Journal of Machine Engineering, 2019, Vol. 19, No. 3, 56–65
ISSN 1895-7595 (Print) ISSN 2391-8071 (Online)

Received: *21 December 2018* / Accepted: *02 July 2019* / Published online: *25 September 2019*

temperature measurement,
calibration, PRT sensor

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EFFECTS OF VARIATION IN MEASUREMENT CHAIN ON TEMPERATURE MEASUREMENT CALIBRATION WITH RESISTANT TEMPERATURE SENSORS

Temperature is one of the most important key parameter to consider in measurement and mechanical engineering, because every measurement has to be conducted with reference to standard temperature conditions (20°C, ISO 1). Strictly speaking, almost every measurement depends on the accuracy of the temperature measurement, which requires proper calibration. Therefore, standards list detailed criteria to fulfil temperature calibration with high precision. In fact, any calibration is only valid, if the whole measurement chain is taken into account. This would make recalibration necessary with each variation of the components in the measuring set-up (varying cable length, different measurement channel etc.), which is time-consuming or even impossible in practice. For that reason, this paper presents a practicable calibration strategy, which specifies each component individually and later combines the calibration results according to the composition of the measurement chain. This provides a fast and useful way to achieve the required accuracy of temperature measurement. The examined, exemplary measurement chain consists of an industrial platinum resistance thermometer (IPRT), cables with different lengths, an electrical amplifier and a reference temperature calibrator.

1. INTRODUCTION

The product and process temperatures are important physical parameters in many manufacturing processes. Inline temperature monitoring is a key factor for high quality production in industries such as chemicals, food, pharmaceuticals, metals or energy production. However, even applications in which the temperature is not the primary parameter to be measured, exact temperature measurement is important. To ensure comparability of measurements, ISO 1 defines standard conditions for temperature measurements [1]. According to this standard, geometrical and dimensional properties of products or machines must be determined at 20°C. In addition, the temperature significantly affects the accuracy of most measuring systems. For example, the length measured by laser interferometers can

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https://doi.org/10.5604/01.3001.0013.4080

vary with up to 1 μm/mK. Therefore, many of these systems apply temperature correction, which makes monitoring of the temperature itself essential for any measuring task.

There is a broad range of methods to measure the temperature based on different physical principles, e.g. thermoelectricity, temperature-dependant variation of the resistance of electrical conductors, and spectral characteristics. They are classified according to the medium of interest. Invasive methods allow direct contact to the medium, while semi-invasive methods treat the medium in some manner. Non-invasive methods observe the medium from a distance [2].

The Chair of Machine Tools and Control Engineering needs temperature measurement to estimate the thermic state of the machine and the correlated thermal error at the Tool Centre Point (TCP). Therefore, a direct measurement on the surface of the machine is necessary and requires good accuracy. To achieve this, twenty PRT-sensors are mounted along the whole machine structure (Fig. 1). The PRT sensor meets the requirement of an accuracy better than 1 K, response time less than 30 s and robustness against external influences.

Although the individual sensors are easy to attach, the installation of the sensors along the entire machine structure is complex. Cables with different length can only follow the machine movement to a limited extent. For that reason, the cable routing is adapted to the motion and difficult to change afterwards. Moreover, there is the obstacle of availability, since this is an experimental machine. This means on the one hand, temperature measurements are performed with long time intervals, so surrounding temperature and environmental conditions change. On the other hand, parts of the measuring chain could be replaced or disconnected in the meantime. In fact, this makes a recalibration necessary for each new measurement.

