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Uncertainty in measurement of a vapor compression system

Messunsicherheit am einfachen Kältekreislauf

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Messunsicherheit, Kaltdampfkompression, Kältekreislauf, GUM

Abstract

Knowledge of measured uncertainty is crucial for the evaluation and interpretation of test bench measurement results. In this research the “Guide to the expression of uncertainty in measurement” (GUM) is used for the calculation of uncertainty of a vapor compression system. Therefore, a test setup for vapor compression systems is described and influences of uncertainties of direct measured values and equation of state are discussed, respectively. The results provide important insights for the selection of proper certainty of measurement equipment and help to assess the accuracy of measurement results in vapor compression systems.

Introduction

Refrigeration machines are used in many engineering applications and 14 % of the energy consumption in 2011 was caused by refrigeration (Preuß 2011). Therefore, the energy efficiency of vapor compression systems is important and is focus of many research and industrial projects. Measurements are an essential part of design and development process of vapor compression systems. Hence, knowledge of measurement uncertainty to evaluate the systems is required. There are various guidelines in the literature for expressing uncertainties in measurement. The “Guide to the expression of uncertainty in measurement” (GUM) is the basic framework for the evaluation of measurement uncertainty (JCGM 2009, Farrance 2014). GUM uses the law of propagation of uncertainty and the description of the output value by a normal or t distribution. Additionally the analytic and the Monte Carlo method are possible calculation methods for measured uncertainties with their own weaknesses and strengths (IOS 2008).
In addition to direct measurements such as temperature and pressure, derived values from the equation of state such as enthalpy are important for the evaluation of thermodynamic systems. For refrigerants, there are different equations of state in the literature. Span et al. developed a 12 parametric equation of state with an uncertainty of 1 % for enthalpy of R134a (Span 2003). Heide measured the properties of the refrigerant-oil mixture ND 8 PAG Oil and R134a with an enthalpy uncertainty of 1% (ILK Dresden). Frutiger et al. used the Monte Carlo method to calculate uncertainty of different working fluids in an organic Rankine cycle due

to uncertainty of fluid property of the Robinson-Peng equation of state (Frutiger 2016). Cheung et al. showed that uncertainty due to equation of state has larger impact on the uncertainty of superheat and subcooling of a vapor compression cycle than the uncertainty of the pressure transducer (Cheung 2017). In 2018 Cheung and Frutiger et al. developed a method to calculate uncertainty of a Helmholtz-energy-based equation of state based on the regression model of Seber and Wild (Cheung and Frutiger et. al 2018) (Seber 1998). In a third paper Cheung et al. used the method presented in Cheung and Frutiger et al. 2018 to calculate measured uncertainty of the performance of an air conditioning system. (Cheung et al. 2018). Cheung et al. showed that the measurement uncertainty due to the Helmholtz equation of state is only 10% of the measurement uncertainty. The explanation of the authors is the correlation of the enthalpy uncertainty at inlet and outlet of the evaporator and thus the uncertainty cancel each other out. However, no information is given about oil influences to the performance of the system, although the oil percentage of the working fluid can have a significant influence to the calculated value (Stalter).

In this paper the GUM analysis is used to calculate uncertainty in measurement of a simple vapor compression system. The method takes into account the effects of direct measured values as well as the sensitivity of these to a composed equation of state according to Span et al. and Heide for R134a refrigerant and ND8 oil. The test bench setup and equipment are presented and the calculation method is discussed. Important information is given on the effects of temperature, pressure, oil content and mass flow on refrigerant capacity and energy efficiency ratio (EER). Thereby important information for the selection of proper certainty of measurement equipment is given as well as information to interpret the accuracy of measured values.

Experimental Setup

The results for measured uncertainty are calculated for an exemplary test bench setup shown in figure 1.

