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High-precision measurement of absolute temperatures using thermistors

Volker H. Hans

Institute of Measurement and Control, University of Duisburg-Essen, Schuetzenbahn 70, 45117 Essen, Germany; volker.hans@web.de

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Abstract. High-precision temperature measuring technique presupposes a high standard of quality of all components of the measuring system. Most important is the temperature sensor. Thermistors have been proved good for long-term stability in a limited temperature range from –20 to +50 °C. The non-linear characteristic of the thermistor can be mathematically described. Multislope analogue-digital converters with very high resolution applying compensation measuring methods are efficient for the exact determination of absolute temperatures with an accuracy better than 1 mK resolution.

Key words: absolute temperature, thermistor, multislope AD converter, compensation.

1. INTRODUCTION

Temperature is the most frequently measured quantity in industrial processes. Nevertheless, not so many papers about temperature measurement have been published in the past in comparison to the measurement of other physical quantities. Only a few of them deal with the application of thermistors in temperature measurement, but not with high precision. Unreasonably, thermistors have an ill reputation.

The National Bureau of Metrology in Switzerland has established that thermistors have a very good long-term stability in the range of –20 to +50 °C. The characteristic in this range is non-linear but well reproducible and can be described by a mathematical function. There are many special applications of thermistors in industry as well as in calibration laboratories with temperature resolution of 1 mK and absolute accuracy better than 10 mK.

A special occasion of precise temperature measurement is precise measurement of the length of large objects. In interferometric length measurement techniques, resolutions of some μm are obtained. Measuring large objects with dimensions up to 10 m, the accuracy of length measurement depends on the knowledge of the coefficient of linear expansion and of the absolute temperature. By the measurement of an object of steel, e.g. with a length of 5 m, a deviation of the temperature of only 0.5 K results in the error in the length of 29.3 μm. To keep an accuracy of 1 μm, the accuracy of the absolute temperature measurement must be better than 10 mK with a resolution of 1 mK. Additionally, due to the large dimension of the object to be measured, the temperature must be determined at many points simultaneously.

2. CHARACTERISTIC OF THE THERMISTOR

The nominal resistances of thermistors at the reference temperature of 25 °C cover a wide range from 100 Ω to some MΩ. The selection depends on the application. A typical thermistor we have used had a nominal resistance of 10 kΩ at 25 °C. The characteristic of thermistors is non-linear, the resistance variation range is relatively wide from 80 to 4 kΩ and the sensitivity of the sensor varies from 4000 to 160 Ω/K in the temperature range from –20 to +50 °C. To realize the expected accuracy, a resolution of at least 15 bits is necessary. Figure 1 shows a typical thermistor characteristic.

The relationship of the resistance in Ω and temperature in K has been expressed mathematically first by Steinhart and Hart [1]:

$$\frac{1}{T} = A + B \ln R + C(\ln R)^3, \tag{1}$$

where A, B and C are curve-fitting coefficients. Exact determination of these coefficients is important for the precision. The needed accuracy of the coefficients can be determined by using derivatives of the temperature relative to the coefficients. Coefficient A must be determined with 8-places precision, coefficient B with 7-places precision and coefficient C with 6-places precision.

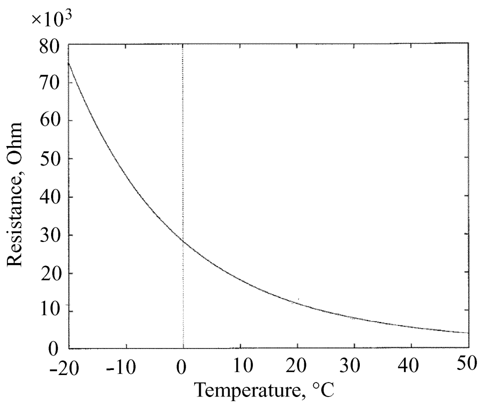

Fig. 1. A typical thermistor characteristic.

Sometimes the manufacturers of thermistors add to Eq. (1) an additional term of second order. Experiments have shown that Eq. (1) is best suited and sufficient for the temperature range mentioned above [2].

The claim for high accuracy of the temperature requires an exact determination of the curve-fitting coefficients. For that different methods can be used. Three exactly measured temperature points lead to a system of three equations with three coefficients. They can be determined according to the International Temperature Scale ITS 90 with fixpoint-cells of mercury (–38.8344 °C), water (0.0100 °C) and gallium (29.7646 °C). Considering systematic deviations of the cells, the greatest error at 50 °C is theoretically about 7.5 mK.

Another procedure aims to determine the curve-fitting coefficients by non-linear regression analysis according to the desired temperature range. This method takes into account that deviations of many measured values are stochastically distributed and the mean square error is minimal [3]. Using this method, the characteristic of the thermistor can be determined in comparison with a platinum resistance transfer standard at constant temperatures in an adiabatic isolated cell.

Many experiments have shown that determination of the curve-fitting coefficients with fixpoint-cells lead to deviations in temperature measurement less than 10 mK. The non-linear regression analysis, however, results in deviations better than 5 mK.