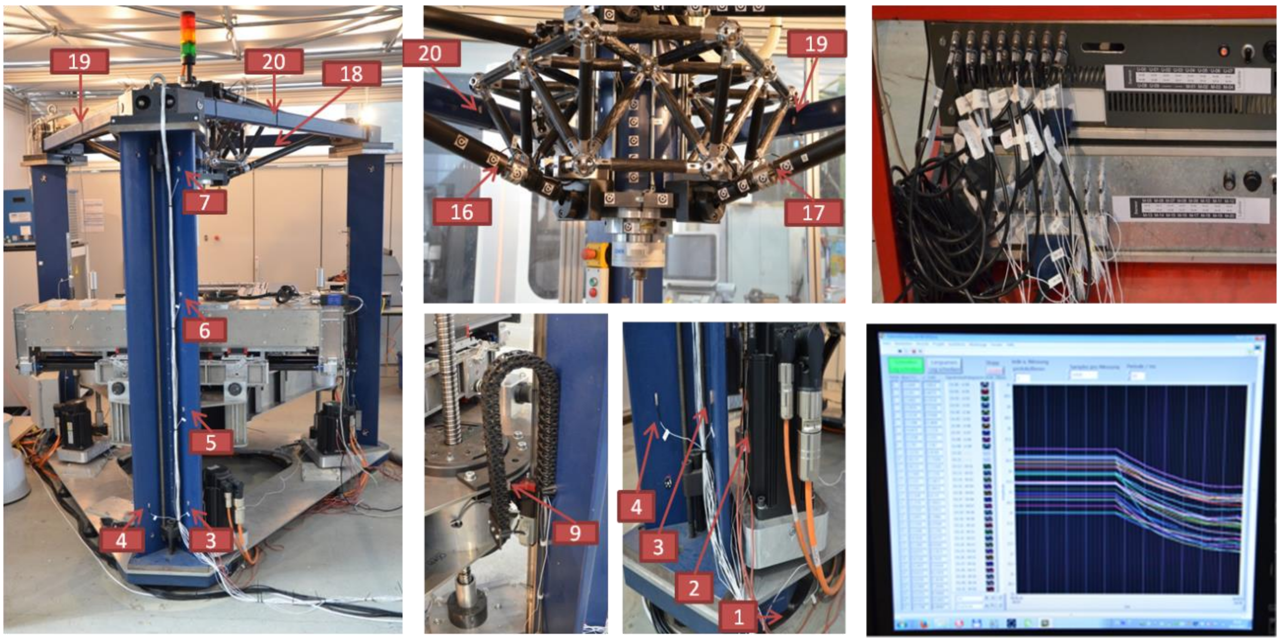

Fig.1. Application of PRT-sensors along a machine structure. On the right: multi-channel-readout and diagram of detected temperature

The regular calibration should be simple and feasible without having to disassemble the sensors and send them to a calibration laboratory. It is also possible, to calibrate each sensor in the available "Reference Temperature Calibrator". But this method is very time consuming to repeat it for all sensors. The new idea is, to estimate the overall characteristic of the system when the influence of the single device is known. With a suitable correction value determined for the used devices, each new measurement setup can be calibrated without great effort and without dismantling. For that reason, this paper presents an experimental setup to quantify the influence of all devices and proposes an easy calibration strategy, which is applicable in the field.

2. STATE OF THE ART

Every application requires a specific measuring method. Davies [2] lists factors to consider when selecting the best suiting method. For example: temperature range, sensor robustness, temperature field disturbance by the sensor, signal type, sensitivity to noise, response time, and uncertainty. Obviously, these factors do not necessarily coincide with desired features such as ease of calibration, availability, cost and size.

Childs [3], Michalski [4] and Nicholas and White [5] give a summary of most of the temperature methods. Davies introduces temperature measurement methods in the field of material removal processes and gives a general historical overview of the increasing research interest and inventions in temperature measurement [2].

This paper deals with an invasive method to measure surface temperature with platinum resistant thermometers (PRT), which are in direct contact to the object of interest. Especially industrial platinum resistant thermometers (IPRT) take into account the harsh conditions in industrial environment, where vibrations, dirt and dust may occur and affect the sensor. The measuring element is a resistor, consisting of a platinum wire or a platinum layer encapsulated in a ceramic housing (insulator). Depending on the actual application, a metal sheath protects it additionally. This sensor is widely used because it provides a linear relation between a certain temperature range and the resistance of the platinum wire. The platinum element is dimensioned in such a way, that the resistance of the device is 100 Ohm at 0°C, what gives the resistor the name Pt-100 [6]. It changes approximately 0.4 Ohm per degree Celsius; detailed lists about the resistance/temperature ratio are given in DIN EN 60751 [7].

