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Development of the method of software temperature compensation for wireless temperature measuring electronic instruments

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Abstract : The main error in monitoring heat consumption in heating systems is determined by accuracy of coolant temperature measurement. For this purpose, the authors have developed a high precision wireless temperature meter (WTM). The error is reduced by temperature compensation in the WTM circuitry. A temperature compensating method and a hardware-software measuring complex have been developed that make it possible to simulate real WTM operating conditions, to determine the influence of temperature changes in the electric circuit components on WTM measurement error, to implement software temperature compensation in the electric circuit, and to perform automatic WTM calibration.

The method of temperature compensation consists in measuring and software correction of the coefficients in the temperature calculating mathematical model. Software temperature compensation is performed during the individual automatic calibration of measuring instruments. Using temperature compensation in manufacturing wireless temperature gauges helped reduce measurements error by ± 0.02 °C.

Keywords : Thermal energy, electronic temperature measuring devices, wireless interface, measurement error, the method of software temperature compensation, hardware and software measurement complex, automated calibration, software.

1. INTRODUCTION

Creating intelligent energy-saving systems for monitoring and controlling consumption of energy resources is an important area in science and technology [1-6]. In such systems, information is usually transmitted via a radio channel [2, 4-8]. For the purpose of implementing the innovative method for determining individual heat consumption in heating systems of apartment buildings developed by the authors, an intelligent system (IS) of energy monitoring has been created[9].

The main error in monitoring heat consumption in heating systems is determined by epy accuracy of coolant temperature measurement. For this purpose, the authors have developed a high precision wireless temperature meter (WTM). The WTM may also be used for measuring the temperature of any non-aggressive environments. Unlike the known analogs based on platinum thermal resistors [10, 11], WTM features low measurement error.

The structural scheme of WTM is shown in Figure 1.

The WTM electronic unit consists of two functional units: the electronic thermometer itself, and a transceiver, on a single printed circuitboard. An electronic thermometer consists of the following electronic components: a sensing element (a platinum thin-film thermal resistor RTD-1000) in a Wheatstone bridge circuit and a MSP430F2003 microcontroller with an analog-to-digital converter (ADC) on the same PCB. The radio channel

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transducer consists of a MSP430F2132 microcontroller, a CC1101 RF transceiver and an antenna. The structural scheme also includes an unauthorized tampering protection unit, the device initialization unit, a quartz resonator, and a battery.

