a uniform distribution is often assumed and then $w = a/\sqrt{3}$ (see figure 6). The actual type is normally not very critical. Note that type A and type B uncertainties are similar but not identical to traditional random and systematic uncertainties. Individual uncertainties are combined by adding variances, i.e. $u^2 = (P \cdot s)^2 + (P \cdot w)^2$ where u is the combined uncertainty and P is a weighting factor (propagation constant). The final result, U, includes a coverage factor to improve the confidence level and is called the expanded uncertainty, $U = k \cdot u$. The value $k = 2$ is commonly chosen and corresponds to an approximate confidence level of 95 %.

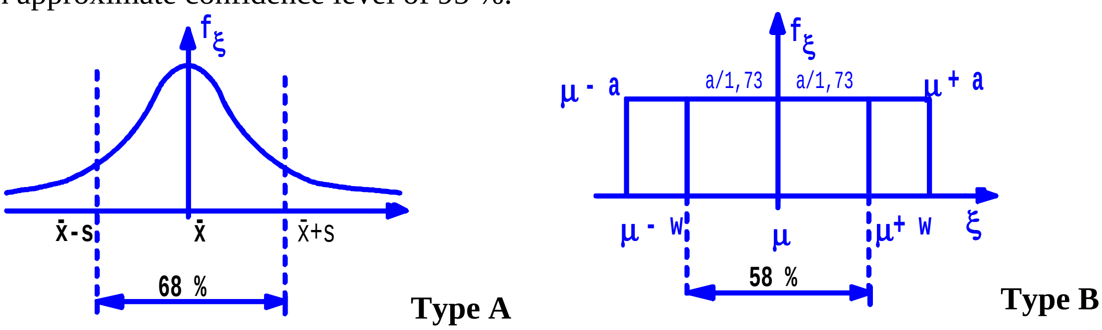


Figure 6. Examples of uncertainty distributions.

Models of the measuring situation are important tools in analyzing uncertainties, in particular type B uncertainties and 5.1 to 5.3 will give some examples.

5.1. Example 1: Liquid temperature

Sensor installations can be modelled by means of general impedances[3]. When measuring a liquid brine temperature, the sensor, including any thermometer-well, must have a low generalized impedance (thermal resistance to the brine) in relation to the impedance of the system (thermal resistance to the ambience). The effort variable (driving potential) will be the temperature difference (in K) and the flow variable is the heat flow (in W). Thus the generalized impedance Z_g, i.e. effort variable/flow variable, can be expressed in terms of the thermal resistance R [K/W]. Thermal resistances (c.f. figure 7) related to convection and conduction respectively can then be estimated as:

$$R_\alpha = \frac{1}{\alpha \cdot A_\alpha} \text{ and } R_\lambda = \frac{L}{\lambda \cdot A_\lambda} \qquad (5)$$

where A_α and A_λ are the convective and conductive heat transfer areas and L the corresponding length of the material. Continuing the impedance considerations, the measuring error (e) due to installation effects can be expressed as:

$$e = t_{meas} - t_b = -(t_b - t_0) \cdot \left[1 + \frac{R_{\lambda 1}}{R_{\lambda 3}} + R_{\alpha 1} \cdot \left(\frac{R_{\lambda 1}}{R_{\lambda 2} \cdot R_{\lambda 3}} + \frac{1}{R_{\lambda 2}} + \frac{1}{R_{\lambda 3}} \right) \right]^{-1} \qquad (6)$$

where t_{meas} = measured temperature, t_b = actual brine temperature, and t_0 = wall temperature of the pipe. In a well executed installation $R_{\lambda 2} << R_{\lambda 3}$ and $R_{\lambda 1} << R_{\lambda 3}$ making the approximation (7) valid. When $R_{\lambda 2} >> R_{\alpha 1}$ the error becomes small.

$$e = t_{meas} - t_b \approx$$
$$\approx -(t_b - t_0) \cdot \left[1 + \frac{R_{\lambda 2}}{R_{\alpha 1}} \right]^{-1}$$