The standard recommends PRT sensors for temperature ranges of –200…+850°C. It defines three classes for the achievable accuracy, where devices with class A have accuracies of $\pm$ $(0.15 + 0.002\ |t|)$ and class B devices $\pm$ $(0.3 + 0.005\ |t|)$ valid for a temperature range of –50…+500°C. Other advantages are low cost, easy to use, sizes of the sensor vary between 0.9 mm to 4 mm and response time is from 2 s to 20 s [2].

To ensure the reliability of the results obtained with temperature instruments, it is crucial to calibrate the used sensors. There are two calibration strategies: in the fixed-point method, a fixed temperature of a reference cell is adjusted. In the comparison method, the object to be calibrated and a reference thermometer are heated to the same temperature in a thermostat and the values are compared to each other. The fixed-point cell and/or standard thermometer must be traceably calibrated with reference to a national standard [8]. Moreover calibration should be done in regular intervals, in order to take into account influences on the instrument introduced by the process or the machine.

There are several attempts in literature to evaluate the accuracy of platinum resistant sensors under different environmental conditions. [6] shows in detail how a calibration by comparison with a reference PRT is performed and gives a detailed determination of the uncertainty values for an IPRT. [9] analyses different environmental influences on the sensor, [10] documents the expected hysteresis of IPRT. Nonetheless, [11] even calculates a new interpolation scheme to improve the temperature deviation of IPRT with respect to the ITS-90 temperature scale.

In summary, there is a lot of research done on the accuracy and use of industrial platinum resistance thermometers (IPRT) for precise measurement. Now, we want to quantify the impact of the single devices in the measurement chain on the calibration result.

3. EXPERIMENTAL SETUP

To show the influence of each device in a measurement chain, the following setup is used (Fig. 2).

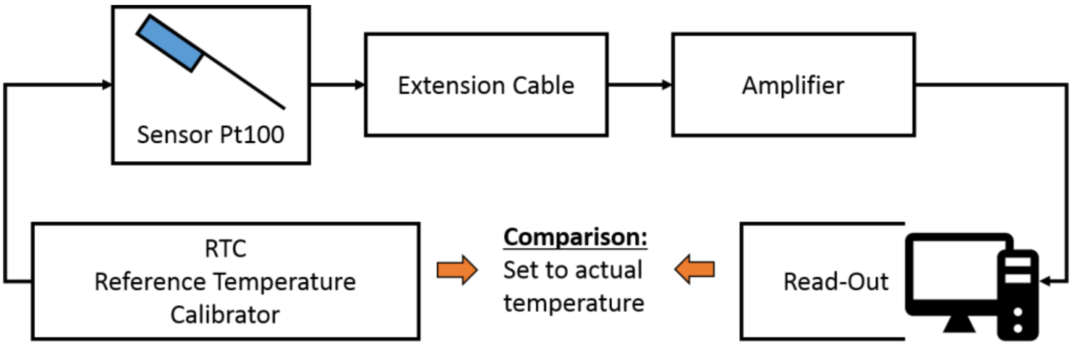

Fig. 2. Elements of measurement chain

The temperature sensors are connected to an amplifier (HBM Quantum X MX840B) with extension cables of different length. To read and save the temperature data the amplifier is connected to a computer. In every experiment, the logged temperature data has to be compared to a reference temperature, which is provided by the Reference Temperature Calibrator (Ametek: type RTC-156 C). This device can set the temperature to an accuracy of 0.04 K. Finally, the set reference temperature compared to the measured temperature by the sensors under test indicates the influence. The tested temperature range is from 0–50°C.

The devices listed in Table 1 are available for variation of the measurement chain. The abbreviations are used in the following diagrams as well as in the discussion of the results. Apart of those sensors and amplifiers, there are five extension cables with different lengths: 10, 20, 30, and 50 m.

This paper has not the purpose to calculate the total accuracy of the entire measurement chain, but to quantify the influence of every single element on the calibration. For that reason, it is a relative measurement, which focuses on the difference in temperature measurement by varying the single devices.

