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To cite this article: A Janzen *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **171** 012117

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Signal-to-noise ratio of temperature measurement with Cernox sensors at various supply currents

A Janzen¹, B Burger², A Ebersoldt², C Heidt^{1,3}, O Langhans³, A Reiner³,
S Grohmann^{1,3}

¹ Institute for Technical Thermodynamics and Refrigeration, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

² Institute of Data Processing and Electronics, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany

³ Institute for Technical Physics, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany

andreas.janzen@kit.edu

Abstract. The Karlsruhe Institute of Technology (KIT) has developed a new thermal method for flow measurement, which is particularly suitable for the application in cryogenic systems. In this method, the stability and the resolution of temperature measurement is important, rather than precision. In other words, constant offsets in temperature measurements can be ignored, and the temperature sensors can be operated at supply currents beyond their nominal design value in order to gain resolution. For this application, the performance of two Cernox™ type CX-1050-SD-HT-1.4L sensors was measured in a temperature range between 300 K and 4 K. The experiments were carried out in the calibration cryostat at the Institute for Technical Physics. Sensors were connected to a Lake Shore Model 121 current source and a Keithley 2701/E digital multimeter for voltage measurements. At constant calibration temperatures, the supply currents were varied such that the resulting voltage drops lay in-between 10 mV and 100 mV. The influence on both the noise and the temperature offset are presented.

1. Introduction

A commercial mass flow meter for application in helium cryostats is presently being developed by the Karlsruhe Institute of Technology (KIT) and the WEKA AG, Switzerland. It is based on a new thermal measuring principle which was developed and patented by KIT [1, 2]. During the measurement, heat is transferred to the cryogenic fluid, and the temperature differences induced in the sensor are evaluated. Through the combination of two independent analytical equations for the calculation of the flow rate, a complete compensation of systematic uncertainties is achieved [2].

Due to the cost of helium cooling, the amount of heat added at cryogenic temperatures needs to be kept at a minimum. Hence, in order to achieve a low uncertainty in the measured flow rate with the new flow meter, temperature measurements with a high resolution and a high signal-to-noise ratio (SNR) are required. For resistance thermometers, temperature measurement is generally a trade-off between self-heating of the used sensor and the desired temperature resolution, whereby the resolution can be increased with the supply current. This, however, results in a systematic temperature uncertainty due to self-heating of the temperature sensor. In the new flow measurement principle, the self-heating



uncertainty of the temperature sensors is eliminated and can thus be ignored, permitting operation at much higher supply currents than specified by the sensor manufacturer.

The present mass flow meter design employs three temperature sensors. For the design of the flow meter electronics, the noise performance of the temperature measurement using Cernox™ sensors was studied in the temperature range of 4 K to 300 K. This paper starts with a brief overview on the experimental setup. It then discusses the influence of a supply current increase at constant temperatures on the noise performance. The noise is evaluated in terms of standard deviation and combined uncertainty of the measured temperature.

2. Experimental setup

For the experimental noise investigation, two Cernox™ type CX-1050-SD-HT-1.4L sensors were used, abbreviated as CX 1 and CX 2 in this paper. The sensors were calibrated on delivery by Lake Shore Cryotronics, Inc. Figure 1 shows the corresponding response and sensitivity curves for the envisaged temperature range.