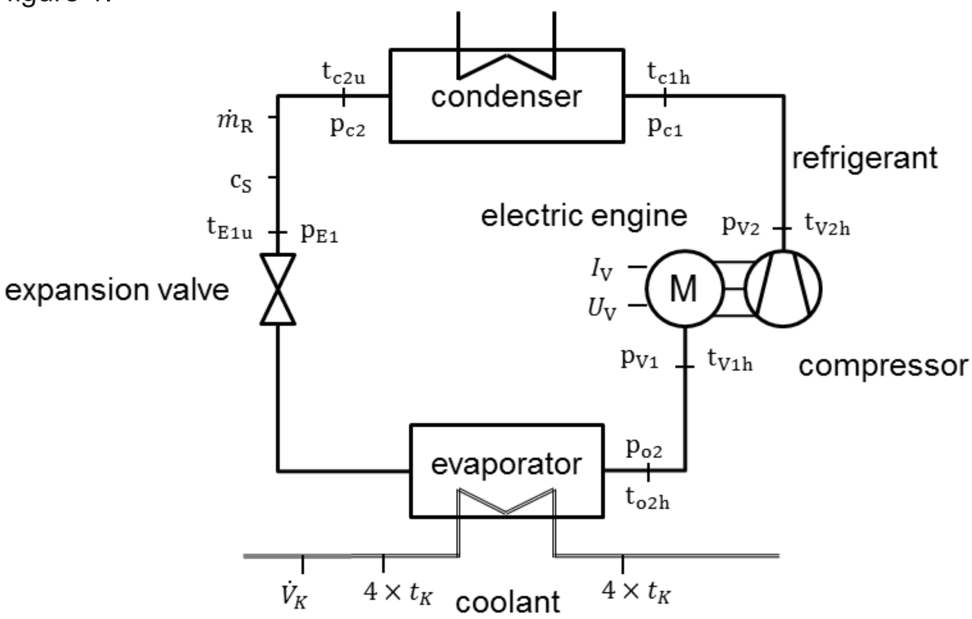

Figure 1: Test bench setup and sensors of a simple vapor compression system according to DIN EN 1861 and DIN 9841

The refrigerant circuit is located in a climate chamber and the heat source of the refrigerant circuit is a coolant circuit with an electric heater. The coolant circuit is equipped with a magnetic inductive flow meter (Siemens MAG Flow Series) and four temperature sensors (Pt100) at inlet and outlet of the evaporator. Therefore the cooling capacity can be calculated according to

$$\dot{Q}_{oK} = \dot{V}_K \cdot \rho \cdot c_p \cdot \Delta T, \tag{1}$$

where $\dot{V}$ is the measured volume flow, ρ is the density, c_p is the specific heat capacity and ΔT is the measured temperature difference between coolant inlet and outlet. The refrigerant circuit is instrumented with temperature (thermocouple) and pressure sensors before and after each component besides between expansion valve and evaporator due to the two-phase flow. Additionally, sound velocity and mass flow of the refrigerant is measured in the liquid tube between condenser and expansion valve. For sound velocity measurement the Anton Paar sensor L-Sonic 6000 and Anton Paar electronic Pico 3000 is used. Sound velocity, temperature and pressure are used to calculate the oil percentage of the refrigerant oil mixture. The polynomial for the calculation is an internal MAHLE research result. For mass flow measurement a micro motion elite coriolis sensor is used. Therefore, the second possibility to calculate the refrigerant capacity is according to equation (2)

$$\dot{Q}_o = \dot{m}_R (h_{02} - h_{E1}), \tag{2}$$

with $\dot{m}_R$ refrigerant mass flow, h_{o2} enthalpy of the evaporator outlet and h_{E1} enthalpy of expansion valve inlet. Detailed information about the uncertainty of the measurement chain is given in table 1 and further information about the test bench is described in Angermeier et al. (Angermeier 2018).