Table 1. Equipment for measurement setup and its abbreviations used in following experiments

Sensors		Amplifier		
Type designation	Abbreviation	Type designation	Abbreviation Amplifier	Abbreviation Channel
Pt100 resistor-based sensor • Ahlborn: type FPA 611, class B • Limiting deviation ±0.3K (0°C), • Temperature range: (–10 ... +90)°C • 4-wire configuration	S1	Amplifier • HBM: QuantumX MX840B • 8 channels available • Limiting deviation 0.05–0.1	V1	Ch 6
	S2		V2	Ch 7
	S3		V3	Ch 8

4. THE EXPERIMENTS

The experiments are carried out to quantify the influence of devices. The experimental setup does not change, unless expressly stated otherwise. First of all, the sensors itself are characterised. For this purpose, there are two experiments carried out.

4.1. RELIABILITY OF SENSORS

The experiment is carried out with sensors plugged in each channel. The sensor-channel combinations remain unchanged during the entire experiment. The directional dependence of the temperature curve is tested. First, the heating cycle gradually increases up to 52°C and RTC-sensors measure at 10, 30 and 50°C. Then the reference calibrator cools down to 8°C and sensors measure at the same temperature marks. This is repeated twice. For a better determination of the temperature values, the heating and cooling cycle is set slightly above or below the target temperature.

The hysteresis is small for all sensors (Fig. 3a). This means, that there is no directional dependency for temperature calibration. Each sensor has linear characteristic, although the gradient differs. For example, sensor S3 in channel 8 (red graph in Fig. 3a) has the lowest difference (–0.17 K) to the set temperature at 10°C, but the highest difference (– 0.65 K) at 50°C. Sensor S2 in channel 7 shows opposite characteristic (–0.31 K at 10°C and –0.52 K at 50°C, green graph).

In the field, there are often situations, in which plugged sensors are repeatedly disconnected, rearranged and re-plugged. This may be due to changes in design, experimental setup, or other cable routing. The following experiment is carried out, to quantify the influence of repeatedly re-plugged sensors on the measurement, which are summarised in Fig. 3b. Each sensor is plugged in and out 10 times. Here, the increase in the deviation with increasing temperature becomes apparent, too. In fact, there is a resulting fluctuation range for the measured temperature, which is usually approx. 0.05K. Except for Sensor S3 and S2 at 10°C, which show the greatest fluctuation with 0.12K and 0.10K respectively. Outliers likely cause these results.

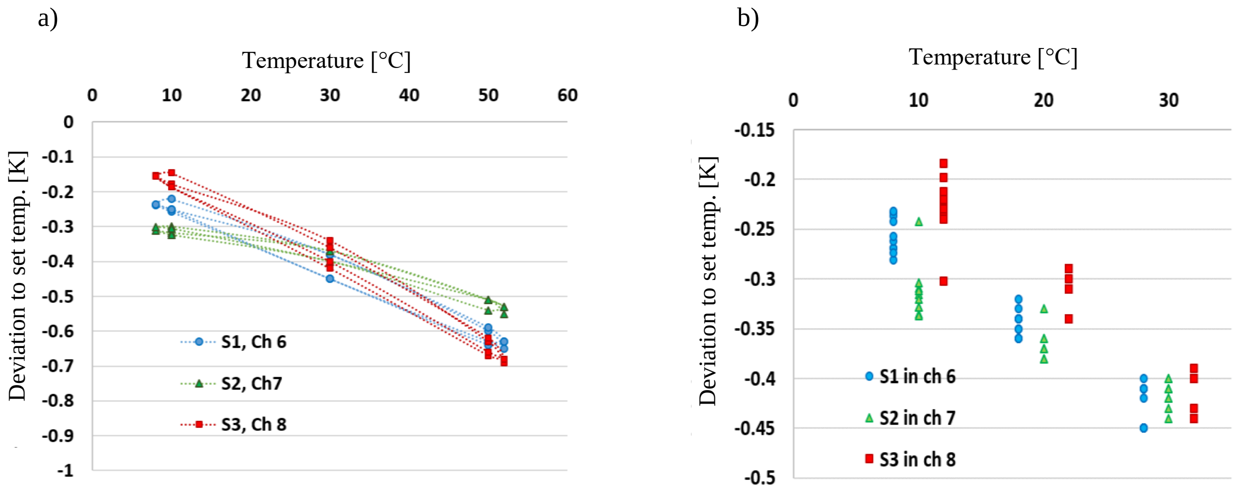

Fig. 3. a) Sensor response to rising and falling temperatures; b) Influence of sensors being re-plugged in channel repeatedly

