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Study of Metrological Characteristics of Low-Cost Digital Temperature Sensors for Greenhouse Conditions

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Abstract: The article focuses on the relevant scientific and applied problem of assessing and analyzing the metrological characteristics of available digital temperature sensors for greenhouse conditions. The hardware and software implementation of the microprocessor system for obtaining calibration characteristics and evaluating the accuracy and performance of temperature sensors for the physical media under greenhouse conditions is studied. A particular type of linear calibration equation for the temperature sensors under study is established. The values of systematic absolute measurement deviations of temperature sensors DS18B20, SHT11, SHT21, BMP180, BME280 and DHT22 are experimentally obtained. Recommendations on improving the accuracy of temperature information and temperature measuring systems under greenhouse conditions are given. The perspective areas of the research on metrological provision of modern means of automatic monitoring and temperature control in industrial greenhouses are substantiated.

Keywords: Sensor, Deviation, Temperature, Greenhouse.

1 Introduction

Currently, increasing the efficiency of agricultural production for growing vegetables under greenhouse conditions is a relevant scientific and applied task [1, 3, 9]. The urgency of this research is due to the need to solve the socio-economic problem of import substitution in order to ensure the state food security. Ensuring a sufficient amount of environmentally friendly products, as well as climatic and structural and sectoral features of the development of

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individual regions and states, in general, determine the increased attention to crop production in industrial greenhouses.

The effectiveness of technological processes of growing crops in greenhouse conditions significantly depends on the accuracy and efficiency of measuring control of microclimate parameters [1, 3]. While solving the problems of automating the technological process control in growing vegetables, automatic monitoring and control systems should be based on modern sensor, microprocessor and infocommunication intellectual technologies [5, 9].

The temperature of soil, air and irrigation solution is one of the most informative microclimate parameters of greenhouses. It is also regulated for compulsory measuring control. This is due to the fact that plants can exist only under certain temperature conditions. The plants, which grow in a particular area, are adapted to temperature fluctuations within certain limits. Therefore, for each type of crops that are grown under greenhouse conditions, reproduction of optimal temperatures, regarding types and periods of crop vegetation, is a necessary condition. In turn, temperature affects processes of photosynthesis, respiration and transpiration, growth and development of plants, as well as their shaping and, as a result, the volumes and quality of products. Consequently, the development and implementation of computerized measuring channels of air, soil and irrigation solution under greenhouse conditions is a prerequisite, as proved by a wide range of scientific research [14, 15].

Thus, the main purpose of the article is to conduct studies on the assessment and analysis of the metrological characteristics of available digital temperature sensors. It will make possible to substantiate scientific and applied provisions for increasing the efficiency of greenhouse complexes in the future. This effect can be achieved through the development and implementation of high-precision and operational methods and means of monitoring and control of temperature regimes of growing crops in greenhouses.

The subject of the research is the metrological characteristics of digital temperature sensors for greenhouse conditions. The object of the research is non-stationary processes and factors that have a destabilizing effect on the metrological characteristics of digital temperature sensors for greenhouses.

The scientific novelty of the obtained results is the development of the method for evaluation of the metrological characteristics of modern low-cost digital temperature sensors. The possibility of identification and reducing random uncertainty by using mathematical processing of observations results of the sensor set has been justified in this method. The proposed method allows performing a quantitative comparison of the temperature measurement uncertainty of the various sensors during the experiment in a wide temperature range. This method, unlike the existing ones, allows choosing the optimal temperature sensor depending on the conditions and measurement range. The obtained results contribute to design of hardware and software methods of estimation and correction of temperature measurement uncertainties. The practical significance of this article is the substantiation of the possibility of low-cost digital temperature sensors use for continuous monitoring of growing crops technological processes with required accuracy in greenhouses.

Section 2 explains current findings in the research area, Section 3 describes the used research methods and tools, Section 4 explains all scientific and practical findings, Section 5 describes suggestions for future investigations, Section 6 explains conclusions from the present work.

2 Current Findings in the Research Area

A wide range of scientific research is devoted to solving the problem of increasing the efficiency of agricultural greenhouse production at the expense of development and introduction of progressive computer, sensor, and microprocessor technologies. The studies [18, 20, 23] present the main findings on the development of systems for the greenhouse climate optimal control on the basis of the Fuzzy logic technology. Having analyzed these papers, we have found that the measuring channels for the air temperature in the growing area, soil temperature in the root zone and irrigation water temperature are mandatory structural elements of the systems ensuring the optimal microclimate. The study [1] and regulatory document [3] substantiate the basic requirements for measurement points, periodicity and accuracy of measurement monitoring of the temperature of greenhouse physical environment: the total absolute deviation of measuring air, substrate and irrigation water temperatures should not exceed ±0.2°C in the working range from 10 to 40°C; measurements must be performed continuously.

It has also been established that the development of systems for monitoring and controlling the temperature regimes of growing greenhouse crops is based on modern available digital temperature sensors that are functionally compatible with serial microprocessor platforms.