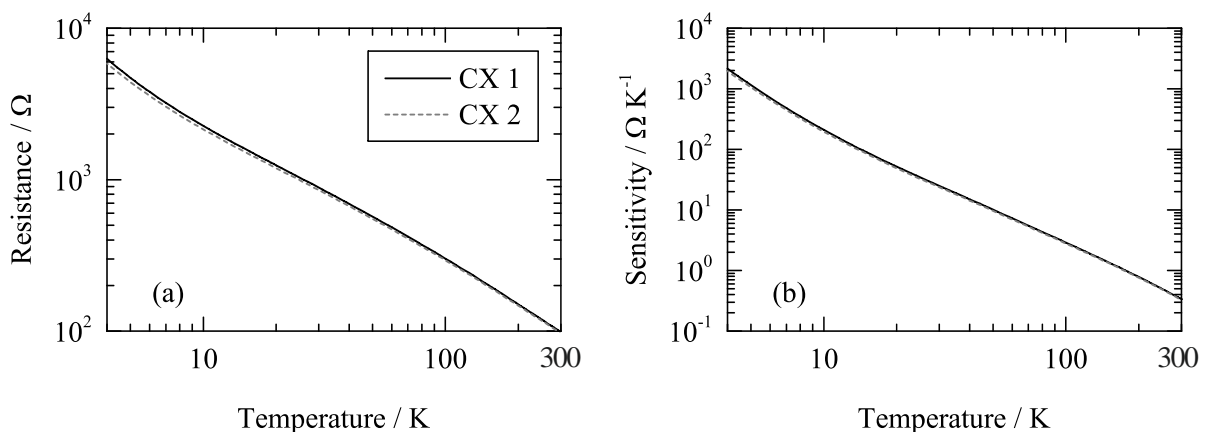


Figure 1. Response curve (a) and sensitivity curve (b) of the used Cernox™ sensors.

The temperature sensors were installed in a calibration cryostat at the Institute for Technical Physics that covers a temperature range of 1.8 K to 300 K. The radiation shielded cryostat is operated either in liquid helium bath mode for temperatures below 4 K, or else in evaporator mode at higher temperatures. A rhodium-iron and a germanium thermometer are available as secondary standards. Additionally, a vapor pressure thermometer is installed to verify the measured temperatures of the secondary standards. [3]

In the experiments, a TVO resistance thermometer that was calibrated against the rhodium-iron standard was used to measure the cryostat temperatures. This allowed higher sampling rates compared to using the secondary standards. The photo in figure 2 shows the installation of the sensors in the sensor holder. The TVO as well as the two Cernox™ were mounted into a calibration block made of oxygen free high conductivity (OFHC) copper. To achieve a good thermal contact, Apiezon® grease was used. The temperature sensors were connected using twisted pairs of cryogenic wire. Outside the cryostat, shielded cables were used for the connection to the measuring instruments.

As shown schematically in figure 2, all temperature sensors were connected using four-wire sensing. For the TVO sensor, the required supply current and the voltage measurement was provided by the electronics of the calibration facility. The two Cernox™ were installed in series with a Lake Shore Model 121 current source. To read out the supply current of the instrument, a 100 Ω precision resistor was installed. The voltage drops of this resistor and the Cernox™ were measured with a Keithley 2701/E digital multimeter (DMM) equipped with a 7703 multiplexer module. The scan rate of the system was about 55 Hz. The scan rate of the calibration facility electronics was much smaller.

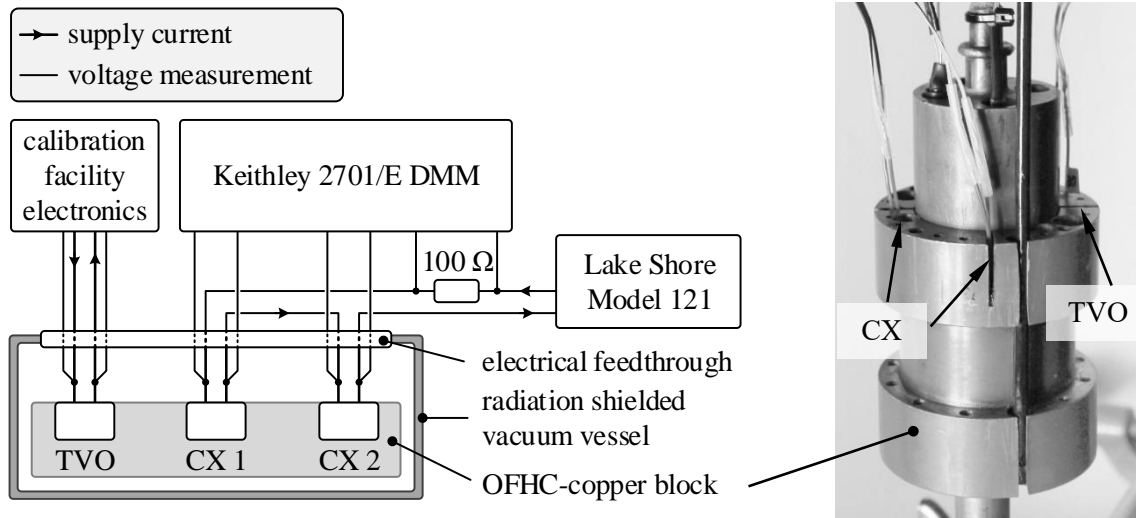


Figure 2. Schematic view of the experimental setup (left) and installation of the sensors in the sensor holder made of OFHC-copper (right photo).