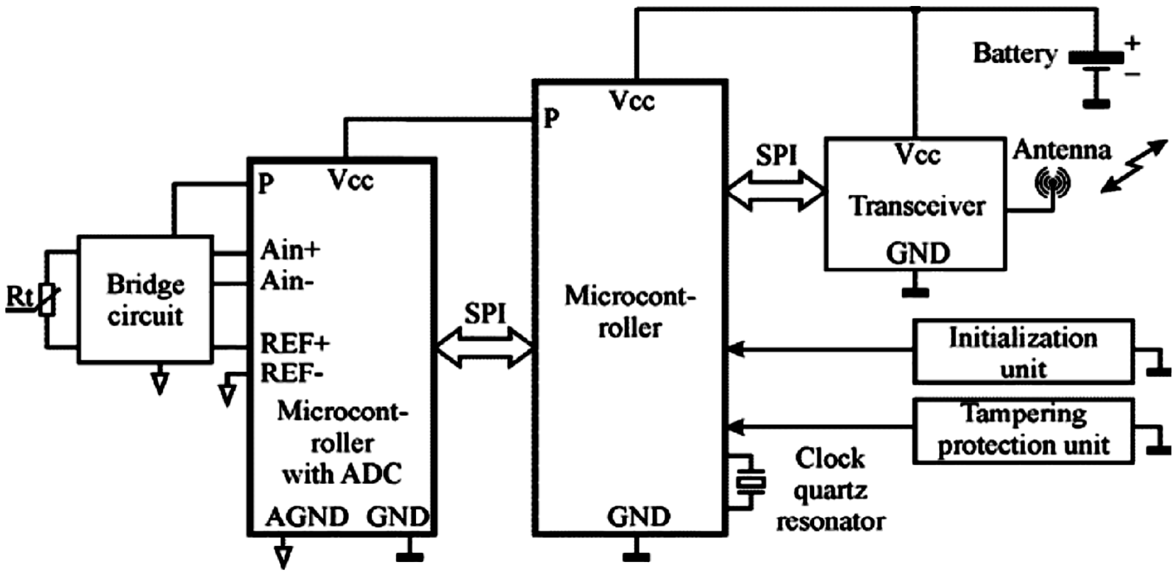

Fig. 1. WTM structural scheme.

The WTM is a wireless software-controlled microprocessor thermometer designed for measuring coolant temperature and transmitting the data to a remote personal computer (PC) via a local repeater (LR) developed by the authors. The WTM communicates with the LR via a short range radio link. Using the software developed by authors, the PC performs the following operations: receives measured data from the WTM; calculates the temperature according to the mathematical model proposed by the authors; configures measurement channels and measurement modes in the IS; displays measurement results in digital form on the PC monitor; and collects, stores and processes measurement results.

The authors have patented several design variants of the WTM, depending on the methods of installation in pipelines (RF patents: No. 2373502, No. 2450250, No. 2466365), the main technical characteristics whereof are shown in Table 1.

Table 1. WTM specifications.

Name	*Value*
The range of measured temperatures	(5 ÷ 95) °C
Basic absolute error of measurement	± 0.02 °C
Thermal inertia index ε_∞	30 *c*
Current consumption in the temperature measurement mode, not more than	1 mA
Current consumption in the receive/data transfer mode, not more than	22 mA
Radio channel carrier frequency	434 MHz
Equivalent radiated power of the radio transceiver, not more than	10 mW
Data transmission speed via radio channel, not less than	38,400 bit/s
Calibration interval, not less than	5 years
Weight with battery, not more than	50 g
Rated voltage	3.6 V
Dimensions	(39 × 39 × 53) mm

In the process of WTM operation, the ambient temperature may vary between 5°C and 50°C, and the temperature of the coolant - between 5°C and 95°C. In these conditions, the temperature of the components of the electrical measuring circuit changes, and therefore their parameters change, too, which results in an error in the measurement process. To eliminate this negative phenomenon, the method of temperature compensation is used [12 - 15].

To study the effect of electronic components' temperature change, and to reduce the error, we have developed a measuring system, hardware and software, and a software method of the WTM measuring circuit temperature compensation.

Development of hardware and software, and performing research

A hardware and software measuring complex, the block diagram of which is shown in Figure 2, has been developed for the following research :

- Simulating the real WTM conditions, and determining the temperature range of the electrical measuring circuit components;
- Studying the effect of changing the temperature of the electrical scheme components on the WTM measurement error;
- Software temperature compensation of the electric circuit and automatic WTM calibration.

The measuring complex includes the following hardware: a high-precision liquid thermostat Lauda PR 3530 with a measuring cell installed in it; a high-precision thermometers MIT-8 and DTI-1000 (measurement error ± 0.001°± 0.004°C, respectively); a power supply (IPR-800) of the measuring cell resistive heater; a programmable precision resistor Meatest V-602A-V1000; a LR; Interface converter N-port and a PC.