The influence of a sensor being replugged to the channel is present and affects the second digit after decimal mark. For precise temperature measurements, it is therefore important to ensure that the sensors remain unchanged in the channel during a running measurement. Nevertheless, the sensor itself has a very good repeatability and no directional dependency of temperature, which shows the small hysteresis between heating and cooling cycle.

4.2. INFLUENCE OF CHANNEL

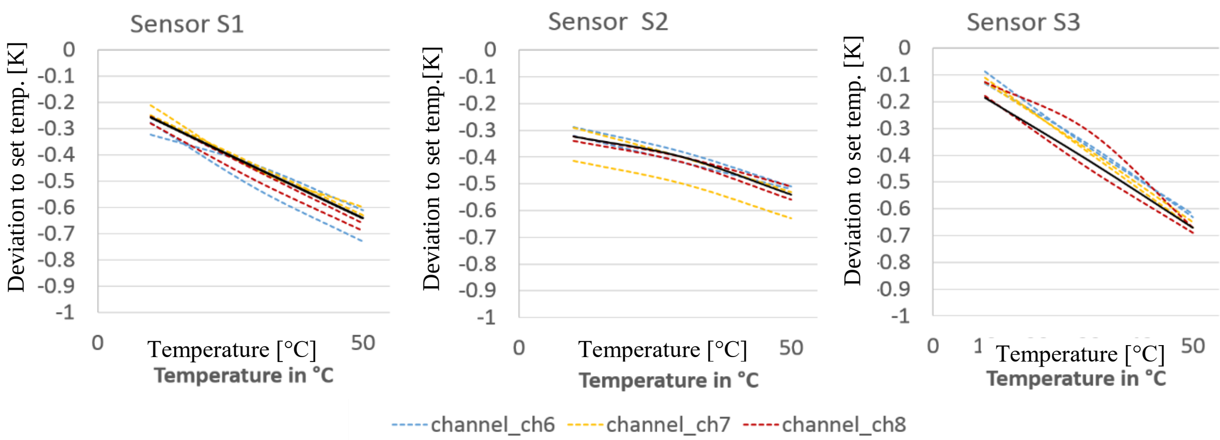

Fig. 4. Influence of channel on sensor

In this context, it is interesting to check whether the choice of channel matters for the temperature measurement. Therefore, the sensors are plugged into different channels of the amplifiers and the temperature is measured. The test is performed twice and Fig. 4. shows the results.

The sensors are sensitive to the influence of the channel, they are plugged in. Nonetheless, it gets evident that relative to the reference sensor line (black graph in Fig. 4) the influence of the channels can be described as a constant offset, they show similar characteristic.

4.3. INFLUENCE OF CABLE LENGTH

This experiment is carried out to test the influence of cable length on sensor response. Five different length of extension cables are available for the experiment. They vary from 10 m to 50 m. In addition, a test was carried out without any extension cable (black graph, marked as "_+0 m" in Fig. 5). This test is the referenced sensor behaviour. A further experiment was performed, in which two cables of 10 m were combined and later a cable with 20 m was used. This serves to directly compare whether the resulting total length is involved or whether an additional uncertainty is introduced into the measuring system by the plug connections (blue graphs, marked as "_+2×10 m" and "_+20 m" in Fig. 5)