3. Experimental results and discussion

3.1. Measurement conditions

The performance of the Cernox™ was measured at ten temperatures in the range of 4 K to 300 K. At every temperature, the supply current was varied until the resulting voltage drops approximately reached predefined values in the range of 10 mV to 100 mV. During current increase, care was taken to keep the power dissipation in the sensors below the limits recommended by the manufacturer (10^{-5} W at 300 K, 10^{-7} W at 4.2 K [4]). Due to the strong increase of the supply current with temperature and thus an increase in power dissipation, only five different settings were used above 20 K and four at temperatures over 100 K. Table 1 summarizes the measurement conditions.

Table 1. Measurement conditions.

$T_{\text{Cryostat}} / \text{K}$	Voltage drop / mV					
	10	20	40	60	80	100
296.0	x	x	x	x		
258.1	x	x	x	x		
206.6	x	x	x	x		
167.0	x	x	x	x		
104.8	x	x	x	x	x	
68.9	x	x	x	x	x	
52.3	x	x	x	x	x	
20.3	x	x	x	x	x	x
10.1	x	x	x	x	x	x
4.0	x	x	x	x	x	x

For every temperature and supply current, denoted as one measurement point, 2000 individual data points for the voltage drops of the two Cernox™ and the 100 Ω resistor were recorded in about 110 seconds. Since the scan rate of the calibration facility electronics was limited, only two readings of

the cryostat temperature were recorded for every measurement point: one at the beginning (data point 0) and one at the end of a measurement point (data point 2000).

3.2. Results

Figure 3 shows the results for the measurement series at 4 K. Every individual plot displays the measured data points of the temperature sensors CX 1 and CX 2 at a measurement point. The scales of the axes are kept constant.

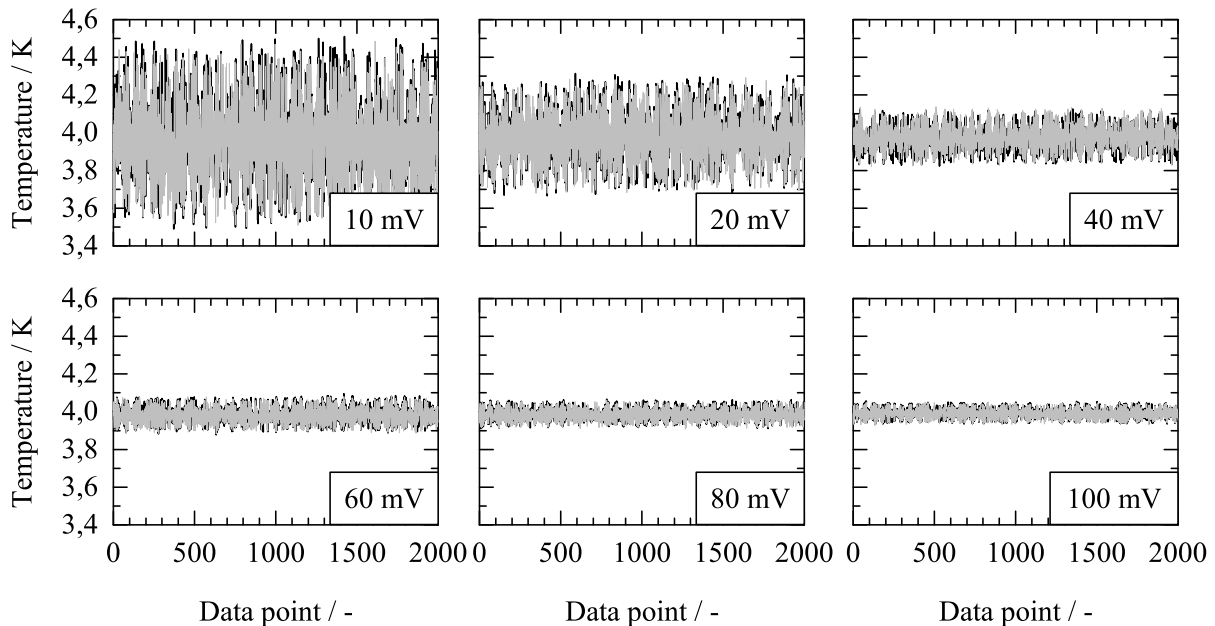


Figure 3. Measured temperatures of CX 1 (black line) and CX 2 (grey line) for different voltage drops resulting from a supply current increase at a constant cryostat temperature of 4 K.