Table 1: Uncertainty of the measurement chain / MR: regarded to measurement range / no declaration: regarded to measured value

Sensor	Measurement chain	Uncertainty	Distribution
Pt100	Sensor	0,15 °C	normal
	Module	0,1 °C	rectangular
thermocouple (calibrated)	Sensor	0,5 °C	normal
	Module	0,4 °C	rectangular
pressure	Sensor	0,3 %	normal
	Module Input	0,02 %	rectangular
		0,02 % MR	rectangular
	Module Output	0,3 %	rectangular
Coriolis (mass flow refrigerant)	Sensor	0,1 %	normal
	Module Input	0,02 %	rectangular
		0,02 % MR	rectangular
	Module Output	0,05 %	rectangular
MID	System	0,15 %	normal
Sound velocity	Sensor	0,1 m/s	normal
	Transducer	0,12 %	rectangular
	Module Input	0,02 %	rectangular
		0,02 % MR	rectangular
	Module Output	0,05 %	rectangular
	Calculation	0,96 %	normal
Current (compressor)	Sensor	83 ppm	rectangular
	Module	0,02 %	rectangular
		0,02 % MR	rectangular
Voltage (compressor)	Module	0,02 %	rectangular
		0,02 % MR	rectangular

Calculation method for measured uncertainty

The GUM defines itself as a guideline to express uncertainty at various levels of accuracy and in many fields (JCGM 2008). Hence, there are different possibilities to use the GUM.

The calculation of uncertainty in measurement in this paper follows the GUM type B. According to this type, knowledge of all uncertainties of the measurement chain is necessary and presented in table 1. It is supposed that systematic errors are eliminated due to calibrations. The Gaussian error propagation is justified for non-correlated values (Testo 2013) and used in this research. Thereby the uncertainty

$$u(x) = \sqrt{\sum u^2(\delta_{x,i})}, \tag{3}$$

of direct measured values x can be indicated with the uncertainty of the different parts of the measurement chain $u(\delta_{x,i})$. For example, the measured uncertainty of the refrigerant mass flow is calculated according to

$$u(\dot{m}_R) = \sqrt{\begin{array}{c} u\left(\delta_{\dot{m}_R,Sensor}\right)^2 + u\left(\delta_{\dot{m}_R,Module,Input,Value}\right)^2 \\ + u\left(\delta_{\dot{m}_R,Module,Input,Range}\right)^2 + u\left(\delta_{\dot{m}_R,Module,Output}\right)^2 \end{array}} \tag{4}$$

To calculate derived values y such as $\dot{Q}_o$, the same law of error propagation is used but rated with sensitivity factors $c_{i,f}$. The variance of a derived value can be calculated by equations (5)

$$u^2(y) = \sum_{i=1}^{n} u_i^2(y) = \sum_{i=1}^{n} c_i u^2(x_i), \tag{5}$$

with the sensitivity coefficient

$$c_{i,f} = \frac{\partial f}{\partial x_i}, \tag{6}$$

of the value x_i to the function f. For example and based on Kline and Mc Clintock 1953 the calculation of the uncertainty of $\dot{Q}_o$ is according to

$$u(\dot{Q}_o) = \sqrt{\begin{array}{c} \left(\frac{\partial \dot{Q}_o}{\partial \dot{m}_R} u(\dot{m}_R)\right)^2 + \left(\frac{\partial \dot{Q}_o}{\partial h_{o2}} \frac{\partial h_{o2}}{\partial t_{o2h}} u(t_{o2h})\right)^2 \\ + \left(\frac{\partial \dot{Q}_o}{\partial h_{o2}} \frac{\partial h_{o2}}{\partial p_{o2}} u(p_{o2})\right)^2 + \left(\frac{\partial \dot{Q}_o}{\partial h_{o2}} \frac{\partial h_{o2}}{\partial x_{WO}} u(x_{WO})\right)^2 \\ + \left(\frac{\partial \dot{Q}_o}{\partial h_{E1}} \frac{\partial h_{E1}}{\partial t_{E1u}} u(t_{E1u})\right)^2 + \left(\frac{\partial \dot{Q}_o}{\partial h_{E1}} \frac{\partial h_{E1}}{\partial p_{E1}} u(p_{E1})\right)^2 \\ + \left(\frac{\partial \dot{Q}_o}{\partial h_{E1}} \frac{\partial h_{E1}}{\partial x_{WO}} u(x_{WO})\right)^2 \end{array}} \tag{7}$$

The sensitivity of enthalpy due to pressure and temperature is calculated as differential quotient

$$c_{i,f} = \frac{\partial f}{\partial x_i} \approx \frac{\Delta f}{\Delta x_i}, \tag{8}$$

and derived from the composed equation of state by Span et al. and Heide.