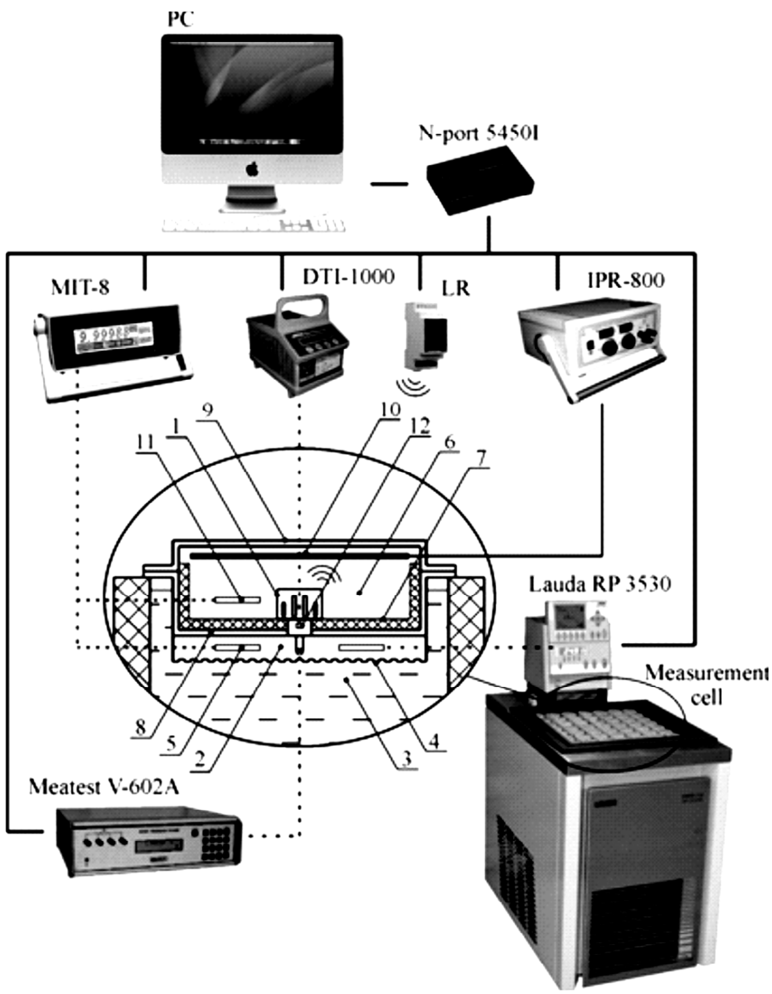

Fig. 2. The structural scheme of hardware-and-software measuring complex for the study and WTM calibration.

Figure 2 also shows the design of the measurement cell installed in the thermostat. The cell is intended for the research and for automatic calibration, including temperature compensation, of 56 WTM samples simultaneously. The studied samples (1) are set in threaded holes in the base of the cell (2) made of copper, having high thermal conductivity, which ensures uniform temperature profile. The base of the cell immersed in the coolant (3) has developed surface (4). For measuring the temperature and the temperature profile of the base, it has five reference platinum resistance thermometers PTSV-2K (5) connected to MIT-8. The WTM is calibrated by the temperature values determined by PTSV-2K installed in the center of the base cell (the reference thermometer). The data of PTSV-2K is also used by the microprocessor unit of the thermostat to control the temperature of the coolant during calibration. The surface of the base in contact with the working volume of the cell (6) is screened with insulating material (7). The body of the measuring cell (8) is mounted on the base and covered by lid (9), where resistance heater (10) is installed. The temperature in the working volume of the cell is controlled by sensor (11). The temperature of the electrical measuring circuit components is measured by the RTD-100 (12) sensor connected to thermometer DTI-1000.

Simulating the real WTM conditions and determining the electrical measuring circuit components temperature range are performed as follows. The temperature of the coolant in the thermostat increases to 95°C; thus, the pipeline of the heating system is simulated. In the working volume of the measuring cell, the temperature is raised from the ambient to 50°C by the resistive heater. To study the effect of the electrical circuit components temperature in the microcontroller and the quartz resonator, film sensors RTD-100 are installed and connected to thermometer DTI-1000.

By the results of the research, it has been established that at the maximum WTM operation temperatures (95°C and 50°C for the coolant and the environment, respectively), the maximum temperature of the microcontroller does not exceed 65°C, and the temperature of the quartz resonator does not exceed 60°C.