The comparison of the plots illustrates that the scattering of the temperature values is strongly dependent on the supply current. It decreases with increasing supply current and increasing voltage drop, respectively. For 10 mV, the standard deviation calculated from the 2000 data points is ± 195 mK. This value is reduced to ± 23 mK at 100 mV voltage drop.

The statistical parameters of the complete measurement series of sensor CX 1 at 4 K are shown in the box-whisker plot of figure 4. It shows that both standard deviations (boxes) and the difference between the maximum and the minimum measured temperatures (whiskers) decrease with increasing voltage drop. The plot also contains the associated histograms, showing that the data have a normal distribution (black lines —). The mean temperature values for CX 1 (•) slightly increased together with the TVO temperature of the cryostat (grey line —) in the course of the measurement series.

At higher voltage drops, an increase of the measured mean temperatures of the Cernox™ sensors compared to the TVO temperature was expected due to electrical dissipation. To examine this possible self-heating effect, a voltage-current plot is given for different cryostat temperatures in figure 5. For resistance thermometers, a change in supply current is directly proportional to a change in voltage. Thus, at constant cryostat temperatures, all measured points should form a straight line through the origin. The electrical resistance of the thermometer can be obtained from the slope. If self-heating starts to dominate at a certain current, the temperature of the sensor will increase. For temperature sensors with a negative temperature coefficient (NTC – increasing electrical resistance with decreasing temperature) the electrical resistance will therefore decrease, resulting in a change of the slope. Since the plotted data shows a perfect line through the origin (max. residuum value: 13 μ V at 52 K and 80 mV for CX 1), the increase in mean temperature can be attributed to the slight temperature shift in the calibration cryostat, measured also with the TVO sensors. Even for lower temperatures, where self-heating becomes more

critical for NTC sensors, the slope does not change. Consequently, a significant systematic uncertainty due to self-heating of the sensors under investigation was not observed.

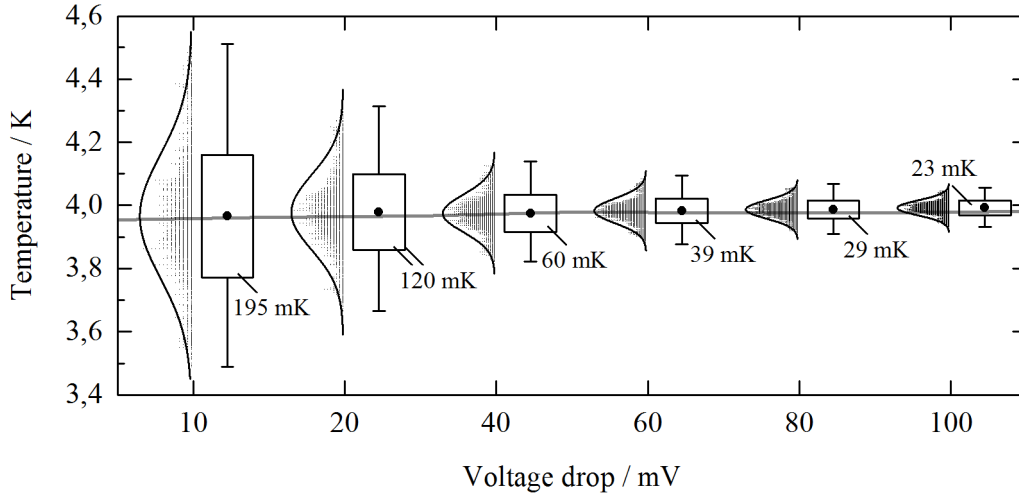


Figure 4. Box-whisker plot for the measurement series at 4 K with sensor CX 1. The boxes with annotated heights represent the standard deviations and the filled circle the mean temperature values. Whiskers mark the minimum and maximum values within a measurement point. Next to each measurement point, a histogram of the data points is shown together with the equivalent standard distribution. The grey line shows the cryostat temperature.