With the shown uncertainty and a normal deviation, only 68.3 % of the values are within the uncertainty. In order to obtain higher percentage, a coverage factor of k=2 is commonly used and an expanded uncertainty

$$u_k(x) = k \cdot u(y), \tag{9}$$

can be calculated with a normal deviation percentage of 95.4 % of the values.

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Results and discussion

Initially the expanded uncertainty u_k of direct measured values are calculated and presented in figure 2.

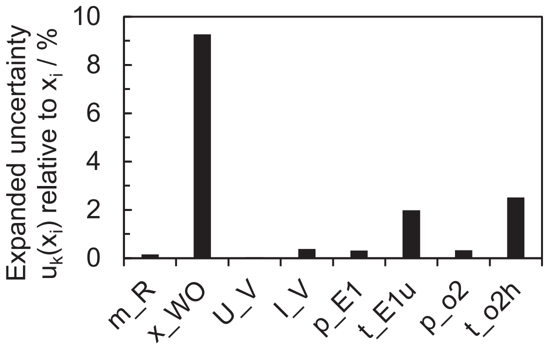

Figure 2: Expanded uncertainty of direct measured values

In addition to the direct measured uncertainty values the calculation of the expanded refrigerant capacity uncertainty $u_k(\dot{Q}_o)$ requires the uncertainty of enthalpy at expansion valve inlet and evaporator outlet. Therefore, the sensitivity coefficients of the enthalpy with respect to pressure, temperature and oil percentage is calculated on the basis of the differential quotient of equation (5) and shown in figure 3. A normalized sensitivity coefficient

$$c_{i,h}^* = \frac{\partial h}{\partial x_i} \cdot \frac{kg}{kJ}, \quad (10)$$

is introduced for appropriate presentation.

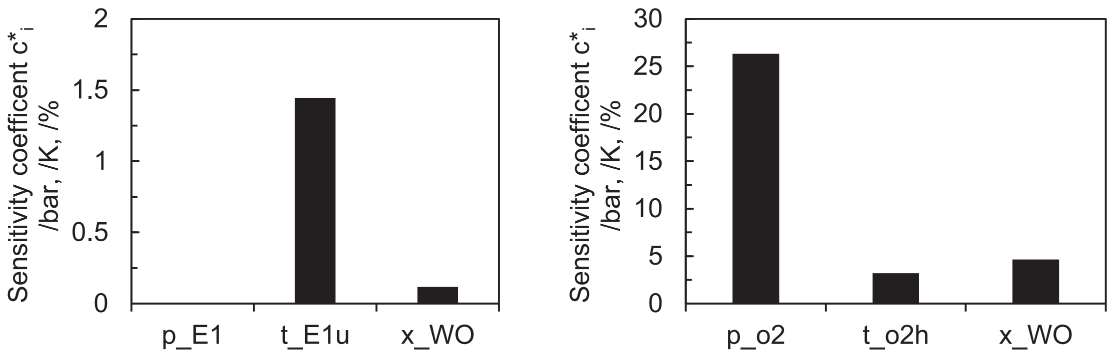

Figure 3: Normalized sensitivity coefficient $\boldsymbol{c_i^*}$ of pressure, temperature and oil percentage for enthalpy at expansion valve inlet (left) and evaporator outlet (right)

The influence of temperature to enthalpy before the expansion valve is dominant compared to oil percentage and pressure. In particular, pressure has a small influence to enthalpy due to the liquid phase. Pressure impact to enthalpy after the evaporator is much higher due to gas phase and also temperature and oil percentage have higher influence. With the knowledge of the sensitivity coefficients and the uncertainty of pressure, temperature and oil percentage, the expanded enthalpy uncertainty $u_k(h)$ relative to the enthalpy can be calculated for the descripted test bench and is presented in figure 4.