3. THE METHOD OF MEASURING THE THERMISTOR RESISTANCE

There are many well-known methods for measuring resistances. In this case it was decided to measure the voltage drop across the thermistor. The postulation of an absolute accuracy of 10 mK results in a resolution, which corresponds to 16 bits. Multislope analogue-digital converters (ADC) have been proved efficient for this kind of measurement. Figure 2 shows the principal block diagram of the measuring circuit [2]. In Fig. 2 R_{th} is the thermistor resistance, U_{ref} is the reference voltage, R_{x} determines the ratio between the ADC input voltage u_{e} and U_{ref}, N_{a} is the number of impulses of the converter and K is a comparator.

The result of impulses N_{a} of the ADC is given by

$$N_{\mathrm{a}} = K u_{\mathrm{e}} / U_{\mathrm{ref}} . \tag{2}$$

That means that instabilities of the reference voltage influence the result. But by feeding the thermistor with the same reference voltage, R_{x} and R_{th} are working as a voltage divider yielding

$$u_{\mathrm{e}} = U_{\mathrm{ref}} R_{\mathrm{x}} / (R_{\mathrm{x}} + R_{\mathrm{th}}). \tag{3}$$

Inserting Eq. (2) into (3) reveals

$$R_{\mathrm{th}} = R_{\mathrm{x}} (K / N_{\mathrm{a}} - 1). \tag{4}$$

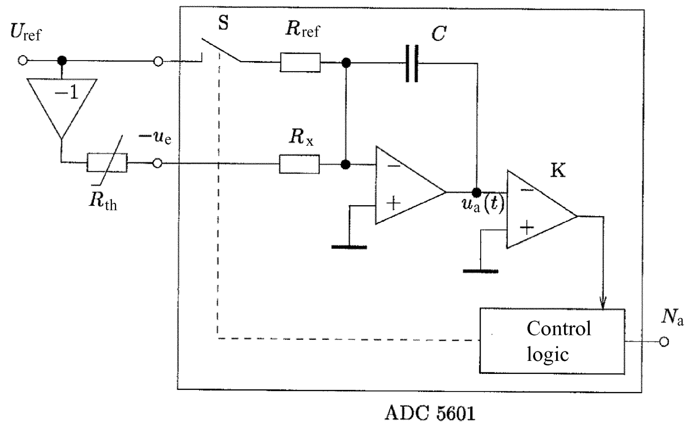

Fig. 2. Principle of the thermistor resistance measurement with multislope ADC.

This equation shows that the reference voltage is completely compensated and does not influence the measurement of the thermistor resistance. The temperature can be determined by Eq. (1).

Two free parameters, K and R_x, are to be determined by calibration of the measurement device. Instead of the thermistors, two different high-precision resistances are used as a reference to find the two parameters.

4. MEASURING DEVICE AND RESULTS

Several measuring devices have been built based on the principles, which are described above. They are equipped with multiplexers so that 15 different temperatures can be measured in a series. The output signal of the ADC is lead to a parallel interface via an opto-coupler. The device can be connected with a computer, or a microcomputer can be integrated in the device for special applications. These compact devices are integrated in other measuring systems, where the temperature is only one of other measured parameters, e.g. interferometric length measurement, etc.

Further applications have been tested in medicine, in hyperthermia for the therapy of cancer, where the temperature must be controlled with an accuracy better than 50 mK. Another application has been temperature measurement in growing bacterial cultures.

Comparisons between independent laboratories and the German National Metrology Institute PTB have shown that the greatest deviation of the measured temperature in the range between –20 and +50 °C has been 5 mK in 1 from 36 measurements at three calibrated thermistors [4]. It can be stated that a measurement accuracy of the absolute temperature of 10 mK with a resolution of 1 mK can be realized with high reliability.

5. CONCLUSIONS

High-precision temperature measurement requires very exact measuring methods, compensating methods, signal processing and calibration standards. Thermistors with long-term stability have been proved reliable. Their non-linear characteristic can be mathematically described. The characteristic curve-fitting coefficients can be determined with non-linear regression analysis. The measuring method bases on the measurement of the voltage drop across the thermistor, which is fed with the same reference voltage as the multislope ADC for further signal processing. With this method the feeding voltage is completely compensated. The temperature can be measured with an absolute accuracy better than 10 mK.

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Absoluutsete temperatuuride kõrge täpsusega mõõtmine termistoride abil

Volker H. Hans

Kõrge täpsusega mõõtmine eeldab mõõtesüsteemi kõikide komponentide kõrgtasemelist kvaliteeti, kuid eriline tähtsus on sensoril. Termistorid on osutunud headeks temperatuurisensoriteks piiratud temperatuurivahemikus töötamiseks. Nende pikaajaline stabiilsus tagatakse vahemikus –20 °C kuni +50 °C. Häiriv mittelineaarsus on matemaatiliselt hästi kirjeldatav ja selle mõju on digitaalselt kõrvaldatav, kui sensorsignaal on digiteeritud suure eraldusvõimega. Mitmekordse integreerimise ja vigade kompensatsiooniga analoog-digitaalmuundur võimaldab saavutada olukorra, kus eraldusvõime on 1 mK piires ning temperatuuri mõõtmise absoluutne viga ei ületa 10 mK.