The method of temperature compensation of electrical measuring circuits

To study the effect of the temperature of electrical circuit components on the WTM measurement error, a set of resistors is connected to the input of the measuring circuit, instead of RTD-1000. The resistance value is set corresponding to the resistance of platinum, for example, at25°C. Then the WTM is installed into the measuring cell. The temperature inside the cell is regulated with a liquid thermostat and the resistive heater of the cell, and is monitored by sensor (11). In the thermostat, the following temperatures are set successively: 5°C, 30°C and 60°C. At each of these temperatures,which correspond to the temperatures of the electric circuit components, the values of resistance are measured with WTM at the output of the precision set. During the tests, the temperature of the circuit elements is also monitored by the internal sensorof the microcontroller.

To eliminate possible errors of mathematical transformations of the ADC code into the resistance, and then into the temperature, the data obtained from WTM are written as ADC code - NR. This data is transmitted from the WTM via a wireless channel to LR, and via the RS – 485 interface to the PC, where it is processed using the developed software.

The results obtained for seven WTM samples are shown in Figure 3.

The obtained data show that changes of the resistance values in the ADC code (N_R), depending on the temperature of the electrical circuit components, have linear nature. The electronic components temperature measurement error in the range between 5°C and 60°C, after recalculating the ADC code into temperature, is within ± 0.15°C.

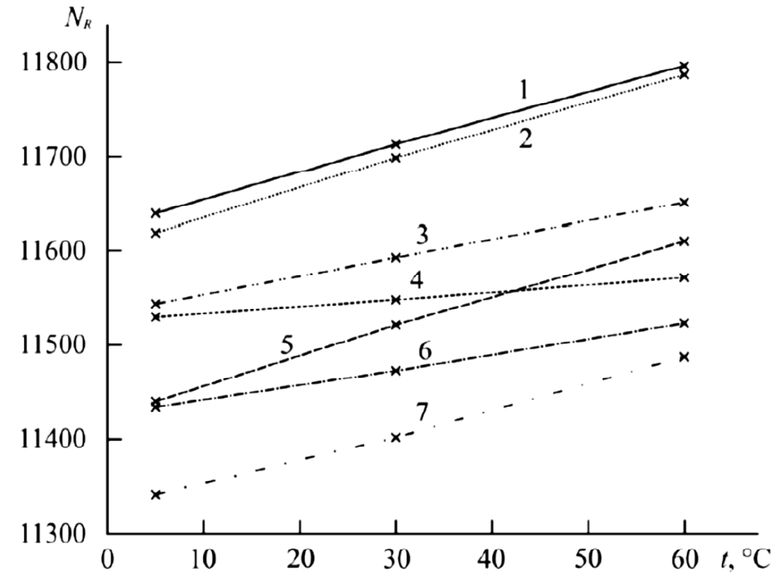

Fig. 3. Dependence of the resistance values in the ADC code (N_R) on the temperature of the WTM electrical circuits components.

Thus, the true value $N_{R(true)}$ may be defined as follows:

$$NR_{(true)} = N_R - \Delta NR, \quad (1)$$

where NR is the resistance value determined by WTM under the influence of the temperature at the circuit elements; ΔNR - deviation NR from the true value caused by the electronic circuit components temperature change.

To reduce the measurement error, we have developed a software method of temperature compensation, which is the following.

Since NR depends linearly on the temperature of the electronic circuit components, we can define ΔNR as follows:

$$\Delta N_R = a.\, N_{mk} + b, \quad (2)$$

then the true value $N_{R(true)}$, considering (2), is determined as follows:

$$N_{R(true)} = N_R - (a.\, N_{mk} + b), \quad (3)$$

where N_{mk} is the temperature of the microcontroller (circuit element), written as ADC code; a and bare the coefficients of temperature compensation.