Thorough analysis of up-to-date scientific works in the subject area, allowed determining the main types of sensors, which can be used for non-destructive computerized monitoring of temperatures of the greenhouse physical environment. In the studies [6, 22, 24], the basic principles of constructing wireless sensor networks of measuring temperature control for greenhouse conditions by means of DS18B20 sensor are investigated. In other scientific sources [10, 21] it is suggested to use SHT11 sensor as a temperature detecting element when developing such systems. Similar studies on the development and simulation of systems for monitoring the physical media temperature are presented by using SHT21 [17], BMP180 [13], BME280 [2] and DHT22 sensors [8, 16]. The articles [7, 19] present the main approaches to the assessment and analysis of the metrological and functional characteristics of sensors, which are used in constructing modern measuring systems for non-destructive testing of parameters of physical and chemical processes.

Moreover, most authors emphasize the relevance and knowledge-intensiveness of developing and researching computerized monitoring systems and adaptive automatic control of the microclimate parameters of industrial greenhouses, as well as the need to continue research in the subject area under consideration. In-depth analysis of the above-mentioned scientific sources suggests that today there is hardly any concept analysis of the metrological characteristics of measuring channels of physical environment temperature in industrial greenhouses. Also, insufficient attention is paid to solving the following problems: assessing the effect of destabilizing factors on the random and systematic components of the total deviation of digital temperature sensors; analysis of dynamic and static components of the deviation in measuring the physical environment temperature under greenhouse conditions; justification of ways to increase the accuracy of measuring air temperature in the growing area, soil temperature in the root zone.

3 Materials and Methods

3.1 Hardware components

To conduct the research, serial digital temperature sensors are selected. The main characteristics of these sensor models are given in **Table 1**.

Table 1

Characteristics of the temperature sensors under study.

Sensor #	Sensor type	Basic specifications
1	DS18B20	Conversion resolution is from 9 to 12 bits; standard 1-Wire interface; the deviation does not exceed ± 0.5°C in the range from –10 to +85°C.
2	SHT11	Conversion resolution is 14 bits; standard serial data exchange interface; the deviation does not exceed ±0.4°C in the range from –40 to +123°C.
3	SHT21	Conversion resolution is from 12 to 14 bits; standard I^2C interface; the deviation does not exceed ± 0.3°C in the range from –40 to +125°C.
4	BMP180	Conversion resolution is 16 bits; standard I^2C interface; the deviation does not exceed ± 0.5°C in the range from –40 to +85°C.
5	BME280	Conversion resolution is from 16 to 20 bits; standard I^2C interface; the deviation does not exceed ±0.5°C in the range from –40 to +85°C.
6	DHT22	Conversion resolution is 8 bits; standard serial data exchange interface; the deviation does not exceed ±0.5°C in the range from –40 to +80°C.

These sensors are selected on the basis of their compatibility with modern microprocessor platforms, their sufficient functional and technical characteristics, and an affordable price category. The observation aggregation and processing unit is based on the Arduino Mega 2560 microprocessor board, which is based on the ATmega2560 microchip with the frequency of 16 MHz. The unit also includes a real-time clock module, which is an integral assembly of the DS1302 and SD-shield for creating and accumulating the database of measurement results.

In order to study the functional and metrological characteristics of the sensors under question, installation and maintenance of thermostat control points in the working range from 10 to 90°C have been performed by means of ZenithLab WH-1/2/4/6. It is a certified water bath with the possibility of microprocessor temperature control in the range from 5 to 100°C at a pitch of 0.1°C.

3.2 Software component

Software of the computerized temperature monitoring system has been developed and tested by using the following standard application packages:

– implementation and testing of the software of the microprocessor subsystem of aggregation and primary processing of observation results have been performed by means of Arduino IDE;

– accumulation of the laboratory observation result base followed by gross deviations identifying and eliminating has been carried out by means of MS Excel;

– graphical interpretation and static analysis of metrological and functional characteristics of temperature sensors have been performed by using MathCad.

3.3 Methods and methodology of the research

The following methods were used: analytical research methods; methods of computer analysis of the results of experimental studies under laboratory conditions using real objects; methods of analysis and synthesis of computerized monitoring and control systems; approximation method; mathematical apparatus of probability theory and statistics; methods of planning and carrying out experimental research and processing experimental results.

The experimental studies have been carried out in specialized laboratories of the State Higher Educational Establishment 'Donetsk National Technical University' (Ukraine) by using certified equipment. As a result of the analysis of a priori information about the object of the study [9, 11, 12], three series of laboratory tests were required.

The series of results were obtained under identical conditions, methods and means of measurement. The method of metrological certification is a method of comparison with the reference measure. The sampling time of the measuring channels is 2 seconds, the time interval for conducting one series of experiments is 6 hours. The physical configuration of the experimental apparatus is shown in Fig. 1. The structural diagram of the computerized temperature monitoring system is shown in Fig. 2.