(7)

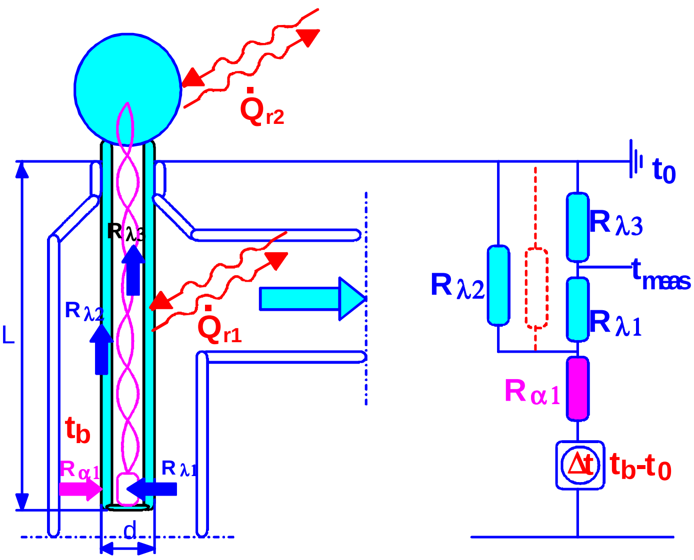


Figure 7. Heat transfer and impedance equivalents of a thermometer installation.

5.2. Example 2: Surface temperature

IR-thermometry is a useful tool in screening display cabinets for temperature profiles. However, IR-cameras need information on background temperature and emissivity of the investigated surface. Investigations[1] have shown that emissivity of typical packing materials can vary between 0.58 to 0.75. The diagram in figure 8 shows the usefulness of simple models to study the sensitivity to changes in the measuring conditions. The IR-camera can interpret the received IR-radiation differently depending on the assumed ratio between emitted energy and reflected background radiation from the measured surface . The total input, $\dot{q}_{tot}$, is the sum of emitted, $\dot{q}_e$, and reflected, $\dot{q}_r$, radiation:

$$\dot{q}_{tot} = \dot{q}_e + \dot{q}_r = \sigma_0 \cdot (\varepsilon \cdot T^4 + (1-\varepsilon) \cdot \varepsilon_{amb} \cdot T_{amb}{}^4) \qquad (8)$$

The differential of this expression describes how the camera will interpret changes in emissivity and ambient temperature as a change in surface temperature ΔT ($\varepsilon_{amb} \approx 1$):

$$\frac{\Delta T}{T} = \frac{\Delta\varepsilon}{4\varepsilon} \cdot \left(\varepsilon_{amb} \left(\frac{T_{amb}}{T} \right)^4 - 1 \right) - \frac{\Delta T_{amb}}{T_{amb}} \cdot \left(\varepsilon_{amb} \left(\frac{1-\varepsilon}{\varepsilon} \right) \cdot \left(\frac{T_{amb}}{T} \right)^4 \right) \qquad (9)$$