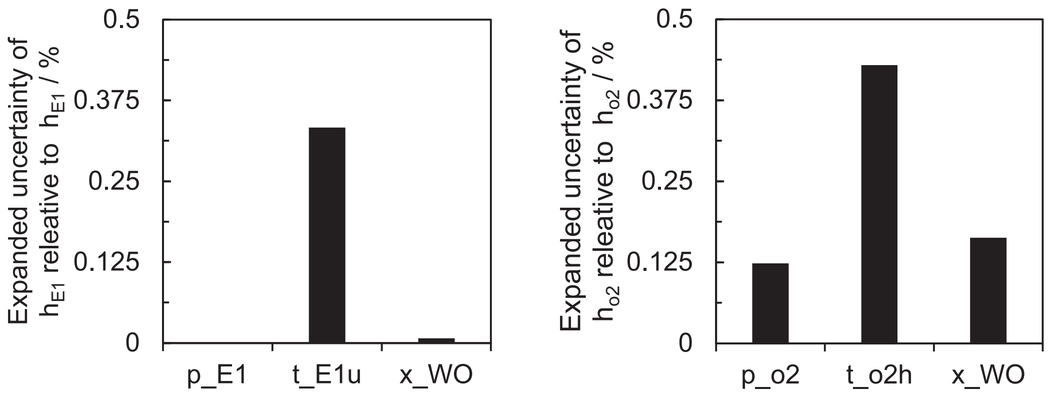

Figure 4: Expanded uncertainty of enthalpy relative to enthalpy due to pressure, temperature and oil percentage for expansion valve inlet (left) and evaporator outlet (right)

As expected from figure 3, uncertainty of enthalpy in liquid phase is mainly determined by the temperature. Due to high accuracy and low sensitivity coefficient of pressure in liquid phase, the influence of enthalpy uncertainty is negligible. In gas phase behind the evaporator the pressure affects the uncertainty by 0.125 %. However, due the higher accuracy of the pressure compared to temperature measurement, the temperature has higher impact. Furthermore the oil percentage has a significant effect to the uncertainty of 0.2 %.

Figure 5 presents the expanded uncertainty of refrigerant capacity $\dot{Q}_o$ calculated by uncertainty of enthalpy and refrigerant mass flow according to equation (7). The uncertainty of the temperature behind evaporator has the highest impact, followed by the temperature before expansion valve. Influence of mass flow is comparable to oil percentage, even the uncertainty of the sensor is much higher (figure 2). The reason is the higher sensitivity coefficient of the mass flow

$$c_{\dot{m}_R,\dot{Q}_o} = \Delta h = h_{o2} - h_{E1}. \tag{11}$$

Hence, high accuracy of the mass flow meter is important for the certainty of refrigerant capacity. The uncertainty of refrigerant capacity $\dot{Q}_{oK}$ according to equation 1 is much higher compared to $\dot{Q}_o$ and shown in figure 5. Reasons are the small temperature difference of the coolant due to high coolant volume flow in this application and the fact that GUM does not take into account the number of temperature sensors.