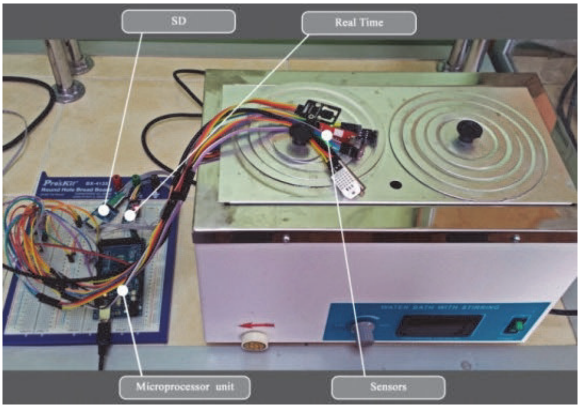

Fig. 1 – *The photo of the experimental apparatus.*

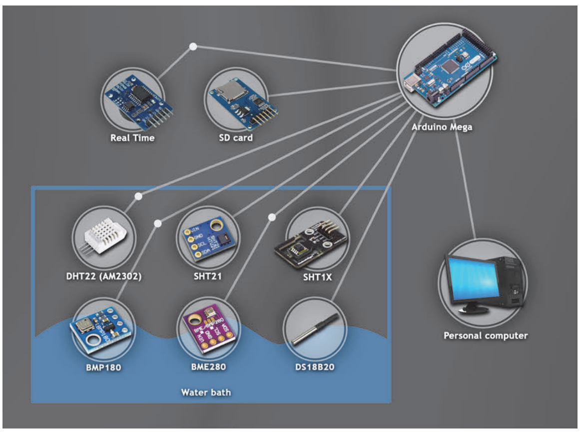

Fig. 2 – *Block diagram of the temperature monitoring system.*

4 Research Findings

When conducting the research, $k = 6$ temperature sensors were used. Their numbers and indication of their technical characteristics are given in **Table 1.** The research was performed by repeated observations of the temperature at the checkpoints ($m = 1, 2 \ldots 10$), each of which corresponds to $T_m = (5; 10; 20; 30; 40; 50; 60; 70; 80; 90)°C$.

We made $i = (i_{j\min} ... i_{j\max}) = 100$ temperature observations at each of the checkpoints (m). When conducting experimental studies, $j = 3$ series of observations were obtained. The temperature variation in the range from +5 to +90ºC for $k = 6$ sensors $j = 1$ series are shown in Fig. 3.

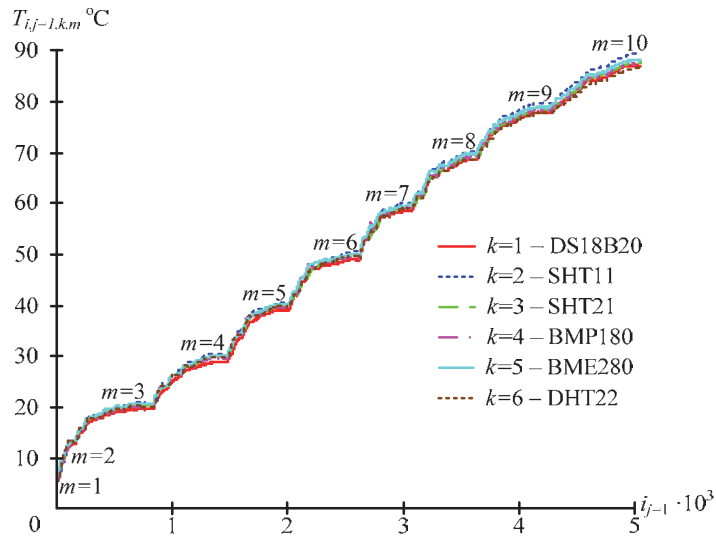

Fig. 3 – *Temperature variation in the range from +5 to +90ºC for k = 6 sensors.*

Having analyzed the temperature observations by one of k sensors (see **Table 1**) at the checkpoint (m) for each series (j), we have found out that the results obey the normal law of probability distribution. In addition, the arithmetic average of the observation results ($T_{i,j,k,m}$) [4] is taken as the result of temperature measurement ($\overline{T_{j,k,m}}$) :

$$\overline{T_{j,k,m}} = \frac{1}{i_{j\max} - i_{j\min}} \sum_{i=i_{j\min}}^{i_{j\max}} T_{i,j,k,m}, \tag{1}$$

where $\overline{T_{j,k,m}}$ °C and $T_{i,j,k,m}$°C – the measurement result and the results of temperature observations; $i_{j\max}$ and $i_{j\min}$ – maximum and minimum counting in j series of the checkpoint m.

Standard deviation of observation results ($T_{i,j,k,m}$) on measurement result ($\overline{T_{j,k,m}}$) is calculated for each checkpoint (m), for each sensor (k) and for each series of observation results (j) [4]:

$$\sigma T_{j,k,m} = \sqrt{\frac{1}{i_{j\max} - i_{j\min} - 1} \sum_{i=i_{j\min}}^{i_{j\max}} \left(T_{i,j,k,m} - \overline{T_{j,k,m}} \right)^2}, \qquad (2)$$

where $\sigma T_{j,k,m}$ – standard deviation of the observation results ($T_{i,j,k,m}$) on the temperature measurement result ($\overline{T_{j,k,m}}$).