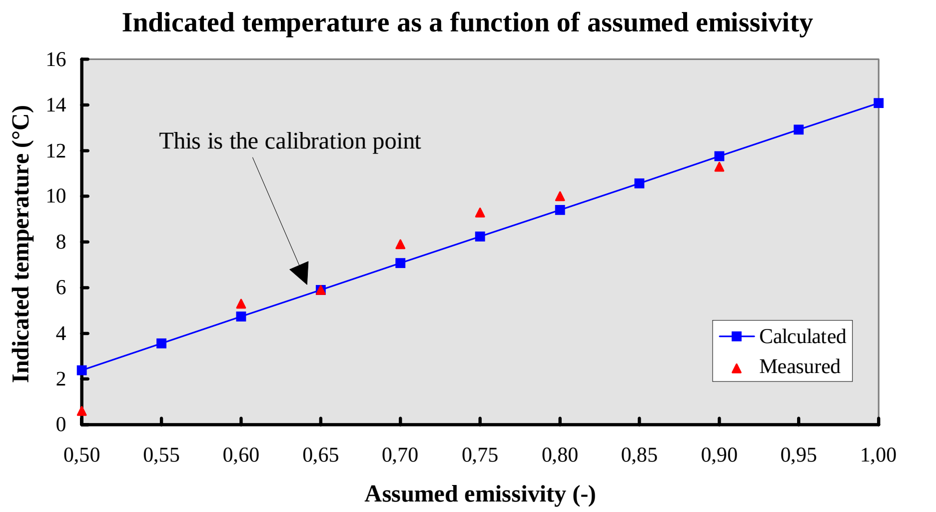


Figure 8. Temperature as a function of assumed emissivity using IR-thermography.

5.3. Example 3: Thermophysical properties of brines

There will be additional uncertainties involved in the determination of cooling capacity in a brine system using tabulated physical property data[3]. As an example, maximum deviation in concentration between tabulated data of aqueous solutions of commercial and pure ethylene glycols is close to 10 $\%_W$ for a given density. Now, consider the following alternative methods of estimating concentration: Initial **mixing volumes**, measured **refractive index** and measured **density**. Using subscripts 0 for true values, r for values based on refractive index, and ρ for values based on density, table 1 lists the estimated heat coefficient *K* at -10 °C assuming either technical or pure ethylene glycol.

Table 1. Heat coefficient based on different methods to determine concentration.

Method		**z** (%$_w$)	K_{tech} (J/m^3/K)	K_{pure} (J/m^3/K)	**ΔK/K** (%)
Initial volumes	z_0	41	3662	3571	2.6
Refractive index	z_r	46	3570	3455	3.3
Density					9.4
(assuming tech. glycol)	z_ρ	42	3644	--	
(assuming pure glycol)	z_ρ	52	--	3333	

The uncertainties emanate from:

- Different methods of determining the concentration give different results; i.e. we do not know the exact concentration.
- Different tables provide different values of ρ and c_p, mainly because of differences between pure and technical anti-freeze components. The diagrams in figure 9 illustrate this situation.

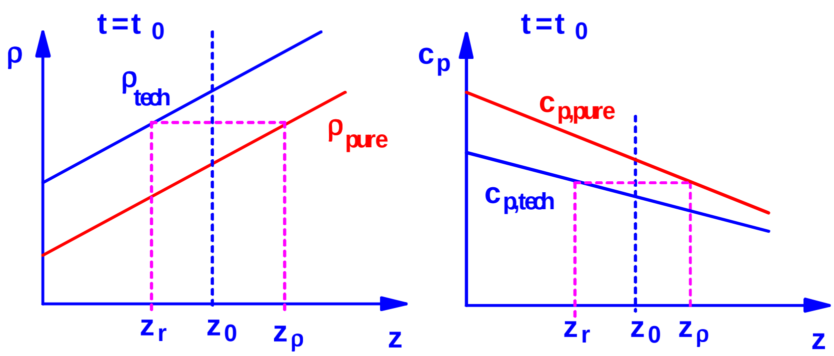


Figure 9. An illustration of the problems involved in estimating ρ and c_p for technical glycol solutions. z_0 = true concentration, z_r = concentration determined by means of a refractometer, z_ρ = concentration determined from density measurements.

5.4. Uncertainty budgets

The overall uncertainty of a derived quantity such has cooling capacity must be calculated from estimates of the uncertainties of individual measurements. A model is then required to analyze how the individual uncertainties influence the final result. Uncertainty budgets can be used to illustrate the relative importance of individual contributions. Case in point[3]: Using equation (1) as a simple model and applying logarithmic differentiation will result in the following expression:

$$\frac{\Delta \dot{Q}_2}{\dot{Q}_2} = \frac{\Delta \dot{V}_b}{\dot{V}_b} + \frac{\Delta \rho_b}{\rho_b} + \frac{\Delta c_{pb}}{c_{pb}} + \frac{\Delta t_{bo}}{(t_{bo} - t_{bi})} - \frac{\Delta t_{bi}}{(t_{bo} - t_{bi})} \qquad (10)$$