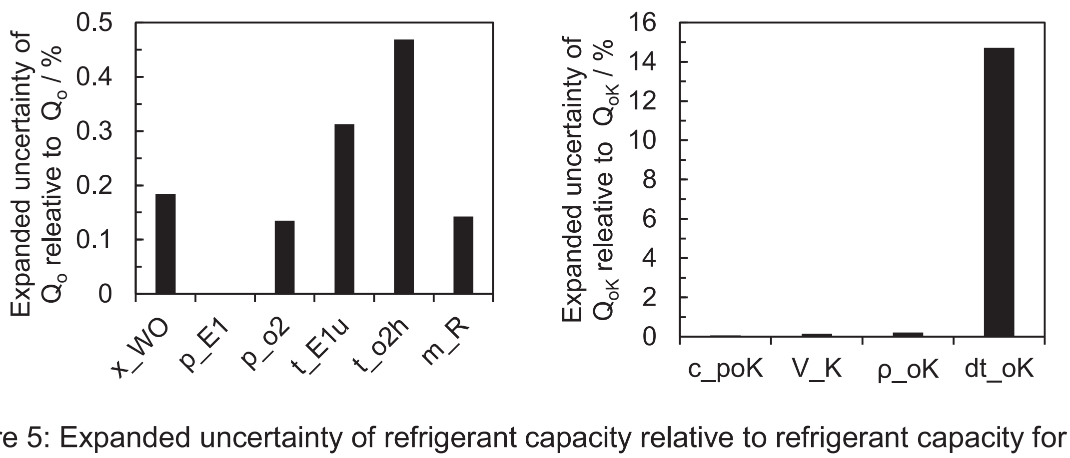

Figure 5: Expanded uncertainty of refrigerant capacity relative to refrigerant capacity for refrigerant balance site (left) and coolant site (right)

For the energy efficiency ratio (EER)

$$EER = \frac{\dot{Q}_o}{P_V}, \tag{12}$$

the measurement of compressor current and voltage have to be taken into account. The sensitivity coefficient of compressor power consumption is higher than the sensitivity coefficient of the refrigerant capacity $\dot{Q}_o$ by the factor of the current EER

$$\frac{c_{P_{V,EER}}}{c_{\dot{Q}_o,EER}} = EER = \frac{\dot{Q}_o}{P_V}. \qquad (13)$$

Therefore, the impact of the compressor current is with an amount of 0.25 % the third highest impact and high accuracy of the sensor is recommended. Voltage has lower impact due to higher sensor accuracy. The results for the different parts of uncertainty to calculate the EER are shown in figure 6.

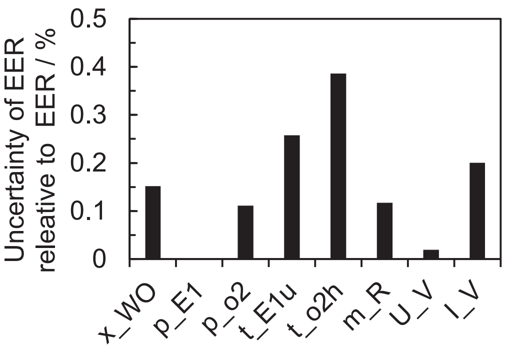

Figure 6: Expanded uncertainty of EER relative to EER due to direct measured values

Conclusion

This paper presents a method to calculate uncertainty in measurement of a vapor compression system (R134a and ND8 oil) according to the “Guide to the expression of uncertainty in measurement” (GUM). Thereby, direct measured values as well as derived values from equation of state are considered. In particular, impact of pressure, temperature and oil percentage to the equation of state is taken into account. The results point out the different influences of measured values to the uncertainty of the refrigerant capacity. A sensitivity analysis reveals high influence of temperature on enthalpy. Pressure has negligible influence to the liquid phase enthalpy but high influence to gas phase enthalpy behind evaporator and a suitable sensor is necessary. Furthermore the oil percentage has a notable impact to the evaporator outlet enthalpy and an accurate sensor is highly recommended. Uncertainty of refrigerant mass flow has a large impact on uncertainty of coolant capacity because of a high sensitivity coefficient. Overall the uncertainty of the refrigerant capacity according to refrigerant mass flow and enthalpy difference is 1.1 % in this application. Calculation of refrigerant capacity according to energy balance of the coolant site indicates high uncertainty of 14.7 % due to high uncertainty of the temperature difference of the coolant flow. The energy efficiency ratio (EER) is influenced by the uncertainty of the coolant capacity and compressor consumption. Thereby, sensitivity coefficient of compressor power consumption is higher by the factor of the current EER. Hence, uncertainty of compressor power consumption has strong impact to uncertainty of EER calculation.

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