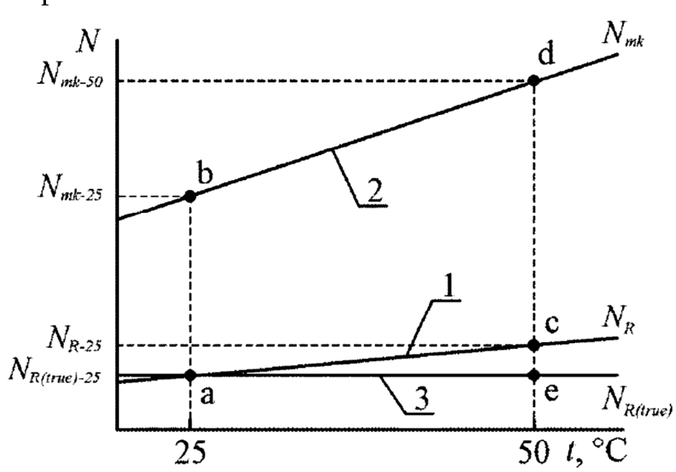

Fig. 4. Dependence of the ADC code values on the temperature of the WTM electrical circuits components.

The temperature compensation method is intended for eliminating the dependence of the measured data on the WTM electronic circuit components temperature change. The method of temperature compensation consists in measurement and software correction of coefficient *a* in equation (3), in order to eliminate measurement errors.

The temperature compensation method was developed with the use of the hardware-and-software complex shown in Figure 2. The WTM batch is put into the measurement cell. In the thermostat and in the cell, the temperature of 25°C is stabilized and monitored. Next, the temperature is measured with the WTM, and the data are transmitted via the radio channel. The temperature is measured by three measuring channels, readings of which are marked in Figure 4. Channel 1 is used for measuring resistance of the platinum WTM thermal resistor (point a), channel 2 is used for measuring the temperature of the microcontroller (point b), and channel 3 is used for measuring the temperature of the base of the cell (point a). The data in channels 1 and 2 are defined in ADC codes: $N_{R(true)\text{-}25}$, and $N_{mk\text{-}25}$, respectively.

Then, without changing the temperature of the coolant in the thermostat, which is 25°C, using a resistive heater, the temperature of 50°C is set in the working volume of the measuring cell,and the resistance of the WTM platinum thermal resistor ITB (point c), and the temperature of the microcontroller in the ADC codes (point d) are measured. In this case, the electronic components of the WTM circuit are at 50°C, and via channel 2, we get the value - Nmk-50. The platinum WTM thermistor is at this moment at the temperature of the coolant in the thermostat, which is maintained constant and equal to 25°C (point e). However, its readings show an error determined by the change of the electronic circuit components temperature. The resistance value measured in channel 1 will be: $N_{R\text{-}25}$ (Figure 4).

To eliminate the resulting error in WTM measurements, let’s define the coefficients of temperature compensation using equations (4) and (5):

$$a = \frac{N_{R(true)\text{-}25} - N_{R\text{-}25}}{N_{mk\text{-}25} - N_{mk\text{-}50}} \tag{4}$$

$$b = \frac{N_{mk\text{-}25} \times (N_{R(true)\text{-}25} - N_{R\text{-}25})}{N_{mk\text{-}25} - N_{mk\text{-}50}} \tag{5}$$

When the calculated coefficients are introduced into mathematical model (3), we obtain values $N_{R(true)}$ (which coincide with the readings of Channel 3) when the temperature of electronic circuit components changes to 50 °C.

Thus, by introducing the coefficients into the mathematical model for temperature calculation, we managed to reduce the measurement error defined by the change of the WTM electrical circuit components temperature.

The results of using temperature compensation

Process diagram of temperature compensation is shown in Figure 5. Five WTM samples were used for the research. Channel 1 was used for measuring the coolant temperature with WTM thermal resistors. Channel 2 was used for measuring the change of the electronic circuit components temperature. Zone A corresponds to temperature stabilization of the thermostat, and to measuring at 25°C. Then the temperature of the WTM electronic circuit components increases to 50°C (zone B), and the temperature of the coolant is measured by each WTM (Channel 1). The deviation in measuring the temperature caused by heating of the electronic components reaches 0.3°C (WTM # 3, Figure 5). After the temperature stabilizes (zone C), the temperature is measured, and the thermal compensation coefficients are calculated for each WTM. Zone Dshowsthe results of coolant temperature measurement with the use of WTM, after the process of software temperature compensation.

After temperature compensation, the deviations of the WTM readings (zone D) shown in Figure 5, relative to the reference thermometer, are determined by the individual characteristics of platinum thermal resistors, including R_0. These deviations are eliminated in the process of WTM calibration.