Taking into account that flowrate is deduced from N counted pulses, the time τ and a meter coefficient K_b [m^3/pulse], that thermophysical properties depend on temperature, pressure and composition etc., then (10) becomes a little more complex:

$$\frac{\Delta\dot{Q}_2}{\dot{Q}_2} = P_1 \cdot \frac{\Delta N}{N} + P_2 \cdot \frac{\Delta\tau}{\tau} + P_3 \cdot \frac{\Delta z_b}{z_b} + P_4 \cdot \frac{\Delta t_{bi}}{(t_{bo} - t_{bi})} + P_5 \cdot \frac{\Delta t_{bo}}{(t_{bo} - t_{bi})} + \\ + P_6 \cdot \frac{\Delta K_{0b}}{K_{0b}} + P_7 \cdot \frac{\Delta\rho_b}{\rho_b} + P_8 \cdot \frac{\Delta c_{pb}}{c_{pb}} \qquad (11)$$

with the propagation coefficients (weighting factors) P_1 to P_8 given by

$$P_1 = -P_2 = P_6 = \left(1 - \frac{\dot{V}_b}{K_b} \cdot \frac{\partial K_b}{\partial \dot{V}_b}\right)^{-1} \equiv \text{A},$$

$$P_3 = \left(\frac{z_b}{\rho_b} \cdot \frac{\partial\rho_b}{\partial z_b} + \frac{z_b}{c_{pb}} \cdot \frac{\partial c_{pb}}{\partial z_b}\right),\ P_5 = P_7 = P_8 = 1 \text{ , and}$$

$$P_4 = \left(A \cdot \frac{(t_{bo} - t_{bi})}{K_b} \cdot \frac{\partial K_b}{\partial t_{bi}} + \frac{(t_{bo} - t_{bi})}{\rho_b} \cdot \frac{\partial\rho_b}{\partial t_{bi}} + \frac{(t_{bo} - t_{bi})}{c_{pb}} \cdot \frac{\partial c_{pb}}{\partial t_{bi}} - 1\right).$$

In the case of uncertainties of type A, the number of pulses from the flowmeter as well as the number of temperature measurements during the measuring period will affect the uncertainty. On the other hand, components such as the nominal flowmeter constant (K_{0b}) and the composition of the brine (z_b) will not influence the type A uncertainty.

To assess the combined uncertainties of type A and B, the component standard deviations replace the Δ in (11), e.g. Δt_{bi} is replaced by s_{tbi} and w_{tbi} respectively. When there is strong correlation between variables, e.g. t_{bi} and t_{bo}, then the covariance must be considered. For the type A uncertainty, however, it is better to use individually computed capacities.

Type A (derived from calculated values of the cooling capacity):

$$s_{\overline{\dot{Q}}2} = \frac{s_{\dot{Q}2}}{\sqrt{n}} = \sqrt{\frac{1}{n(n-1)} \sum_{j=1}^{j=n} (\dot{Q}_{2,j} - \overline{\dot{Q}}_{2,j})^2} \qquad (12)$$

Type B (derived from the individual measurands). Since B-type components cannot be deduced by statistical methods, the propagation equation must be used:

$$w_{\dot{Q}2} = \overline{\dot{Q}}_2 \cdot \left[\left(P_1 \cdot \frac{w_{\dot{V}b}}{\dot{V}_b}\right)^2 + \left(P_3 \cdot \frac{w_{zb}}{z_b}\right)^2 + \left(P_4 \cdot \frac{w_{tbi}}{(t_{bo} - t_{bi})}\right)^2 + \left(P_5 \frac{w_{tbo}}{(t_{bo} - t_{bi})}\right)^2 + \right. \\ \left. + \left(P_6 \cdot \frac{w_{K_{0b}}}{K_{0b}}\right)^2 + \left(P_7 \cdot \frac{w_{\rho b}}{\rho_b}\right)^2 + \left(P_8 \cdot \frac{w_{c_{pb}}}{c_{pb}}\right)^2\right]^{1/2} \qquad (13)$$

Table 2 gives an example of the use of uncertainty budgets. The combined and expanded uncertainties are given both for single values and for mean values.