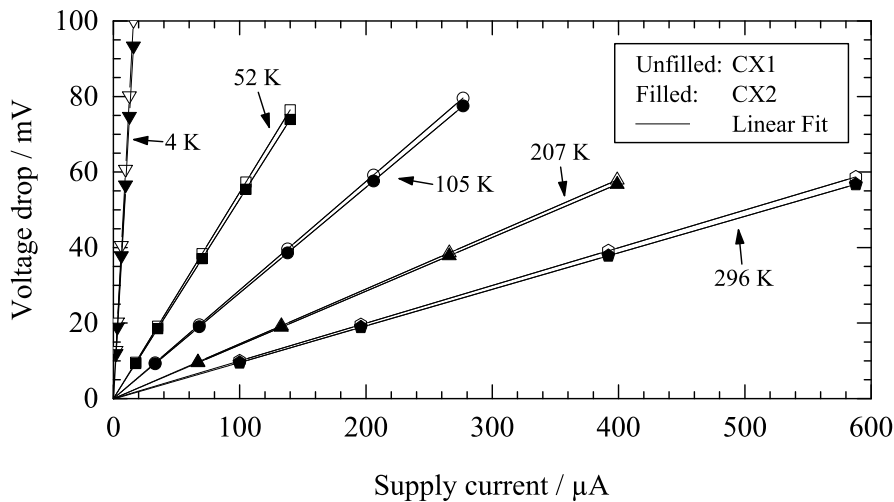


Figure 5. Voltage current plot for the two Cernox™ sensors at different cryostat temperatures.

Figure 6 shows the percentage change in the temperature resolution ΔT_i for different cryostat temperatures. All values are related to the temperature resolution $\Delta T_{10\text{ mV}}$ calculated for measurements at Lake Shore's recommended standard operation voltage of 10 mV [4] as given by:

$$\frac{\Delta T_i}{\Delta T_{10\text{ mV}}} = \frac{I_i}{I_{10\text{ mV}}} \frac{S_i}{S_{10\text{ mV}}} \quad (1)$$

with the sensors sensitivity S and the supply current I for different temperatures and voltage drops.

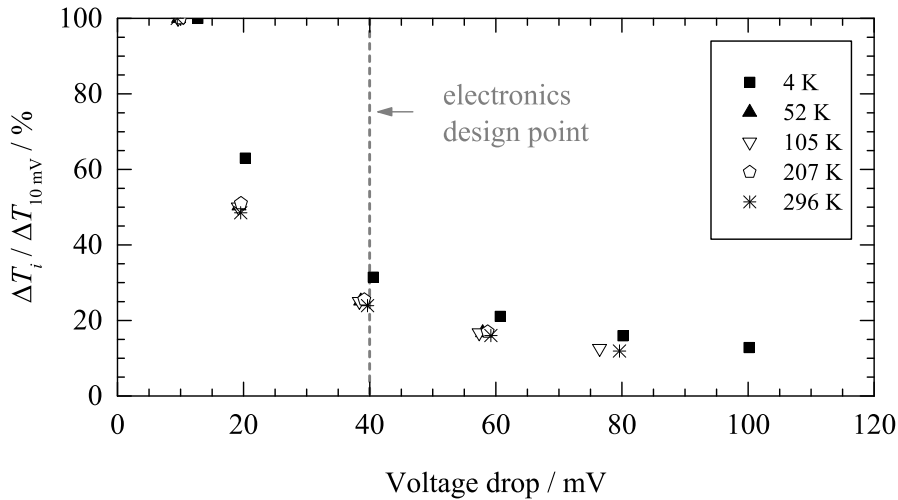


Figure 6. Percentage change in the temperature resolution ΔT_i at various voltage drops related to the temperature resolution at 10 mV, $\Delta T_{10 \text{ mV}}$. The characteristic is given for different cryostat temperatures.

Figure 6 illustrates that the largest gain in temperature resolution (decrease of $\Delta T_i / \Delta T_{10 \text{ mV}}$) is achieved at low to medium voltage drops. A voltage increase from 10 mV to 40 mV results in an improved resolution with ΔT s of only 25 % to 30 % with regard to the reference value. At higher voltages, the slope becomes flatter and the gain in resolution smaller.

The determination of the optimal sensor voltage, however, does not only depend on the gain in resolution. It is also important to limit the risk of failure. At high supply currents, temperature sensors may still overheat in case of insufficient thermal anchoring, resulting in calibration shifts or even in total failure. Therefore, a value of 40 mV was selected for the design of the electronics.