Taking into account the assumption that unequal accuracy temperature measurements were made, the weighted average of the measurement result [4] was taken as the nearest to its true value for each of the sensors (k) at each checkpoint (m):

$$\overline{\overline{T_{k,m}}} = \frac{\sum_{j=1}^{3} \left(\overline{T_{j,k,m}} \cdot P_{j,k,m} \right)}{\sum_{j=1}^{3} \left(P_{j,k,m} \right)}, \qquad (3)$$

where $\overline{\overline{T_{k,m}}}$ – the weighted average temperature measurement result ($\overline{T_{j,k,m}}$); $P_{j,k,m}$ – weight coefficient of each of the series (j), each of the sensors used (k) and at each checkpoint (m).

The nearest value of the weight coefficient ($P_{j,k,m}$) in the formula (3) for this result is its probability of occurrence. For unknown probability values, the weight coefficients are the squares of the inverse standard deviation values of the observations ($T_{i,j,k,m}$) from the temperature measurement result ($\overline{T_{j,k,m}}$):

$$P_{j,k,m} = \frac{1}{\left(\sigma T_{j,k,m} \right)^2}. \qquad (4)$$

Having analyzed the measurement results ($\overline{T_{j,k,m}}$) calculated by the formula (1), standard deviation ($\sigma T_{j,k,m}$) of the observation results from the temperature measurement result, calculated by the formula (2), and weight coefficients, calculated by the formula (4), we can calculate the weighted average of the temperature measurement:

$$\overline{\overline{T_{k,m}}} = \frac{\sum_{j=1}^{3} \left(\overline{T_{j,k,m}} \cdot \frac{1}{\left(\sigma T_{j,k,m} \right)^2} \right)}{\sum_{j=1}^{3} \left(\frac{1}{\left(\sigma T_{j,k,m} \right)^2} \right)}, \qquad (5)$$

where $\overline{\overline{T_{k,m}}}$ – the weighted average of the temperature measurement at each checkpoint (m) and each of the sensors used (k).

The standard deviation weighted average from $\sigma T_{j,k,m}$ is characterized by the deviation of the result in unequal accuracy measurements:

$$\overline{\sigma T_{k,m}} = \frac{1}{\sqrt{\sum_{j=1}^{3}\left(\frac{1}{\left(\sigma T_{j,k,m}\right)^2}\right)}}, \tag{6}$$

where $\overline{\sigma T_{k,m}}$ – the standard deviation of the weighted average with multiple observations of the temperature for each of the sensors used (k) and at each checkpoint (m).

Since the measurements made by each of the sensors (k) are considered to be of unequal accuracy, the weighted average of the temperature measurement [4] is the nearest to the true temperature value at each checkpoint (m):

$$TT_m = \frac{\sum_{k=1}^{6}\left(\overline{\overline{T_{k,m}}} \cdot \frac{1}{\left(\overline{\sigma T_{k,m}}\right)^2}\right)}{\sum_{k=1}^{6}\left(\frac{1}{\left(\overline{\sigma T_{k,m}}\right)^2}\right)}, \tag{7}$$

where TT_m – the weighted average of the temperature measurement at each checkpoint (m).

The standard deviation of the weighted average for each checkpoint (m) is characterized by the deviation in the result of unequal accuracy measurements according to the results of calculating the weighted average of k sensors:

$$\overline{\overline{\sigma T_m}} = \frac{1}{\sqrt{\sum_{k=1}^{6}\left(\frac{1}{\left(\overline{\sigma T_{k,m}}\right)^2}\right)}}, \tag{8}$$

where $\overline{\overline{\sigma T_m}}$ – standard deviation weighted average with multiple temperature observations at each checkpoint (m).

To analyze and compare the results of temperature measurements with the technical characteristics of the sensors under study, the absolute measurement deviation values are calculated:

$$\Delta T_{k,m} = \overline{\overline{T_{k,m}}} - TT_m, \tag{9}$$

where $\Delta T_{k,m}$ – the absolute deviation of temperature measurement by the sensor (*k*) at each checkpoint (*m*).

On the basis of preliminary analysis of the research results, it was found out that each k sensor has a systematic component of the deviation in the temperature range from +5 to +90ºC. This component has both additive and multiplicative character. This fact was established by analyzing of the sensors technical characteristics and experimentally confirmed (see Fig. 4 and **Table 2**). To reduce its value, was proposed to use a linear equation:

$$T_{calibr_{i,j,k,m}} = T_{i,j,k,m} - \left(a_{calibr_k} \cdot T_{i,j,k,m} + a_{0calibr_k}\right), \tag{10}$$

where T and T_{calibr} – the measured temperature before and after sensor calibration; a_{calibr_k} – multiplicative calibration factor for the sensor (*k*); $a_{0calibr_k}$ – additive calibration component for the sensor (*k*).

To estimate the value of the additive systematic component of the temperature measurement deviation in the range from +5 to +90ºC, the sensor (*k*), the average value of the absolute measurement deviations is used:

$$\overline{\Delta T_{real\ k}} = \frac{1}{10}\sum_{m=1}^{10} \Delta T_{k,m}; \tag{11}$$

$$\overline{\Delta T_{calibr\ k}} = \frac{1}{10}\sum_{m=1}^{10} \Delta T_{calibr\ k,m}, \tag{12}$$

where $\overline{\Delta T_{real\ k}}$ and $\overline{\Delta T_{calibr\ k}}$ – average values of absolute deviations in temperature measurement in the range from +5 to +90ºC before and after calibrating the sensors (*k*).