Table 2. Uncertainty budget regarding the determination of cooling capacity $\dot{Q}_2$.

Cause of the uncertainty	**Propagation constant,** P_j	**Uncertainty type A, (%)**	**Uncertainty type B (%)**
Measurands:			
$\Delta\dot{V}_b(N,\tau,K_{0b})$	$P_1 \approx 1.0019$ $P_2 = -P_1$	< 0.22, < 0.02 (mean)	< 0.29
Δz_b	$P_3 \approx -0.271$	≈ 0	≈ 2.3
Δt_{bo}	$P_4 \approx -1.0025$	< 9.3, < 0.93 (mean)	< 0.75
Δt_{bi}	$P_5 = 1$	< 9.3, < 0.93 (mean)	< 0.75
Constants:			
$\Delta\rho_b$	$P_7 = 1$	≈ 0	< 0.12
Δc_{pb}	$P_8 = 1$	≈ 0	< 1.9
Total contribution of types A and B respectively; $\sqrt{\sum\left(P_j \cdot s_j\right)^2}$, $\sqrt{\sum\left(P_j \cdot w_j\right)^2}$		$\frac{s_{\dot{Q}2}}{\dot{Q}_2}$ <13.17, $\frac{s_{\bar{\dot{Q}}2}}{\bar{\dot{Q}}_2}$ <1.32 $\frac{s_{\dot{Q}2}}{\dot{Q}_2}$ <1.13*, $\frac{s_{\bar{\dot{Q}}2}}{\bar{\dot{Q}}_2}$ <0.11*	$\frac{w_{\dot{Q}2}}{\dot{Q}_2}$ < 2.20
Combined uncertainty of the cooling capacity (calculated and measured for individual values and mean values respectively)		$\frac{u_{\dot{Q}2}}{\dot{Q}_2}$ < 13.35 %, $\frac{u_{\dot{Q}2}}{\dot{Q}_2}$ < 2.47* %	$\frac{u_{\bar{\dot{Q}}2}}{\bar{\dot{Q}}_2}$ < 2.81 %, $\frac{u_{\bar{\dot{Q}}2}}{\bar{\dot{Q}}_2}$ < 2.20* %
Expanded uncertainty of the cooling capacity ($U = k\cdot u$; $k = 2.0$)		$\frac{U_{\dot{Q}2}}{\dot{Q}_2}$ < 26.7 %, $\frac{U_{\dot{Q}2}}{\dot{Q}_2}$ < 4.9* %	$\frac{U_{\bar{\dot{Q}}2}}{\bar{\dot{Q}}_2}$ < 5.6 %, $\frac{U_{\bar{\dot{Q}}2}}{\bar{\dot{Q}}_2}$ < 4.4* %

*These uncertainties are based on the measured instantaneous capacities. There is obviously a high degree of correlation between t_{bo} and t_{bi}. Hence large variations in t_b do not reflect in large variations in $\dot{Q}_2$ and the derived uncertainty of $\dot{Q}_2$ will be considerably overestimated.

6. CONCLUSION

There are numerous handbooks and guides to assist in general planning of field measurements. There are, however, few standards for the specific evaluation of refrigeration equipment but for purposes of commissioning and auditing, the Nordtest methods NTVVS076, 115 and 116 can be useful. These methods provide accuracy classes of ±5, ±10, and ±15 % respectively.

In planning and evaluation of measurements the use of models is often necessary and will always be a help. You will need models both for the measured object and for your measuring system. Simple models will often suffice and the use of generalized impedances can be helpful in analyzing sensor installations. An estimate of the total uncertainty should always accompany a measured result, preferably as the expanded uncertainty in accordance with GUM (ISO Guide to the Expression of Uncertainty in Measurement).