3.3. Uncertainty analysis

The data were evaluated with a detailed uncertainty analysis in order to determine the influence of the SNR on the combined measurement uncertainty. According to the guide to the expression of uncertainty in measurement (GUM) [5], the different contributions were divided into Type A (statistic) and Type B (systematic) uncertainties. Table 2 gives an overview on the uncertainties and their probability distribution used for the analysis.

Table 2. Overview of different uncertainty contributions and their probabilities.

Property	Uncertainty type	Probability distribution
voltage drop 100 Ω resistor	A	normal
voltage drop Cernox TM	A	normal
Cernox TM calibration	B	normal
Cernox TM fit equation	B	normal
Keithley DMM	B	rectangular
cryostat temperature	B	rectangular

All contributions with a rectangular probability distribution were calculated from their half widths divided by the square root of three. For the uncertainty of the Keithley DMM the one year data sheet accuracy for a measurement range of 100 mV was used. The supply current was derived from the measured voltage drop across a precision resistor. Its uncertainty was calculated by means of the law of uncertainty propagation. Following GUM, the Type A uncertainty caused by statistical scattering of the

measurement result decreases by the inverse square root of the number of observations. Therefore, if the amount of measured data points is large, the influence of the statistical scattering of the temperature values due to a low SNR (cf. figure 3) can be neglected and the Type B uncertainties will dominate the combined uncertainty. This is illustrated in figure 7, where the combined uncertainty of CX 1 is plotted against the number of data points for different voltage drops at 4 K. For the standard operation voltage of 10 mV (\square), roughly 60 to 80 data points are sufficient to decrease the influence of the Type A uncertainty to a minimum. The consideration of more data points yields only insignificant further reductions of the combined uncertainties.

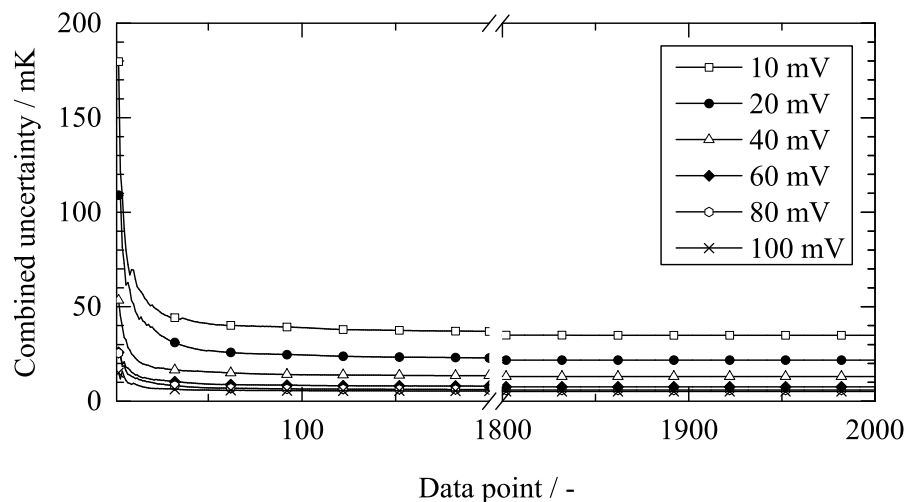


Figure 7. Dependence of the combined temperature uncertainty on the number of data points for different voltage drops that were measured at 4 K for CX 1.

4. Conclusion

In this paper, the results of a noise performance investigation of two Cernox™ type CX-1050-SD-HT-1.4L temperature sensors were discussed. The measurements were conducted in a calibration cryostat at the KIT Institute for Technical Physics in a temperature range of 4 K to 300 K. The aim of the investigation was to identify the influence of a supply current increase at constant cryostat temperatures on the signal-to-noise ratio and the temperature resolution. The different measurement series showed that the signal-to-noise ratio is higher for larger voltage drops and therefore a gain in temperature resolution can be obtained by increasing the supply current. At the same time, it was shown that the risk of systematic uncertainties due to sensor self-heating was very low. A comprehensive uncertainty analysis according to GUM [5] indicated that the influence of the temperature noise level on the combined uncertainty can be strongly reduced if the amount of data points used for evaluation is raised to more than 60. Above this limit, Type B uncertainties dominate. The results were used to define the design conditions for the electronics of a new thermal mass flow meter, which is currently under development in cooperation with the WEKA AG, Switzerland.

References

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