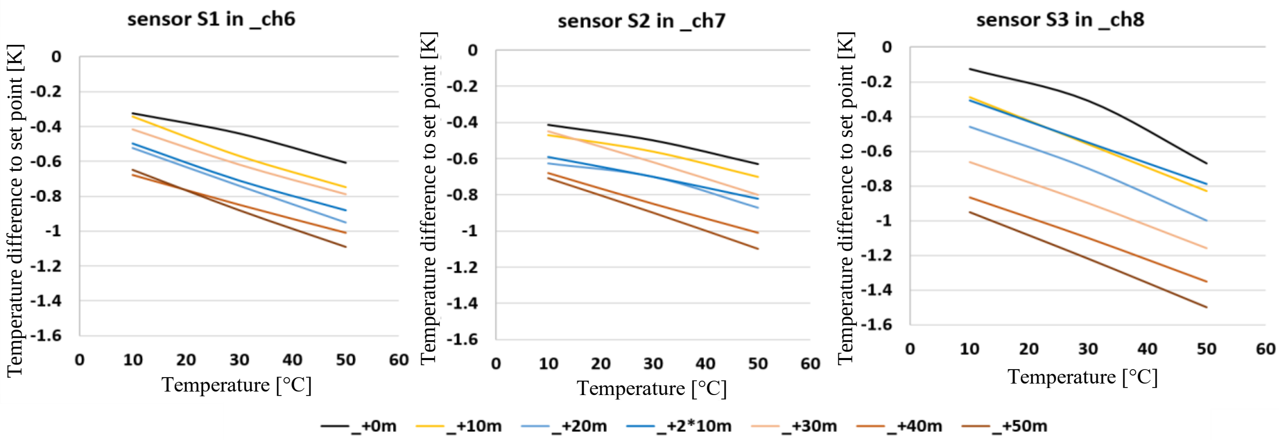

Fig. 5. Influence of different cable length on sensors

It gets evident, that the influence of the cable length is significant for the system. The deviation of the measured values to the set temperature increases with increasing temperature. The gradient of the curves differs slightly, but the influence of the variation of the cables is constant and can be described as an offset to the reference line (sensor without influence of cables "+0 m"). This systematic deviation is suitable for establishing a calibration correction factor.

In addition, the total resistance along the resulting cable length mainly influences the behaviour of the sensors. This is shown by the two curves "+2×10 m", which is carried out with two connected cables of 10 m each and "+20 m", where a single cable of 20 m was used. Both curves have similar characteristics. Although, they differ slightly, the influence of the plug connection is minor to the influence of the resistance. Again, sensor S3 differs from that characteristic. The difference is approximately 0.2 K.

4.4. INFLUENCE OF AMPLIFIER

In this experiment, the influence of different electrical amplifiers is tested. Here, the test with amplifier V1 is reference, as it is used in the initial sensor tests (Chapter 4.1). The third amplifier V3 shows similar characteristics for all sensors. Surprising results are achieved with the device V2, that differs completely from the linear characteristic obtained so far (blue graph, Fig. 6). The temperatures measured with sensor S1 show nearly no deviation (max. 0.015 K at 10°C).