The method of software calibration presented by the authors in [16] consists of individual adjustment of the mathematical model for each WTM, relative to the reference thermometer. Calibration is performed automatically at two temperatures - 25°C and 85°C with the use of the SW developed for this purpose. The data discrepancy is determined by the temperature between readings of each WTM and the reference thermometer. Then the coefficients in the mathematical model for each WTM are automatically adjusted. After temperature compensation at the temperature of 85°C, the final calculation and automatic adjustment of the coefficients are made in the mathematical model of each ITB. The process of software calibration, including temperature compensation, is completed. A distinctive feature of the calibration method developed by us, as compared to the known ones [17 - 19], is that it is performed automatically according to a specified program.

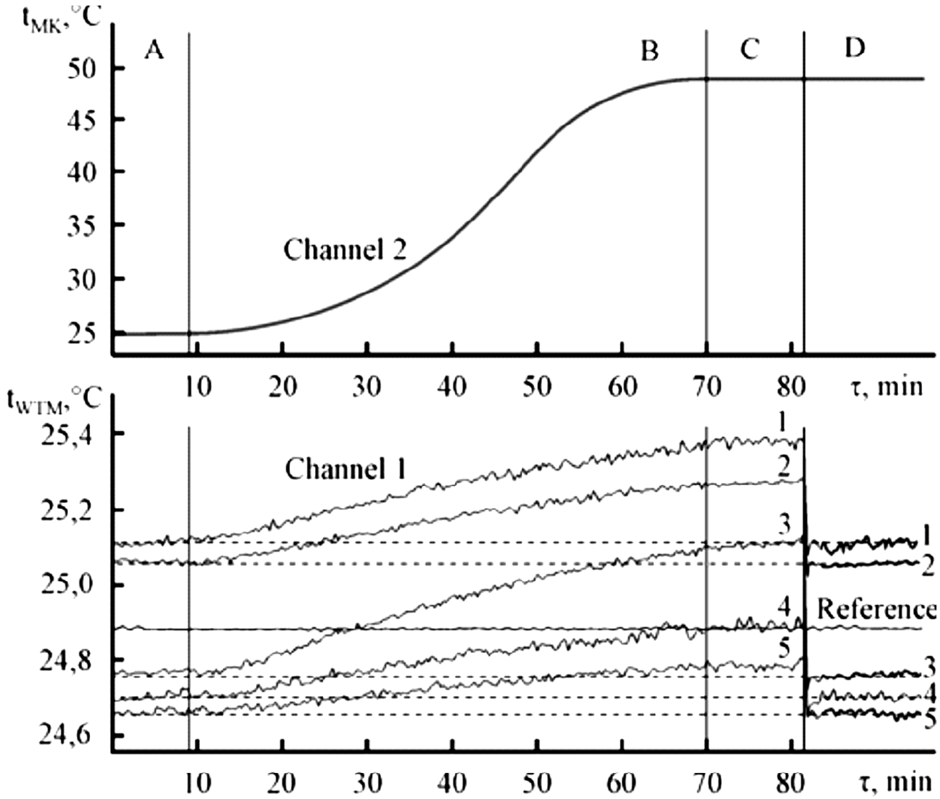

Fig. 5. The diagram of the temperature compensation process.

2. CONCLUSIONS

In this paper we have proposed a method and hardware-and-software complex for temperature compensation of electrical circuits in high-precision measuring instruments that operate in the conditions when the temperature of the electronic circuit components changes, which results in a measurement error.

The method of temperature compensation consists in measuring and software correction of the coefficients in the temperature calculating mathematical model. Temperature compensation is performed during individual automatic calibration of the measuring instruments. Using temperature compensation in manufacturing wireless temperature gauges helped reduce measurements error by ± 0.02 °C.

The method of temperature compensation proposed in this paper has also been applied by the authors in developing wireless pressure sensors used in the intelligent system for monitoring energy sources, along with WTM [9].

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