6. NOMENCLATURE

Quantity		**Unit**	**Subscript**	
a	half-width of uniform distrib.		*1*	condenser/heating
COP	Coefficient of Performance	(W/W)	*2*	evaporator/cooling
f	heat loss factor	(W/W)		
h	specific enthalpy	(J/kg)	*amb*	ambient
k	coverage factor $(U = k \cdot u)$	(-)	*b*	brine
K	heat coefficient (= $\rho \cdot c_p$)	($J/m^3/K$)	*e*	electric
M	mass	(kg)	*e*	emitted
$\dot{M}$ (q_m)	mass flowrate	(kg/s)	*f*	fan
p	pressure	(Pa)	*inf*	infiltration
P	propagation coefficient	(-)	*loss*	heat loss
Q	heat (thermal energy)	(J)	*m*	mean
$\dot{Q}$ (P)	capacity (thermal power)	(W)	*m*	motor
s	standard deviation, type A	(...)	*max*	maximum
t	temperature (Celsius)	(°C)	*p*	pump
T	temperature (absolute)	(K)	*pers*	persons
u	combined uncertainty	(...)	*R*	refrigerant
U	expanded uncertainty $(U=k \cdot u)$	(...)	*r*	reflected
U	thermal transmittance	($W/m^2/K$)	*rad*	radiation
$\dot{V}$ (q_v)	volume flowrate	(m^3/s)	*trans*	transmission
w	standard deviation, type B	(...)	*vent*	ventilation
W	work (mechanical or electric)	(J)		
$\dot{W}$ (P_e)	power (mechanical or electric)	(W)	α	convective heat transfer
z	concentration	(kg_{EG}/kg_b)	λ	conductive heat transfer
ρ	density	(kg/m^3)		
τ	time	(s)		

SP = Swedish National Testing and Research Institute

7. REFERENCES

1. Axell, M, 1999. Investigation of the variation in emissivity between different surface materials (in Swedish). (Internal report, SP, Borås, Sweden.)

2. DOE/EE-0157:IPMVP-1997, 1997. International performance measurement and verification protocol. (Department of Energy, Washington DC, USA.)

3. Fahlén, P, 1994. Performance tests of air source heat pumps under frosting conditions - Quality of Results. (SP, Borås, Sweden).

4. Fahlén, P & Johansson, K, 1989. Capacity measurement on heat pumps - A simplified measuring method (in Swedish). (Swedish Council for Building Research, Stockholm, Sweden.)

5. Fahlén, P & Lagerkvist, K, 1987. Experiences from performance testing of large heat pumps. (Conference on the large scale application of heat pumps, 25 -27 March, Oxford, England.)

6. Fracastoro, G V & Lyberg, M D, 1983. IEA Annex III: Residential Buildings Energy Analysis - Guiding principles concerning design of experiments, instrumentation and measuring techniques. (Swedish Council for Building Research, Stockholm, Sweden.)

7. ISO, 1993. Guide to the Expression of Uncertainty in Measurement. (ISO.)

8. Lyberg, M, et al, 1987. Source Book for Energy Auditors - Volume 1 & 2. (Swedish Council for Building Research /International Energy Agency, Stockholm, Sweden.)

9. NTVVS076, 1989. Large heat pumps - Field testing and presentation of performance. (Nordtest, May1, Esbo, Finland.)

10. NTVVS115, 1997. Refrigeration and heat pump equipment: General conditions of field testing and presentation of performance. (Nordtest, Esbo, Finland.)

11. NTVVS116, 1997. Refrigeration and heat pump equipment: Check-ups and performance data inferred from measurements under field conditions in the refrigerant system. (Nordtest, May1, Esbo, Finland.)

12. Phelan, J, Brandemuehl, M & Krarti, M, 1997. Review of laboratory and field methods to measure fan, pump, and chiller performance. (ASHRAE Transactions, vol. 103, no. 2, pp. 914-925.)

13. Phelan, J, Brandemuehl, M J & Krarti, M, 1996. Final report, ASHRAE Project 827-RP: Metodology development to measure in-situ chiller, fan, and pump performance. (University of Colorado, Boulder, Colorado, USA.)