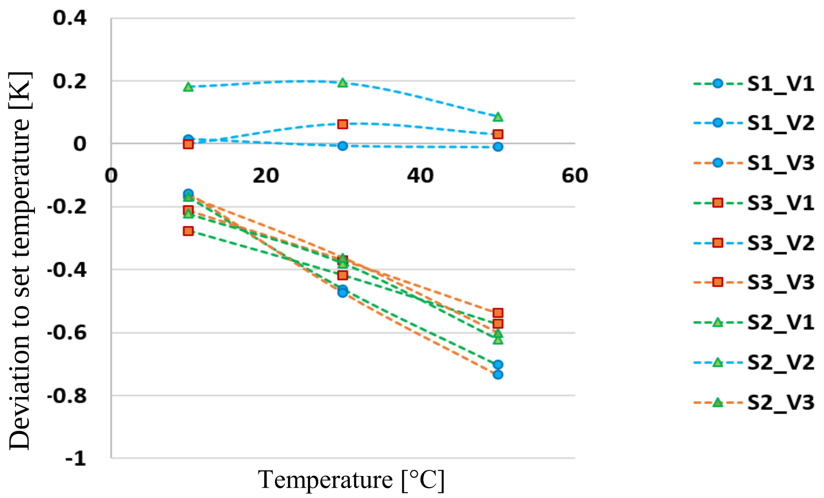

Fig. 6. Influence of electrical amplifier on sensor

5. CALIBRATION STRATEGY

By knowing the influence of the single devices, it is possible to estimate the overall correction of the system. Therefore, the configuration of the initial sensor test (Chapter 4.1) is defined as reference: the amplifier V1 is used, Sensor S1 is connected to channel Ch 6, sensor S3 to channel Ch 8 and sensor S2 is plugged in channel Ch 7. All values have been adjusted for the influence of the sensors (deviations of sensors were calculated in initial test in Chapter 4.1, too). The mean value of the results are shown in Table 2.

The mean values show the impact of the devices on the overall uncertainty in the measurement chain. The examined amplifier V2 (Chapter 4.4) seems to interfere well with the basic deviation of the sensors. Now that this influence is subtracted, it gets clear that V2 is markedly different in value from the others of the sample. Apart of this outlier, the extension cables have the greatest influence on the overall measurement chain.

In a fist attempt, the influence of the devices can be expressed as a constant offset (Table 2). Variation of the gradient is not yet included. With this offset values for every device, it is possible to assemble a measurement chain flexibly. The devices, which are available on site, can be used and calibrated by adding the corresponding offset value.

Table 2. Mean values for each device in a measuring chain. Values are given in Kelvin

Reference configuration		S1, V1, Ch 6	S2, V1, Ch 7	S3, V1, Ch 8
Basic deviation of sensor		–0.425	–0.405	–0.400
Extension cable	10 m	–0.130	–0.172	–0.160
	20 m	–0.313	–0.560	–0.302
	2×10 m	–0.271	–0.144	–0.149
	30 m	–0.184	–0.219	–0.508
	40 m	–0.364	–0.442	–0.706
	50 m	–0.448	–0.498	–0.824
Electrical amplifier	V1	-	-	-
	V2	0.425	0.559	0.43
	V3	–0.030	0.028	0.026
Channel	Ch 6	-	–0.001	0.033
	Ch 7	–0.007	-	0.012
	Ch 8	–0.049	–0.021	-

To improve the correction, the gradient factor has to be included. Therefore, in further research a correction of the calibration curve can be defined, which considers different characteristics.

6. CONCLUSION

Temperature measurement on machines with complex structure, difficult environmental conditions, long time intervals and changing equipment showed the need for an easily applicable calibration strategy. The calibration should be executed in the field with the equipment available at the institute. With good knowledge about the influence of every device on the temperature result, it is possible to define a device-specific offset value for the calibration. Moreover, those offset values can be combined in any way, so that the final setup for the measurement is very flexible.

Therefore, a setup was presented that allows quantifying the influence of every device in a temperature measurement chain. This normally consists of a PRT-sensor, an electrical amplifier, extension cables and a read-out to save the data. To verify the measurement a precise reference temperature was provided by an additional dry-block calibrator. The devices were interchanged with identical devices (same company, configuration, type) and results were compared.

At first, a general consideration of the IPRT-sensors showed a good repeatability and small hysteresis, so that there is no dependency on the temperature cycle (heating up or cooling down). The extension cables have the most significance for the temperature result. The longer the extension, the greater is the deviation to the set temperature. The investigation on the influence of the channels showed just small deviations. On the contrary, the investigation on the influence of the electrical amplifier showed surprising results. While the first two devices show similar behaviour, the third device is completely different. Here, more experiments should be performed with different devices to ensure the results. The first attempt to use an offset approach for the correction value is practicable, in further research the correction curve may be modified to take into account the gradient. The presented calibration strategy is practicable. The tests of the devices is time-consuming, but is required just one time. If the experiments are carried out once to calculate the correction values, it can be adapted to any setup configuration.

ACKNOWLEDGMENTS

This research was funded by the German Research Foundation – Project-ID 174223256 – TRR 96, project C06, which is gratefully acknowledged.

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