To estimate the value of multiplicative systematic component of the temperature measurement deviation in the range from +5 to +90ºC by means of the sensor (*k*), standard deviation of absolute measurement deviations is used:

$$\sigma\Delta T_{real\ k} = \sqrt{\frac{1}{9}\sum_{m=1}^{10}\left(\Delta T_{k,m} - \overline{\Delta T_k}\right)^2}; \tag{13}$$

$$\sigma\Delta T_{calibr\ k} = \sqrt{\frac{1}{9}\sum_{m=1}^{10}\left(\Delta T_{k,m} - \overline{\Delta T_{calibr\ k}}\right)^2}, \tag{14}$$

where $\sigma\Delta T_{real}$ and $\sigma\Delta T_{calibr}$ – standard deviation of absolute temperature measurement deviations in the range from +5 to +90ºC before and after calibrating the sensors (k).

By using formulas (11–14), the multiplicative and additive components of the absolute deviation of the measurement result were calculated in the temperature range from +5 to +90ºC for each of the k sensors. The calculation results for sensor DS18B20 are shown in Fig. 4. Similar studies were carried out for the other sensors. The results of the determining of the coefficients optimal values are presented in **Table 2.**

The standard deviation of the absolute errors (see (a) in Fig. 4a) of the temperature measurement by means of the DS18B20 sensor ($k = 1$) on the change in the value of the calibration factor and the additive component (see (b) in Fig. 4) is shown in Fig. 4.

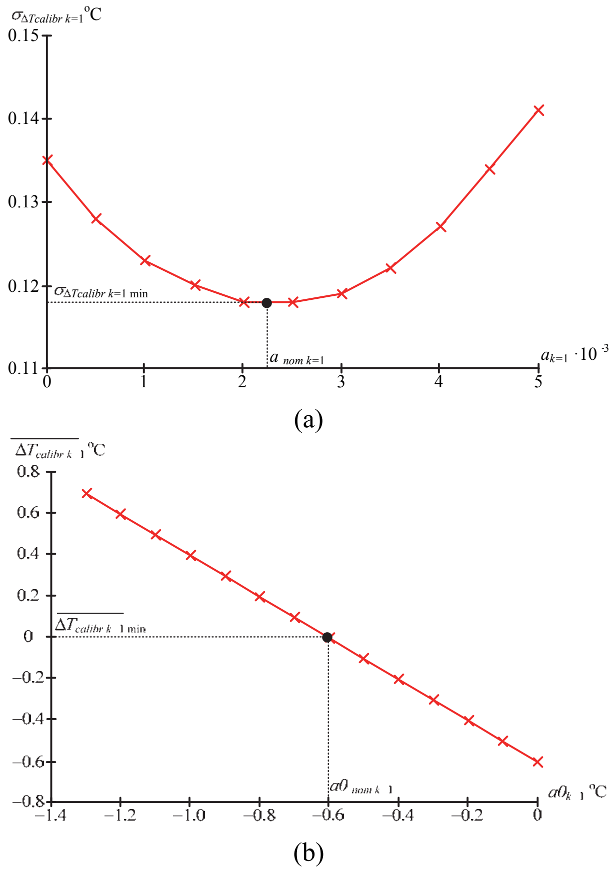

Fig. 4 – *Change in the value of the calibration coefficient:* (a) *and additive calibration component;* (b) *for the sensor DS18B20* ($k = 1$).

The studies are aimed at minimizing the values of the absolute deviations of the temperature measurement results in the specified range. The results of the study are summarized in **Table 2**, which shows the calibration coefficients (a_{calibr_k}) and additive components $(a_{0calibr_k}\,°\mathrm{C})$, as well as the values of the additive and multiplicative components of the absolute measurement deviation before ($\overline{\Delta T_{real}}$ ºC and $\sigma\Delta T_{real}$ ºC) and after ($\overline{\Delta T_{calibr}}$ ºC and $\sigma\Delta T_{calibr}$ ºC) using the calibration equation (10).

The selected additive calibration coefficients $a_{0calibr_k}$ using for each of the sensors considered allowed to obtain the magnitude of the absolute error of temperature measuring $\overline{\Delta T_{calibr}} = 0.000°\mathrm{C}$ (see **Table 2**).

Table 2

Calibration coefficients (a_{calibr_k}) *and additive components* $(a_{0calibr_k}\,°\mathrm{C})$, *as well as the values of the additive and multiplicative components of the absolute measurement deviation before and after calibration.*

k	Sensor type	$a_{calibr_k}\cdot 10^{-3}$	$a_{0calibr_k}$ ºC	$\overline{\Delta T_{real}}$ ºC	$\overline{\Delta T_{calibr}}$ ºC	$\sigma\Delta T_{real}$ ºC	$\sigma\Delta T_{calibr}$ ºC
1	DS18B20	2.75	–0.617	–0.493	0.000	0.135	0.118
2	SHT11	9	0.391	0.797		0.301	0.137
3	SHT21	0	0.072	0.072		0.186	0.186
4	BMP180	–2.75	–0.153	–0.277		0.120	0.090
5	BME280	0	0.426	0.426		0.046	0.046
6	DHT22	–13.5	0.132	–0.478		0.461	0.241

The variation in the absolute deviation of temperature measurement in the range from +5 to +90ºC for the DS18B20 sensor is shown in Fig. 5, where the following is indicated: 1 and 3 – maximum values in the technical specifications; 2 – nominal values regulated by technical specifications; 4 and 5 – before and after calibration.

Detailed analysis of the results of the DS18B20 sensor research ($k = 1$) proved that the variation in the absolute deviation of temperature measurement before calibration (see 4 in Fig. 5) is beyond the maximum limits regulated by the technical specifications of the DS18B20 sensor (see 1, 3 in Fig. 5). The measurement results include both the multiplicative component, the value of which in the temperature range from +5 to +90ºC is equal to 0.135ºC, and the additive component which is equal to –0.493ºC (see **Table 2** and Fig. 5).

To reduce the value of the multiplicative component of the deviation by means of (10), studies were conducted and the value $a_{calibr_{k=1}} = 2.75\cdot 10^{-3}$ was set. At this value there is the minimum standard deviation of the absolute temperature measurement deviations ($\sigma\Delta T_{calibr\;k=1} = 0.118°\mathrm{C}$) calculated by (14).

In addition, the value at which the average value of the absolute deviations in temperature measurement in the range from +5 to +90ºC after calibration is $\overline{\Delta T_{calibr\ k}} = 0.000\ °C$.

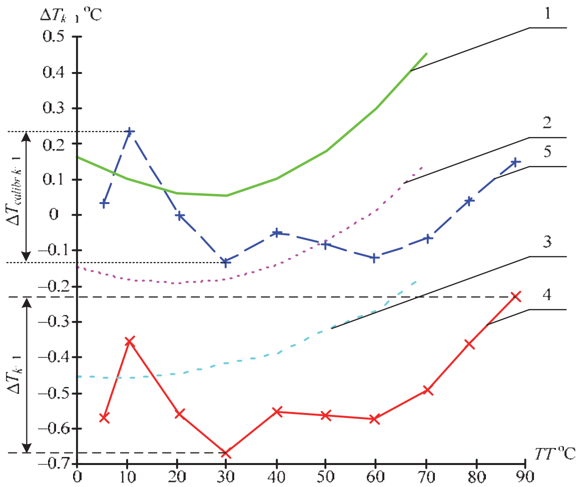

Fig. 5 – *Variation in the absolute deviation of temperature measurement in the range from +5 to +90ºC for DS18B20 sensor* ($k = 1$).

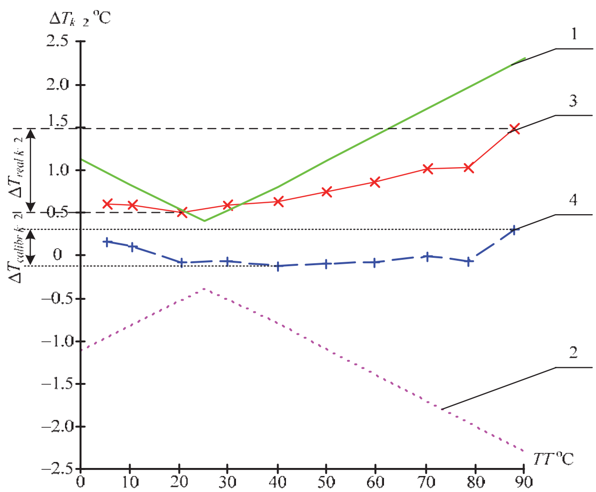

Fig. 6 – *Variation in the absolute deviation of temperature measurement in the range from +5 to +90ºC for the SHT11 sensor* ($k = 2$).

Thus, it can be concluded that the use of the linear calibration equation (10) with the set values $a_{0calibr_{k=1}} = -0.617°C$ and $a_{calibr_{k=1}} = 2.75 \cdot 10^{-3}$ enabled us to reduce the temperature measurement deviation by means of the DS18B20 sensor by 0.5ºC (see Fig. 5). The variation in the absolute deviation of temperature measurement does not exceed the permissible limits regulated by the manufacturer (see 1 and 3 in Fig. 4). The variation in the absolute deviation of temperature measurement in the range from +5 to +90ºC for the SHT11 sensor is shown in Fig. 6, where: 1 and 2 – maximum values in the technical specifications; 3 and 4 – before and after calibration.

The results of the SHT11 sensor research ($k = 2$) showed that the variation in the absolute deviation of temperature measurement before calibration (see 3 in Fig. 6) is beyond the maximum limits regulated by the technical specifications of the SHT11 sensor (see 1, 2 in Fig. 6) in the temperature range from +20 to +32ºC. The value of the multiplicative component of the deviation, which is equal to 0.301ºC in the range from +5 to +90ºC, as well as the additive component, which is equal to 0.797ºC, is set (see **Table 2** and Fig. 6).

To reduce the systematic deviation of the temperature measurement results, the value $a_{calibr_{k=2}} = 9 \cdot 10^{-3}$ is set. At this value, $\sigma\Delta T_{calibr\ k=2} = 0.137°\text{C}$, and $a_{0calibr_{k=2}} = 0.391°\text{C}$ at which $\overline{\Delta T_{calibr\ k}} = 0.000\ °\text{C}$.

The use of the calibration equation (10) with the values $a_{0calibr_{k=2}} = 0.391\ °\text{C}$ and $a_{calibr_{k=2}} = 9 \cdot 10^{-3}$ allows reducing the measurement deviation of the SHT11 temperature sensor by 0.8ºC (see 4 in Fig. 6). In addition, the variation in the absolute temperature measurement deviation is not beyond the permissible limits regulated by the manufacturer (see 1 and 2 in Fig. 6). Similar studies were carried out for the SHT21 ($k = 3$), BMP180 ($k = 4$), BME280 ($k = 5$) and DHT22 ($k = 6$) sensors. The research results are summarized in **Table 2**.

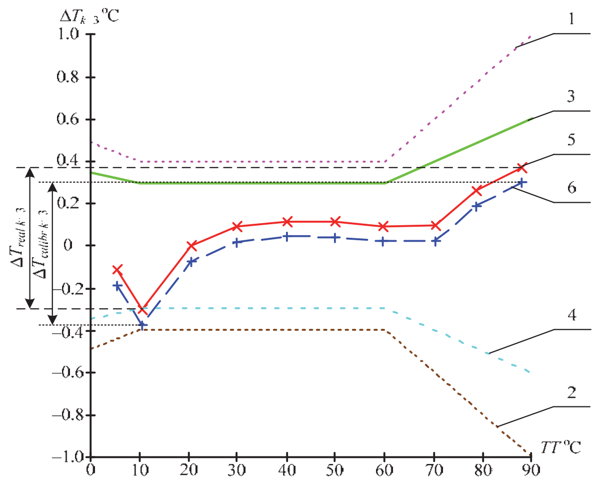

Fig. 7 – *Variation in the absolute deviation of temperature measurement in the range from +5 to +90ºC for the SHT21 sensor* ($k = 3$).

The variation in the absolute deviation of the temperature measurement in the range from +5 to +90ºC for the SHT21 sensor is shown in Fig. 7, where: 1 and 2 – maximum values in the technical specifications; 3 and 4 – nominal values regulated by technical specifications; 5 and 6 – before and after calibration.

The variation in the absolute deviation of the temperature measurement in the range from +5 to +90ºC for the BMP180 sensor is shown in Fig. 8, where: 1 and 2 – maximum values in the technical specifications; 3 and 4 – nominal values regulated by technical specifications; 5 and 6 – before and after calibration.

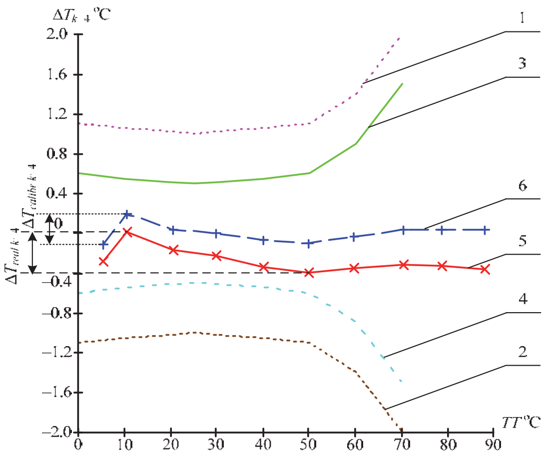

Fig. 8 – *Variation in the absolute deviation of temperature measurement in the range from +5 to +90ºC for the BMP180 sensor* ($k = 4$).

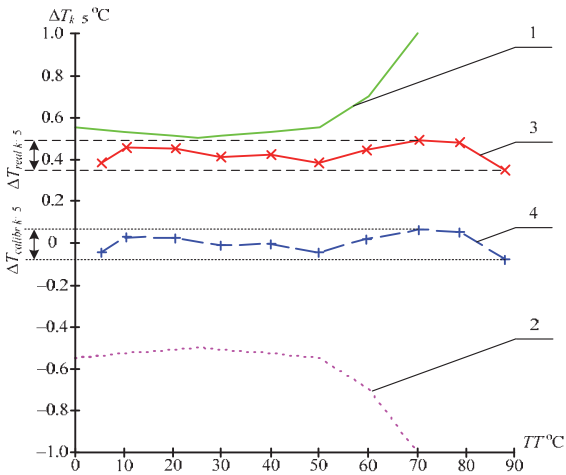

Fig. 9 – *Variation in the absolute deviation of temperature measurement in the range from +5 to +90ºC for the BME280 sensor* ($k = 5$).

The variation in the absolute deviation of temperature measurement in the range from +5 to +90ºC for the BME280 sensor is shown in Fig. 9, where: 1 and 2 – maximum values in the technical specifications; 3 and 4 – before and after calibration.

The variation in the absolute deviation of temperature measurement in the range from +5 to +90ºC for the DHT22 sensor is shown in Fig. 10, where: 1 and 2 – maximum values in the technical specifications; 3 and 4 – before and after calibration.

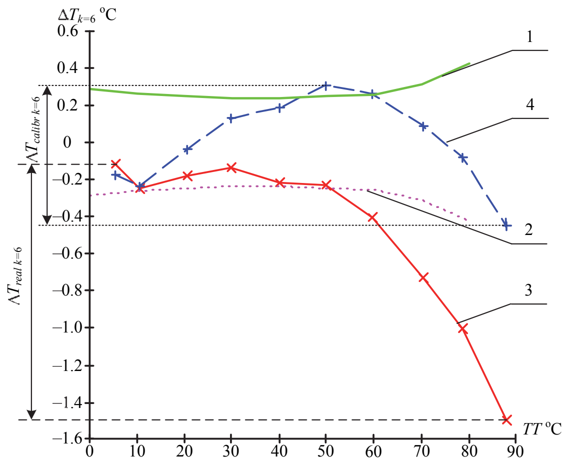

Fig. 10 – *Variation in the absolute deviation of temperature measurement in the range from +5 to +90ºC for the DHT22 sensor* ($k = 6$).

In-depth analysis of the research results, allows concluding that by using the linear calibration equation (10) with the established values of the calibration coefficient and the additive calibration component for the corresponding sensor:

- the absolute deviation of temperature measurement by the SHT21 sensor is reduced by 0.07ºC (see 6 in Fig. 7), and the results of temperature measurements before and after calibration do not exceed the permissible limits regulated by the manufacturer (see 1 and 2 in Fig. 7);
- the measurement deviation of the temperature measurement by the BMP180 sensor is reduced by 0.28ºC (see 6 in Fig. 8), and the results of temperature measurements before and after calibration do not exceed the permissible limits (see 3 and 4 in Fig. 8);
- the absolute deviation of temperature measurement by the BME280 sensor is reduced by 0.4ºC (see 4 in Fig. 9), and the results of temperature measurements before and after calibration do not exceed the permissible limits regulated by the manufacturer (see 1 and 2 in Fig. 9);

– the temperature measurement deviation of the DHT22 sensor is reduced by 0.5ºC (see 6 in Fig. 10), and the results of temperature measurement before calibration exceed the permissible limits in the temperature range from +50 to +90ºC (see 1 and 2 in Fig. 10). After using the calibration equation, the measurement results are beyond the permissible limits only in the temperature range from +45 to +65ºC (see 1 and 2 in Fig. 10).

5 Prospective Research Areas

Priority areas of research on the metrological provision of modern means of automatic monitoring and control of temperature regimes of growing crops in greenhouse conditions are as follows:

– extrapolation of the results of laboratory tests of temperature sensors on real agricultural facilities for growing crops under industrial greenhouse conditions;

– optimization and adaptation of the structural-algorithmic organization of the computerized system for measurement monitoring and automatic control of temperature regimes of cultivation, taking into account the types and periods of the plant growing seasons;

– justification of scientific and applied provisions regarding the effect of air temperature in the growing area, soil temperature in the root zone and irrigation water temperature on the qualitative and quantitative indicators of the greenhouse crops growth.

6 Conclusion

As a result of the research, the article solves a relevant scientific and applied problem regarding the assessment and analysis of the metrological characteristics of available digital temperature sensors for greenhouse conditions. This makes it possible to substantiate the scientific and applied provisions for improving the efficiency of greenhouse complexes through the development, design and implementation of high-precision and operational methods and means of monitoring and controlling the temperature regimes of growing crops under greenhouse conditions. The research findings presented in the article are the following:

– analysis and logical synthesis of the existing results of scientific research on the development of computerized monitoring systems and temperature control for growing greenhouse vegetable crops;

– synthesis of scientific and applied provisions on the structural-algorithmic organization and technical implementation of microprocessor means for obtaining calibration characteristics and for evaluating the metrological parameters of the serial available sensors for the physical medium temperature under greenhouse conditions;

– a particular type of linear calibration equation for the temperature sensors under study, which makes it possible to reduce the value of the systematic measurement deviation by 0.5ºC for DS18B20, by 0.8ºC for SHT11, by 0.07ºC for SHT21, by 0.28ºC for BMP180, by 0.4ºC for BME280 and by 0.5ºC for DHT22 in the temperature range from +5 to + 90°C;

– experimental confirmation of the fact that for the SHT21, BMP180 and BME280 sensors the value of the systematic absolute deviation of temperature measurement does not exceed the regulated values indicated in the technical specifications of the sensors;

– the use of the linear calibration equation for the temperature sensors DS18B20, SHT11 and DHT22 allows us to ensure that the value of the systematic absolute deviation in temperature measuring does not exceed the permissible limits regulated by the manufacturers of these sensors;

– justification of priority research areas on the metrological provision of modern means of automatic monitoring and control of temperature regimes of growing crops under greenhouse conditions.

The results of analytical and experimental studies can be used as a scientific and practical basis for justifying agrotechnical methods to improve the quality indicators and the volume of crops cultivation under protected ground conditions.

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